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1 **Strong reorganization of multi-domain microbial networks associated with primary producers**  
2 **sedimentation from oxic to anoxic conditions in an hypersaline lake**

3

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18

19 **ABSTRACT**

20

21 Understanding the role of microbial interactions in the functioning of natural systems is often impaired by  
22 the levels of complexity they encompass. In this study, we used the relative simplicity of an hypersaline  
23 crater lake hosting only microbial organisms (Dziani Dzaha) to provide a detailed analysis of the microbial  
24 networks including the three domains of life. We identified two main ecological zones, one euphotic and oxic  
25 zone in surface, where two phytoplanktonic organisms produce a very high biomass, and one aphotic and  
26 anoxic deeper zone, where this biomass slowly sinks and undergoes anaerobic degradation. We highlighted  
27 strong differences in the structure of microbial communities from the two zones and between the microbial  
28 consortia associated with the two primary producers. Primary producers sedimentation was associated with a  
29 major reorganization of the microbial network at several levels: global properties, modules composition,  
30 nodes and links characteristics. We evidenced the potential dependency of Woesearchaeota to the primary  
31 producers' exudates in the surface zone, and their disappearance in the deeper anoxic zone, along with the  
32 restructuring of the networks in the anoxic zone toward the decomposition of the organic matter.  
33 Altogether, we provided an in-depth analysis of microbial association network and highlighted putative  
34 changes in microbial interactions supporting the functioning of the two ecological zones in this unique  
35 ecosystem.

36

37 **Keywords:** Archaea, Bacteria, Picoeukaryota, hypersaline ecosystem, microbial association network,  
38 *Arthrospira fusiformis*, *Picocystis salinarum*

39

40

## 41 INTRODUCTION

42

43 The functioning of ecological systems depends on a synergy of interacting organisms  
44 (Anantharaman *et al.* 2016; Hug and Co 2018). However, the levels of complexity in most natural systems  
45 and the communities they host make understanding the role of these interactions in the functioning of the  
46 system a daunting task. This is particularly true in microbial systems, which host thousands of species and  
47 where interactions are difficult to assess owing to the microscopic nature of the partners involved. In  
48 addition, microorganisms not only interact with each other but also with their predators, whether these are  
49 micro- (*e.g.* zooplankton, protozoa) or nanoscopic (*i.e.* phages), along with macro-organisms and their  
50 associated microbiomes (Troussellier *et al.* 2017). Such biological complexity is almost always associated  
51 with environmental variability, which modifies the composition of communities, and thus the interactions  
52 between their members, across spatial and temporal scales (Sunagawa *et al.* 2015; Bahram *et al.* 2018).  
53 Altogether, these various levels of complexity and variability limit our capacity to characterize, describe and  
54 ultimately understand the role of biological interactions in the functioning of natural systems. Nonetheless,  
55 some ecosystems present lower biological diversity and more stable environmental conditions, facilitating  
56 the study of the communities they host and the interactions between organisms. These include for instance  
57 aquatic ecosystems with extreme physico-chemical conditions such as hypersaline lacustrine ecosystems  
58 (Ventosa *et al.* 2015), which typically host a lower richness and diversity of organisms than other types of  
59 lakes and present less variable environmental conditions.

60 The recently characterized Lake Dziani Dzaha (Leboulanger *et al.* 2017) exhibits particularly stable  
61 geochemical and biological characteristics, and constitutes a modern analog of Precambrian ecosystems  
62 (Cadeau *et al.* 2020). This tropical thalassohaline crater lake is characterized by an important methane  
63 production (Cadeau *et al.* 2020; Sarazin *et al.* 2020) and contains only microbial organisms. It is  
64 characterized by extreme geochemical characteristics (salinity exceeds 60 psu, periodically high  $H_2S/HS^-$   
65 concentrations, pH is higher than 9) along with the presence of at least two contrasted environments. An oxic  
66 layer, in surface, allowing autotrophic metabolisms, where a very high and stable biomass is produced  
67 ( $mean_{2014-2015} = 652 \pm 179 \mu g \text{ chlorophyll a.L}^{-1}$ ), mostly by two co-dominant photosynthetic organisms that  
68 exhibit complementary functional traits (Bernard *et al.* 2019), the cyanobacteria *Arthrospira fusiformis* and  
69 the picoeukaryote *Picocystis salinarum* (Chlorophyta, Cellamare *et al.*, 2018). Beside these two dominant  
70 taxa, the lake hosts bacterial, archaeal and eukaryotic communities of low diversity (Hugoni *et al.* 2018). In  
71 the deeper layers of the lake, *i.e.* below 2 m depth, there is no light nor oxygen all year round. A halocline  
72 periodically develops at around 2 m depth, mostly due to a density contrast induced by the abundant rainfalls  
73 of the rainy season. When it is in place, the concentration of  $H_2S/HS^-$  in the deep layers is high ( $mean_{2014-2015}$   
74  $= 3052 \pm 1963 \mu mol.L^{-1}$ ). In this anoxic layer the primary producers decrease drastically in abundance while

75 still maintaining high abundances (*i.e.*  $10^5$ - $10^6$  cells.mL<sup>-1</sup>), and the bacterial and archaeal communities  
76 change along the depth profile (Hugoni *et al.* 2018). This water column is structured around the two  
77 dominant phytoplanktonic taxa (Leboulanger *et al.* 2017; Hugoni *et al.* 2018; Bernard *et al.* 2019). In the  
78 oxic surface layer, they constitute the point of entrance of the energy in the system and are expected to  
79 redistribute this energy to the whole microbial consortium in the form of secondary metabolites (Seymour *et*  
80 *al.* 2017). In the anoxic and light-depleted layer, the photosynthetic biomass is also the main source of  
81 energy and is anaerobically decomposed by heterotrophic prokaryotes. Consequently, the structure of the  
82 microbial assemblages and the interactions between organisms are of particular interest to better understand  
83 this atypical system and further, owing to its analogies with some Precambrian environments, to ultimately  
84 gain insights into their functioning.

85         During the last decade, association networks have gained a lot of interest in microbial ecology and  
86 their use for deciphering potential microbial interactions is now widespread (Faust *et al.* 2015; Röttjers and  
87 Faust 2018; Delmas *et al.* 2019; Faust 2021). This appeal for network approaches comes from their ability to  
88 synthesize in a single object (*i.e.* a graph), the amount of information that is contained in dozens or hundreds  
89 of microbial community profiles, each of them being composed of thousands of features (*e.g.* OTUs, ASVs,  
90 genes). However, most studies report only the analyses of global network properties (*e.g.* number of nodes or  
91 links, diameter, centralized metrics) and there are few studies that dare to dive into the complexity of the  
92 graph objects to provide deeper analyses of their structure. Indeed, networks are organized into different  
93 structural levels (network, modules, nodes and links) that complement each other and could provide deeper  
94 insights about the studied system if considered simultaneously (Niquil *et al.* 2020). Nodes identity and  
95 associations with each other provide information on their putative interactions, modules are groups of taxa  
96 closely associated that could correspond to functional groups with similar or complementary capabilities, and  
97 global network characteristic represent the system as a whole (Karimi *et al.* 2017; Pellissier *et al.* 2018;  
98 Delmas *et al.* 2019). In this study, we analyzed the attributes of microbial association networks from the two  
99 main ecological zones of the Dziani Dzaha lake (*i.e.* oxic and anoxic) at four structural levels of resolution  
100 (network, module, nodes, links), in order to better understand the linkages between network structure,  
101 interactions between organisms and the functioning of microbial communities in these zones.

102         In the present work, we aimed at understanding the associations between microorganisms from the  
103 three domains of life in the Dziani Dzaha lake to understand in greater details the functioning of this  
104 exceptional and unique ecosystem, hopefully also shedding light on Precambrian ecosystems. We  
105 hypothesized that the structure of the microbial assemblages and the interactions between the organisms  
106 surrounding the dominant taxa (the prokaryote *Arthrospira fusiformis* and the picoeukaryote *Picocystis*  
107 *salinarum*), will change between zones, but this remains to be tested. To achieve our purpose, we used data  
108 from a metabarcoding study of the three domains of life and applied a statistical network approach to

109 characterize the associations between microorganisms and the structure of microbial networks in the different  
110 ecological zones of the lake.

111

112

## 113 MATERIAL AND METHODS

114

### 115 Study site, sampling, and environmental parameters

116 The Dziani Dzaha lake is a volcanic crater lake located on the Mayotte Island (Western Indian  
117 Ocean), that is characterized by an important salinity (ranging from 34 to 71 psu), a high alkalinity (0.23  
118 mol.L<sup>-1</sup>) and a permanent green color due to high primary production. Water samples were collected along a  
119 depth profile located at the deepest point of the lake (0m, 1m, 2.5m, 5m, 11m, 15m and 17m depth), using a  
120 horizontal 1.2L Niskin bottle. Sampling campaigns occurred at end of both rainy (April) and dry (October-  
121 November) season, over two consecutive years (2014 and 2015). Vertical profiles for pH, dissolved O<sub>2</sub>,  
122 temperature and conductivity were taken using either a MPP350 probe connected to a Multi 350i data logger  
123 (WTW GmbH) or a YSI 6600 probe. Salinity was calculated from conductivity and temperature measures.  
124 The concentrations of soluble sulfide ( $\Sigma S(-II)$ , hereafter referred to H<sub>2</sub>S/HS<sup>-</sup>), ammonium and ammonia  
125 ( $\Sigma N(-III)$ ; NH<sub>4</sub>/NH<sub>3</sub>), and soluble-reactive phosphorus (SRP; PO<sub>4</sub><sup>3-</sup>) were determined by colorimetry in the  
126 field-lab using Aqualytic SpectroDirect spectrophotometer and Merck reagents kits. The concentration of  
127 Chla was analyzed after extraction using 96% ethanol by ultra-sonication in an ice bath for 30", and further  
128 extraction was allowed overnight at 4 °C in dark. The extract was filtered, and the filtrate was analyzed  
129 spectrophotometrically at 400–750 nm. The concentration of Chla was calculated according to Camacho *et*  
130 *al.* (2009).

131

### 132 Delineation of ecological zones

133 To analyze the structure of association networks in the different ecological zones observed in the  
134 Lake Dziani Dzaha, the first step was to delineate these zones. To do so, we used six variables describing the  
135 physico-chemistry of the water column (temperature, pH, percentage of oxygen saturation, salinity, redox  
136 potential (Eh), H<sub>2</sub>S/HS<sup>-</sup> concentration) and one biological variable (total chlorophyll a concentration). These  
137 data were scaled to account for their differences in range and absolute values (*scale* function in R) and we  
138 computed Euclidean distance between samples. Then, we applied a kmeans classification approach using the  
139 *NbClust* package (Charrad *et al.* 2014) to determine the optimal number of groups based on a consensus  
140 estimated across 30 different indices evaluating the quality of the partition of samples into groups.  
141 Visualization of samples clustering was done using a hierarchical classification based on the Ward clustering  
142 algorithm. Differences between the identified ecological zones in terms of environmental parameters were  
143 tested using Wilcoxon rank sum test and p-values were adjusted using the Bonferroni correction.

144

#### 145 **DNA extraction, Illumina sequencing and sequence processing**

146         Details regarding methodological procedures were described in Hugoni *et al.* (2018). Briefly, total-  
147 to-3 $\mu$ m and 3-to-0.2 $\mu$ m fractions of water samples were collected through successive filtration on 3  $\mu$ m and  
148 0.2  $\mu$ m filters. DNA was extracted using the Power Water DNA isolation kit (MoBio Laboratories).  
149 Amplicons libraries were produced in triplicate using the universal bacterial primers 357F (Schuurman *et al.*  
150 2004) and 926R (Walters *et al.* 2016), archaeal 519F and 915R (Hugoni *et al.* 2015) and eukaryotic 515F  
151 (Caporaso *et al.* 2011) and 951R (Hugoni *et al.* 2018). Sequencing was done on an Illumina HiSeq 2500  
152 system (GATC Biotech, Konstanz, Germany). Paired-end reads from both 3 $\mu$ m and 0.2 $\mu$ m filters were  
153 pooled. Trimming, clustering and chimeric sequences removing was performed using the FROGS pipeline  
154 (Escudié *et al.* 2018). To allow sample comparisons, bacterial, archaeal and eukaryotic datasets were  
155 randomly resampled to 124,779, 37,529 and 36,840 sequences, respectively.

156

#### 157 **Analyze of composition and structure of microbial communities**

158         Microbial communities from the identified ecological zones were compared using PERMANOVA  
159 (Anderson 2001) as implemented in the R package *vegan* (function *adonis*, Oksanen *et al.*, 2016).  
160 Differences in community composition were tested using Jaccard dissimilarity and differences in structure  
161 were tested using Bray-Curtis dissimilarity. This was done for the three domains of life combined and  
162 separately for each of them. The OTUs that contributed the most to differences in structures between zones  
163 were subsequently identified using similarity percentage (SIMPER) analysis (function *simper* in the R  
164 package *vegan*).

165

#### 166 **Construction and characterization of association networks**

167         Microbial association networks for each community were constructed using SParse Inverse  
168 Covariance Estimation for Ecological Association Inference (Kurtz *et al.* 2015), as implemented in the R  
169 package *SpiecEasi* (Kurtz *et al.* 2019). This approach allows the combination of independent compositions  
170 matrices generated during separate sequencing run and is thus well suited for cross-domain studies (Tipton *et*  
171 *al.* 2018). We followed the overall methodology described in Wagg *et al.* (2019). First, we used centered log-  
172 ratio transformation (Gloor *et al.* 2017) on the OTUs tables from the three domains and combined them to  
173 generate a meta-network using all available samples from each zone. The most parsimonious network  
174 structure was identified for each zone using Stability Approach to Regularization Selection (StARS, Liu,  
175 Roeder, & Wasserman, 2010) and the Meinshausen and Buhlmann algorithm. Second, sub-set networks for  
176 each sample were extracted from the meta-network by selecting OTUs detected within the sample and these  
177 were used to estimate networks characteristics at the sample level.

178 Association networks are composed of nodes (OTUs) that can be more or less connected to each  
179 other by edges (associations). Different but complementary insights about the studied system can be gained  
180 depending on whether one characterizes the properties of the entire network, of its individual components  
181 (nodes or groups of nodes, *i.e.* modules) or their relationships (Niquil *et al.* 2020). Here we analyzed  
182 networks attributes at four levels of resolution (network, module, nodes, links) using the functions from the  
183 R package *igraph* (Csardi and Nepusz 2006).

184 First, the global characteristics of each sub-network were described using indices from the graph  
185 theory: number of nodes and edges, network density, average inter-nodes distance, centralized degree,  
186 betweenness and closeness, hub score (Pellissier *et al.* 2018; Delmas *et al.* 2019).

187 Second, we identified modules, *i.e.* groups of taxa that tend to have many associations between them  
188 and fewer outside of the group, and that potentially constitute a functional group because of their similar or  
189 complementary capabilities. There are many algorithms available to cluster taxa into modules and to reduce  
190 biases related to the choice of a single method we used six algorithms: edge betweenness, fast greedy,  
191 infomap, leading eigen vector, Louvain and walktrap. Then, we analyzed only the clustering from the  
192 algorithm that provided a number of modules within each zone comparable to the average estimated across  
193 all methods. Then, we compared the sizes and taxonomic composition of modules from the two zones.

194 Third, we computed centrality indices at the node level (degree, betweenness, closeness and hub  
195 score) and identified central and peripheral nodes as those whose average rank across indices fell within the  
196 first and tenth decile. Then, we compared taxonomic composition of central and peripheral nodes from the  
197 two zones.

198 Fourth, we identified the proportion of positive and negative links in different zones, the links that  
199 were maintained between zones along with the identity of the nodes associated with *Arthrospira fusiformis*  
200 and *Picocystis salinarum*.

201

## 202 **Phylogenetic analyses of the Dziani Dzaha microbial communities**

203 Representative OTUs sequences were compared with the SILVA database v 138.1 (Kim *et al.* 2019)  
204 using BlastN (Camacho *et al.* 2009) to identify the percentage of similarity between the queried sequences  
205 and their top hits. To assess sequences commonness, the distribution of their percentage identity was fitted  
206 with a normal distributions by using a maximum-likelihood method implemented in the PAST program  
207 (Hammer, Harper and Ryan 2001). This approach allowed us to define sequences as known (>95% identity  
208 to the SILVA database), poorly characterized (80-95%) or unknown (<80%).

209

210

211

212

## 213 RESULTS

214

### 215 Delineation of two strikingly different ecological zones in the lake

216 The kmeans classification approach suggested that the best grouping of samples based on their  
217 physico-chemical characteristics was in two clusters, one containing 16 samples and the other 12 (Figure 1).  
218 Overall, the samples were clustered according to depth (Figure 1-A). One cluster contained all the surface  
219 samples (*i.e.* depth from 0m to 2.5m) and two deeper samples (5m and 11m, Figure 1-B). The other contained  
220 all the samples taken at 5m depth and below, plus two samples from 2.5m. Overall, the depth of clusters  
221 separation corresponded well with the halo/chemo-cline observed periodically in the lake at the end of rainy  
222 seasons and below which reduced species (including  $\text{H}_2\text{S}/\text{HS}^-$  and  $\text{NH}_4^+/\text{NH}_3$ ) accumulated. At the end of  
223 dry seasons although the halocline was not present and the concentration of reduced species remained quite  
224 low, bottom waters remained anoxic below 2 m depth. The surface samples exhibited significantly higher  
225 values in redox potential (Eh) and chlorophyll-a concentration while the bottom samples exhibited higher  
226 values in salinity and periodically higher concentrations of  $\text{H}_2\text{S}/\text{HS}^-$  (Table 1, Wilcoxon rank sum test, p-  
227 values  $< 0.05$  with Bonferroni correction). The two groups of samples thus correspond well to two contrasted  
228 ecological zones. Hereafter, the oxic and euphotic zone will be termed “surface” while the deeper anoxic and  
229 aphotic zone will be termed “bottom”. This bottom layer could itself be separated in two sub-zones,  
230 alternating with time, depending on their concentration of reduced species which depends on the presence or  
231 absence of halocline. But our sample size was too low to allow a meaningful statistical characterization of  
232 the two sub-zones.

233

### 234 Similarity of Dziani Dzaha OTUs with reference databases

235 Overall, the Dziani Dzaha OTUs showed a little degree of similarity with the SILVA database, but  
236 this depended on the domain and phylum considered (Figures S1-S2-S3). We found that a third of bacterial  
237 (36%) and eukaryotic (34%) OTUs could be considered as well known ( $>95\%$  sequence similarity), while  
238 this proportion dropped to 23% for archaeal OTUs. For Bacteria, 61% of OTUs were poorly characterized  
239 (80-95% similarity) and only 3% were considered as unknown ( $<80\%$ ). The proportion of unknown OTUs  
240 was much greater in Archaea (15% including a large proportion of Woesearchaeota and Euryarchaeota from  
241 the MEG class) and Eukaryota (44%, including almost all the Stramenopiles and all the Jakobida).

242

### 243 Structure of microbial communities in the two zones

244 The total and average OTUs richness were lower in the surface zone ( $n = 410$  and  $281 \pm 36$ , on  
245 average) compared with the bottom one ( $n = 427$  and  $317 \pm 30$  on average, t.test p-value  $< 0.05$  for the  
246 average richness). A total of 399 OTUs were shared between the two zones, which represented 91% of all the  
247 observed OTUs.



248 The microbial communities from the two environmental zones presented significantly different  
249 composition and structure (PERMANOVA,  $p$ -value  $< 0.05$ ). This was confirmed for the multi-domain  
250 communities and for each domain separately (Table 2). The composition of bacterial communities differed  
251 the most, followed by archaeal and picoeukaryotic communities, as shown by the decreasing  $F$  values and  $R^2$   
252 of the PERMANOVA models. Differences were even stronger when considering OTUs abundance, as  
253 supported by higher  $F$  values of the PERMANOVA models. We identified 18 OTUs whose cumulative  
254 contribution represented 70% of the differences in structure between the microbial communities from the two  
255 zones (SIMPER analysis, Table S1). These included 9 bacterial, 7 archaeal and 2 eukaryotic OTUs. The  
256 highest bacterial contributor was by far the cyanobacteria *A. fusiformis*, followed by the Firmicutes ( $n = 4$ )  
257 and the Bacteroidetes ( $n = 3$ ). Archaea corresponded mostly to Woesearchaeota ( $n = 4$ ) and the methanogen  
258 group WSA2 ( $n = 2$ ), while the highest picoeukaryotic contributors were the picophytoplankton *Picocystis*  
259 and the protist *Jakoba libera*.

260

261

## 262 **Global characteristics of association networks**

263 The networks from the two zones differed significantly regarding most of the global network  
264 properties tested (Figure 2 and S4, Table 3). The networks from the surface zone had a significantly lower  
265 number of nodes (272 vs. 310) and edges (790 vs. 1099), which were associated with a longer network  
266 diameter (maximum path length), a lower density and longer distance between nodes (*i.e.* average number of  
267 steps from one node to another). Centralized degree and hub score were lower in the surface zone.

268

269

## 270 **Composition of network modules**

271 The surface zone tends to have a higher number of modules across all clustering algorithms, but this  
272 was not significant ( $16.2 \pm 10.6$  and  $12.2 \pm 7.4$  for the surface and bottom zones, respectively, Wilcoxon test,  $p$ -  
273 value = 0.377). Hereafter, we present only the results for the walktrap algorithm as the number of identified  
274 modules (13 and 10 for surface and bottom zones, respectively) reflects the average value estimated across  
275 all algorithms (Table S2). In the surface zone, near half of the modules (7/13) included OTUs from the three  
276 domains of life against less than a third (3/11) in the bottom zone. We observed one module composed of  
277 Archaea only in each zone (S\_6 and B\_7, Figure 3), and there were two modules composed of Bacteria only  
278 in the bottom zone (B\_5 and B\_9).

279

280 In both zones, the two dominant phytoplanktonic species belonged to separate modules (S\_11 and  
281 B\_9 for *A. fusiformis* and S\_5 and B\_8 for *P. salinarum* in surface and bottom zones, respectively) and these  
modules represented most of the total number of sequences in both zones (Figure 3).

282 *A. fusiformis* surface module (S\_11) was composed of 22 OTUs belonging to three domains and 10  
283 phyla. Firmicutes were the most represented phylum (5 OTUs), followed by Woesearchaeota (4),  
284 Bacteroidetes (3), Euryarchaeota (3) and Proteobacteria (2). The number of OTUs within *A. fusiformis*  
285 modules increased from 22 in surface to 36 in the bottom zone (module B\_9, +64%). This was associated  
286 with a high dissimilarity in the composition and structure of the modules between zones, with dissimilarity  
287 ranging from 0.92 to 1 at the OTU level (Table S3). Changes in composition corresponded to the  
288 disappearance of all the archaeal (-8) and eukaryotic (-1, *Nitzschia* sp.) OTUs, which were replaced by  
289 Bacteria from the Firmicutes (+9), Bacteroidetes (+6), Proteobacteria (+4), Elusimicrobia (+2), along with  
290 Actinobacteria and Synergisetae (+1 each).

291 *P. salinarum* surface module (S\_5) was by far the one with the highest number of OTUs (n = 115),  
292 which belonged to three domains and 27 phyla. Again, the Firmicutes were the most diverse phylum (27  
293 OTUs), followed by Woesearchaeota (18), Bacteroidetes (11), Proteobacteria (11), Actinobacteria (7) and  
294 Euryarchaeota (7). Contrarily to *A. fusiformis*, the number of OTUs within *P. salinarum* modules decreased  
295 from the 115 in surface to 64 in the bottom zone (B\_8, -44%). Here again this was associated with a very  
296 high dissimilarity in module composition and structure between zones, with dissimilarity ranging from 0.8 to  
297 0.94 at the OTU level (Table S3). The diversity of Archaea dropped sharply from the surface to the bottom  
298 zone (-28 OTUs), with a notable loss of Woesearchaeota (-13) and Euryarchaeota (-6). Bacterial richness also  
299 decreased (-23 OTUs), with loss of Clostridiales (-8), Bacteroidia (-5) and Alphaproteobacteria (-8).  
300 Interestingly, while the number of picoeukaryotic OTUs remained stable (10) there was a strong turnover in  
301 their composition (> 0.75 and > 0.8 at the Order and OTU levels, respectively), with the replacement of  
302 Ascomycota (3 OTUs), Basidiomycota and Ciliophora (1 each) by the genus *Ancyromonas* (3 OTUs),  
303 *Jakoba* (3 OTUs) and *Suigetsumonas* (1).

304

305

### 306 **Characteristics of network nodes**

307 The node-level centrality indices differed between zones in terms of degree, closeness, and hub score  
308 (Wilcoxon test, p-values < 0.05), with the first two being higher in the bottom zone (Figure S5). We observed  
309 that the relationships between the average node rank across indices and its standard deviation exhibited a bell  
310 shape (Figure S6), meaning that the most central and most peripheral nodes were the same whatever the  
311 index and that the centrality of many nodes in the network depended on the selected index. Hereafter, we  
312 analyze in detail the taxonomy of the most central and peripheral nodes, identified as those whose average  
313 rank across indices fell within the first and tenth decile (n = 36 and 37 in surface and bottom zones,  
314 respectively).

315 Picoeukaryotes and Archaea represent around 10% and 30% of the total number of OTUs,  
316 respectively. However, Picoeukaryotes appeared over-represented in the central nodes, as they represented

317 17% and 14% of the central nodes in the surface and bottom zones, respectively (Figure 4). Contrarily,  
318 Archaea were over-represented in peripheral nodes, as they represented >50% of them in both zones. In  
319 addition, we observed a strong turnover in the taxonomic composition of both central and peripheral nodes  
320 (Jaccard dissimilarity = 0.92), with only 5 out of 36 OTUs being central in both zones. These included 4  
321 Bacteria (2 Clostridiales, 1 Anaerolineae and 1 Deltaproteobacteria) and one WSA2 Archaea. Among the taxa  
322 that lost their central position in the network in the bottom zone, we identified Stramenopiles, Bacteroidetes,  
323 Woesearchaeota, Acidobacteria and the MEG Euryarchaeota, while the taxa that became central included  
324 mainly Jakobida, Firmicutes and Proteobacteria (Table S4).

325 The two dominant taxa were not identified as peripheral nor central nodes but several members of  
326 their modules were identified as central nodes. In surface, 26 of the 36 central OTUs (72%) originated from  
327 *P. salinarum* module (S\_5), including notably five Firmicutes, four Woesearchaeota and four Bacteroidetes,  
328 while only two were from *A. fusiformis* module (S\_11). In the bottom zone, the dominant taxa modules were  
329 less represented in central nodes (4 and 9 for *A. fusiformis* and *P. salinarum*, respectively), and these OTUs  
330 corresponded mostly to Firmicutes (n = 2 and 4), with also one Jakobida OTUs from *P. Salinarum* module.

331

332

### 333 **Characteristics of network links**

334 Overall, the proportion of positive links was lower in the surface zone (54% vs. 60%) but their  
335 absolute strength was higher (0.15 vs. 0.13). We observed that seven out of the ten strongest positive links  
336 involved two archaeal OTUs and six of them involved pairs of OTUs from the same class. Among these  
337 strong links, Woesearchaeota and WSA2 were only involved in links from the surface while Euryarchaeota  
338 (Methanomicrobia and Thermoplasmata) were found in strong links from both zones. We found 44 links that  
339 were conserved in both zones, which represents less than 2% of the total number of links, and they were  
340 positive for a wide majority (84%, 37/44). These conserved links involved 79 OTUs, with only 9 OTUs  
341 being involved in more than one link. These included three Woesearchaeota and one Euryarchaeota, two  
342 Clostridiales and one Bacteroidetes, along with the Eukaryote *Planomonas micra*.

343 The dominant taxa exhibited a similar number of linkages but the proportion of positive links was  
344 much higher in *P. salinarum* (57 and 86%, in surface and bottom zone) than *A. fusiformis* (43 and 22%). The  
345 taxonomic identity of the OTUs directly linked with dominant taxa differs greatly between zones and no link  
346 was maintained in both zones (Table 4).

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## 352 **DISCUSSION**

353

### 354 **The two contrasted environmental zones of the water column**

355         Samples clustering based on their physico-chemical characteristics confirm previous observations of  
356 the existence of two ecological zones (Leboulanger *et al.* 2017), one oxic and euphotic layer in surface  
357 dominated by photosynthetic processes (0-2.5m depth), and one anoxic and aphotic zone at greater depth (2-  
358 17m). The depth of zone separation corresponded well with the halo/chemo-cline periodically observed in  
359 the lake in the form of large changes in salinity, redox potential, H<sub>2</sub>S/HS<sup>-</sup> and chlorophyll *a* concentration.  
360 The periodical stratification of the lake that results from rainfalls was shown to be associated with the  
361 presence of a third ecological zone in the deepest part of the lake (*i.e.* below 14m) where the concentrations  
362 of H<sub>2</sub>S/HS<sup>-</sup> are the highest (Sarazin *et al.* 2020). However, the statistical approach used here to delineate  
363 ecological zones was not able to separate deep samples from the stratified period from the others deep  
364 samples. Nonetheless, our results validate previous studies on Dziani Dzaha lake suggesting that the two  
365 main zones of the lake represent totally different environments from the microbial point of view.

366

### 367 **Reorganization of microbial communities and networks from one zone to the other**

368         Despite 91% of shared OTUs between zones, the distribution of their abundances strongly differed  
369 between them, suggesting a reorganization of the microbial communities. This included notably changes in  
370 abundances within the bacterial Firmicutes and Bacteroidetes phyla, along with the archaeal Woesearchaeota  
371 phylum and the methanogen group WSA2. In addition, we observed slightly higher total (+4%) and average  
372 (+13%) number of OTUs in the bottom zone.

373         These differences in community structure were associated with modifications of the structure of  
374 association networks at several levels of their organization. Global network properties suggested that the  
375 network increased in complexity in the bottom zone, with more taxa being involved and more connections  
376 between them, and became more compact, as the inter node distance shortened and its density increased. In  
377 addition, the associations between taxa were weaker and more positive in the bottom zone. Overall, these  
378 results provide a picture of a more balanced network in the bottom zone, with a high number of inter-taxa  
379 associations, most likely corresponding to cross-feeding and metabolic handoff (Anantharaman *et al.* 2016;  
380 Hug and Co 2018), in order to anaerobically degrade the carbon provided by the lysis of sinking cells from  
381 the primary producers (10% of the cells remaining in the bottom zone, (Bernard *et al.* 2019). It was  
382 previously shown that strong dominance by cyanobacteria in freshwater plankton communities, as observed  
383 here in the surface zone, resulted in unbalanced networks and a higher proportion of negative associations  
384 than when dominance is less marked (Escalas *et al.* 2019).

385         We observed a very strong reorganization of the components of Dziani Dzaha lake microbial  
386 networks from the surface to the bottom zone, with less than 2% of the links (n = 44) that were conserved in

387 both zones. In other terms, the associations between microorganisms changed from one zone to the other to  
388 support the different metabolic processes occurring in each zone. Here, we can hypothesize that the surface  
389 microbial network is organized around the metabolic byproducts released by the two primary producers  
390 while the bottom network is organized around the decomposition of their biomass.

391 In addition, the position of taxa within the network changed between zones, as 86% of the central  
392 OTUs in the surface zone were not central any more in the bottom zone. Only five OTUs were found to be  
393 central within both zones. These included two Firmicutes from the Clostridia class: one was a  
394 Halanaerobiales, a group of anaerobic and halophilic organisms presenting a great metabolic diversity  
395 including the ability to ferment carbohydrates and to grow chemolithoautotrophically on hydrogen and  
396 elemental sulfur, and the other a Peptostreptococcaceae, recognized as hyper-ammonia-producing bacteria  
397 (Gomes Carvalho Alves *et al.* 2021). The remaining two bacterial OTUs included a Bdellovibrionaceae  
398 (Deltaproteobacteria), which are intraperiplasmic predator that prey upon a variety of plant-pathogenic and  
399 growth-enhancing Bacteria (Jurkevitch *et al.* 2000), and an Anaerolineaceae (Chloroflexi), a family found  
400 in sulfidic environments and known for their capacity to degrade hydrocarbons and participate in  
401 syntrophic CH<sub>4</sub> production (Liang *et al.* 2015). The last OTU was an archaeal WSA2, a group of  
402 methanogens that may bridge the carbon and sulfur cycles in eutrophic methanogenic environments (Nobu  
403 *et al.* 2016).

404 The number and composition of network modules also changed from one zone to the other. The total  
405 number of modules decreased (13 to 10), with notably a sharp drop in the number of modules composed of  
406 taxa from the three domains of life (7 to 3), and the presence of two modules composed of Bacteria only in  
407 the bottom zone. The lower number of modules in the bottom zone could be explained by its more  
408 homogeneous environmental conditions (*e.g.* Mühlenbruch *et al.*, 2018; Kharbush *et al.*, 2020) which could  
409 limit our ability to estimate co-variations of abundance between microorganisms, a prerequisite for the  
410 identification of modules. It is worth noting that ecological significance of network modules is not yet clearly  
411 defined nor understood (Faust 2021), and could correspond to groups of organisms (i) with similar  
412 environmental preferences (*e.g.* anaerobic Firmicutes), (ii) with complementary functional traits and that  
413 cooperate to realize a particular step in the nutrient cycle (*e.g.* fermentation of polysaccharides by  
414 Clostridiales), (iii) that consume each other and constitute a trophic network (*e.g.* Jakobida predation on  
415 bacteria) or (iv) that interact in a parasitic, commensal or symbiotic manner (*e.g.* associations between  
416 Woesearchaeota and primary producers).

#### 417 418 **Focus on microbial modules associated with the dominant primary producers**

419 We found that the two dominant primary producers, the prokaryote *Arthrospira fusiformis*  
420 (Cyanobacteria, Oscillatoriales) and the picoeukaryote *Picocystis salinarum* (Chlorophyta, Prasinophyceae),  
421 were members of distinct modules and thus were associated with different microbial consortia. The first

422 striking result is that the consortium associated with *P. salinarum* in the surface zone contained five times  
423 more OTUs than the one of *A. fusiformis* (105 vs. 22). Hence, the number of OTUs associated to the much  
424 smaller phytoplanktonic species was higher than the number of OTUs associated with the larger ones. This is  
425 contradictory with the expectation that the number of microbial taxa associated with phytoplanktonic cells is  
426 positively correlated with their size (Seymour *et al.* 2017). Regarding the taxonomic structure of these  
427 consortia in the surface zone, we observed similarities in the archaeal communities, with notably  
428 Woese archaeota being dominant, but bacterial and picoeukaryotic communities differed greatly. It is well  
429 known that several characteristics of phytoplanktonic taxa determine their associations with specific  
430 prokaryotic taxa (Goecke *et al.* 2013; Guedes *et al.* 2018; Jackrel *et al.* 2021). Hence, different hypotheses  
431 can be proposed to explain the unexpected differences between the two phytoplanktonic species modules in  
432 terms of OTUs number and taxonomic classification.

433  
434 First, it could be related with the metabolic differences between the two dominant species, their  
435 ability to secrete various type of organic molecules and thus to support different microbial consortia  
436 (Grossart *et al.* 2005; Bagatini *et al.* 2014; Guedes *et al.* 2018). Indeed, in pelagic marine ecosystems,  
437 phytoplankton constitute a source of a large diversity of organic molecules that influence heterotrophic  
438 prokaryotes, including substrates that support their growth (Fouilland *et al.*, 2014) but also signaling  
439 molecules that determine synergetic or antagonist relationships among and with them (*e.g.* Amin *et al.* 2015;  
440 Cirri and Pohnert 2019). High concentrations of dissolved organic carbon were reported in the euphotic layer  
441 of the Dziani Dzaha lake (*i.e.* 3-9 mMol.L<sup>-1</sup>, Sarazin *et al.* 2020), which likely result from the release of  
442 various organic molecules by the large biomasses of the cyanobacteria *A. fusiformis* (600-700 µg Chla.L<sup>-1</sup>,  
443 Bernard *et al.*, 2019).

444 However, the two phytoplanktonic dominant taxa differ in many ways regarding their potential for  
445 exudates production, and particularly exopolysaccharides (EPS). EPS are generally composed of various  
446 substances, such as proteins, polysaccharides, lipids, humic-like substances, DNA, lipopolysaccharides and  
447 glycoprotein heteropolymers. EPS may be entirely released into the extracellular environment or may be  
448 associated with the cell surface as sheaths, capsules or slime (Pereira *et al.* 2009).  
449 Indeed, while *P. salinarum* appears unable to produce such polymers (Gaignard *et al.* 2019), the whole  
450 *Arthrospira* genus is well known for its ability to produce EPS and was shown, in experimental conditions,  
451 to produce the largest amounts with light and temperature levels similar to those of the euphotic layer of the  
452 Dziani Dzaha lake (Trabelsi *et al.* 2009; Phélippé *et al.* 2019). Antibacterial properties have been reported for  
453 cyanobacterial EPS (Xiao *et al.* 2018) and could explain the limited number of heterotrophic prokaryotic  
454 OTUs observed within *A. fusiformis* module. From a mechanical standpoint EPS act as a gel matrix which  
455 can protect *Arthrospira* against bacterial colonization or other stressors and then reduce the number of taxa  
456 able to move around the cyanobacteria surface. From a chemical standpoint, EPS are complex polymers that

457 only certain bacterial taxa are able to metabolize. Here, we found one Rhodobacteraceae and two ML635J-40  
458 aquatic group OTUs in *A. fusiformis* module, and six Rhodobacteraceae, seven ML635J-40 aquatic group  
459 and one Flavobacteria OTUs in *P. salinarum* module. The two bacterial groups are often associated with  
460 oceanic phytoplankton blooms for their putative role in the degradation of EPS, the Flavobacteria class  
461 (Bacteroidetes phylum) and the genus *Roseobacter* (Alphaproteobacteria from the Rhodobacteraceae family,  
462 (Buchan *et al.* 2014). Flavobacteria are able to transform high molecular weight (HMW) compounds such as  
463 EPS or transparent exopolymer particles (TEP) into low molecular weight (LMW) compounds (*e.g.* free  
464 amino acids, sugars, mono- and dicarboxylic acids, (Buchan *et al.* 2014), while *Roseobacter* is considered as  
465 mainly able to uptake and use the resulting LMW compounds (Taylor *et al.* 2014). This complementary  
466 association might underlie the co-occurrence of these two bacterial groups already reported in several studies  
467 (Pinhassi *et al.* 2004; Teeling *et al.* 2016). Another group of Bacteroidetes, the ML635J-40 aquatic group,  
468 observed in the dominant organisms' modules might be related to the degradation of EPS. This group was  
469 found to play a prominent role in the anaerobic digestion of *Arthrospira* in extreme alkaline conditions  
470 (Nolla-Ardevol, Strous and Tegetmeyer 2015) and the authors report that their representative sequences were  
471 classified as ML635J-40 using the SILVA database and as Flavobacteria using the RDP database. Thus, our  
472 results suggest the involvement of these taxa in the breakdown of the substrates released by the  
473 phytoplankton, and notably the EPS produced by *A. fusiformis*.

474         Less data is available on the biochemical composition and the kinds of molecules produced by the  
475 picoeukaryote *P. salinarum*. Chemical analyses revealed that it contains a large number of different  
476 carotenoids and that the sugar moieties of the cell wall matrix were mannose (68%), galactose (17%) and  
477 glucose (5%) (Lewin *et al.* 2000), while the major fibrous component of its cell wall is polyarabinose. *P.*  
478 *salinarum* contains a high proportion of lipids, especially when the cells are submitted to nitrogen limitation  
479 (Tarazona Delgado *et al.* 2021), and strains isolated from Mono Lake synthesize a variety of fatty acids, with  
480 palmitic acid (C<sub>16</sub>) being the most abundant (Phillips *et al.* 2021).

481         Second, the unexpected difference in the number OTUs in the two phytoplanktonic species modules  
482 could be a consequence of physical differences between them (Bernard *et al.* 2019). Indeed, with an average  
483 biovolume of 10  $\mu\text{m}^3$  *P. salinarum* appears to belong to free living microbes, while *A. fusiformis* is on  
484 average 23.5 times larger (235  $\mu\text{m}^3$ ). In addition to its smaller size, *P. salinarum* has a surface/volume ratio  
485 (2.2) that is five time higher than the one of *A. fusiformis* (0.45). As a result of these two features, *P.*  
486 *salinarum* is well mixed with free living microorganisms, which increases its chances of interacting with  
487 them and could explain the higher number of OTUs observed in its module. A step further, *A. fusiformis* and  
488 its surrounding EPS may be assimilated to the large size particles observed in marine ecosystems where  
489 anoxic micro-zones can develop (Bianchi *et al.* 2018), which could explain the presence of Clostridiales in *A.*  
490 *fusiformis* module. It is thus likely that around the circle of primary EPS degraders intimately associated to  
491 *A. fusiformis* (*e.g.* Rhodobacteraceae, ML635J-40 aquatic group), many free-living OTUs are able to use the

492 different LMW compounds resulting from the degradation of these long polymers along with the substrates  
493 produced by *P. salinarum*. Furthermore, the size differences between the two dominant organisms are  
494 expected to impact their physical behavior within the system, and notably the way they sink from the oxic to  
495 the anoxic part of the lake.

496

497

#### 498 **Modifications of microbial corteges associated with the primary producers from the euphotic zone to** 499 **the aphotic and anoxic one**

500

501           Considering only the biovolume of the two phytoplanktonic species, one can expect that *A.*  
502 *fusiformis* filaments will sink faster to the bottom zone than *P. salinarum* cells. To evaluate this hypothesis,  
503 we estimated the sinking speed of each species by combining models relating the sinking speed of  
504 phytoplanktonic cells with their volume and their morphometry (Durante *et al.* 2019), and using biovolume  
505 measurements from Cellamare *et al.* (2018). Doing so, we estimated a sinking speed of 0.142 and 0.01  
506 m.day<sup>-1</sup> for *A. fusiformis* filaments and *P. salinarum* cells, respectively. In other words, these organisms will  
507 theoretically take near 120 and 1700 days to sink from the bottom of the surface of the lake down to the  
508 bottom of the studied water column (18 m deep), respectively. These estimates do not account for the  
509 viscosity of the water (which is expected to increase with the concentration of EPS), nor the fact that cells  
510 have to cross several clines (thermal, haline and chemical) and that *A. fusiformis* have the capacity to modify  
511 its buoyancy thanks to specialized cells. Nonetheless, the combination of higher biomass and faster sinking  
512 rates should result in a higher flux of *A. fusiformis* cells from the oxic to the anoxic zone compared with *P.*  
513 *salinarum*. However, estimations of these two species abundances using flow cytometry revealed that on  
514 average 32% of the *P. salinarum* cells from the surface reached the bottom of the water column compared  
515 with only 5% for *A. fusiformis* filaments (Bernard *et al.* 2019). Thus, if the rate of disappearance of  
516 individuals of *A. fusiformis* and *P. salinarum* were identical, then individuals of the slower sinking species (*P.*  
517 *salinarum*) would have to disappear more rapidly than those of the faster sinking species (*A. fusiformis*). Yet,  
518 the opposite was observed. It is therefore likely that the survival of *P. salinarum* cells is much higher than  
519 that of *A. fusiformis* filaments.

520           We observed strong modifications of the associations between the dominant organisms and other  
521 members of the microbial assemblages from one zone to the other. The most striking result was the total  
522 disappearance of the associations between Archaea and *A. fusiformis*, which notably included the loss of six  
523 Woese archaeota OTUs (four from the module and two with a direct link). These uncultivated Archaea are  
524 ubiquitous in anoxic and saline ecosystems but very little is known about their ecology and metabolic  
525 potential (Casamayor, Triadó-Margarit and Castañeda 2013). In addition, comparisons with reference  
526 databases showed that Woese archaeota from the Dziani Dzaha lake can be considered as totally unknown (<



527 80% of sequence similarity). Previous studies based on bioinformatics analyses highlighted their small  
528 genome size while metabolic reconstructions support an anaerobic heterotrophic lifestyle with conspicuous  
529 metabolic deficiencies (Castelle and Banfield 2018; Dombrowski *et al.* 2020). This incomplete metabolic  
530 potency strongly suggests an obligate associative lifestyle with a dependency on other microbes for  
531 metabolic complementarity and is in line with their association with the dominant taxa and potential reliance  
532 on phytoplanktonic exudates or their by-products following degradation by other microbes. Recent studies  
533 predicted the role of Woesearchaeota in carbon cycling, through syntrophic relationship with methanogens,  
534 and an involvement in nitrogen and sulfur cycle in sulfur rich ecosystems (Liu *et al.* 2018; Liu, Wang and Gu  
535 2021). Thus, we hypothesized that they could benefit from anoxic microenvironments provided by  
536 phytoplanktonic phycospheres or by aggregates formed with methanogens (the later also explaining the  
537 presence of WSA2 in the oxic zone). These lost Archaea were notably replaced by members of the bacterial  
538 ML635J-40 aquatic group (six OTUs in bottom module and four direct links) that are known for their ability  
539 to degrade dead phytoplanktonic cells and notably *Arthrospira* (Nolla-Ardevol, Strous and Tegetmeyer  
540 2015). This turnover in the taxa associated with *A. fusiformis* clearly suggests a shift of this species role from  
541 an active photosynthetic organisms that feeds dependent taxa (*e.g.* Woesearchaeota), to a substrate that is  
542 degraded in anaerobic conditions by specialized taxa (*e.g.* Rhodobacteraceae, ML635J-40 aquatic group),  
543 resulting into a myriad of organic matter types that might support the observed reorganization of microbial  
544 networks.

545         Regarding the fate of *P. salinarum* in the bottom zone, it appears more likely that this organism is  
546 able to maintain a certain level of activity or at least to survive for a longer period of time than *A. fusiformis*.  
547 Although the ability of this picoeukaryotic species to survive at extremely low light level was already  
548 reported, Phillips *et al.* (2021) were the first to question its *in situ* ecophysiology in the hypolimnion of the  
549 Lake Mono, where light conditions are similar to those found in the Lake Dziani Dzaha, *i.e.* no or a very  
550 limited amount of light. These authors reported transcripts of photosynthetic genes from deep water samples  
551 and proposed a fast-sinking speed of *P. salinarum* cells ( $0.5-1 \text{ m.day}^{-1}$ ) to explain the presence of such  
552 transcripts. Thus, these transcripts would be the result of the survival of fast sinking cells rather than an  
553 active growing process (no light, no photosynthesis). This hypothesis cannot be retained in the Dziani Dzaha  
554 lake considering the sinking speed estimated for *P. salinarum*. The alternative hypothesis proposed by  
555 Phillips *et al.* (2021) was that the survival of *P. salinarum* in the deep hypolimnion of Lake Mono, and  
556 potentially in the Lake Dziani Dzaha, could be the consequence of a shift from photosynthetic to  
557 fermentative pathways, as demonstrated for other green algae (Catalanotti *et al.* 2013), allowing it to survive  
558 in anoxic and aphotic waters. To our knowledge, this interesting feature has not been confirmed in the Lake  
559 Dziani Dzaha. We also found various Picoeukaryotes (Ancyromonadida, Stramenopiles and Jakobida) within  
560 *P. salinarum* module in the bottom zone, suggesting a potential predation on this species. However, the size

561 difference between *P. salinarum* (3µm) and these potential predators (<7µm) does not seem to validate this  
562 hypothesis and rather suggest a grazing pressure on its associated prokaryotes.

563

## 564 CONCLUSIONS

565

566 In this study, we described the associations between microorganisms from the three domains of life  
567 in a hypersaline and hyperalkaline crater lake, modern analog of Precambrian ecosystems. We showed that  
568 the Dziani Dzaha lake is characterized by two main ecological zones, one euphotic and oxic zone in surface  
569 where two co-dominant phytoplanktonic organisms with complementary traits produce a steady and very  
570 high biomass, and one aphotic and anoxic deeper zone where the sinking particles of primary producers,  
571 especially *A. fusiformis*, are degraded and support the microbial production of methane. We highlight  
572 differences in the microbial communities' structure between the two zones, associated with a major  
573 reorganization of the microbial networks. Notably, we showed the potential dependency of Woesearchaeota  
574 to the primary producers' exudates in the oxic zone along with the disappearance of this group in the deeper  
575 layers of the lake. In the anoxic zone, the microbial networks are restructured toward the decomposition of  
576 the organic matter through microbial reassociations and notably the higher importance of Bacteroidetes from  
577 the ML635J-40 aquatic group.

578 The very active productivity of Dziani Dzaha lake has been shown to remain stable over long time  
579 periods and has already inspired biomimetic technological development. Here, three groups of prokaryotes  
580 appeared particularly important in the microbial dynamics and association networks of this lake:  
581 Clostridiales, Bacteroidetes and Woesearchaeota. Unfortunately, representatives of these taxa from Dziani  
582 Dzaha lake showed very little similarity with reference databases and limited their taxonomic identification.  
583 This further highlighted the exceptional and unique aspect of this ecosystem, not only from a geochemical  
584 standpoint but also considering its biodiversity. The need for further studies on this ecosystem is even more  
585 pronounced as it is currently under the threat of strong perturbations including its possible disappearance due  
586 to the emergence of a submarine volcano associated with an intense seismic activity leading to the  
587 subsidence of the Mayotte archipelago. These could allow to test fundamental concepts in microbial ecology  
588 such as the resistance and resilience of microbial communities to environmental disturbances.

589 Although we identified some potential interactions between the primary producers and  
590 Woesearchaeota, such association are purely statistic and remain to be validated using analyses at finer  
591 scales, such as cell sorting of the phytoplanktonic cells followed by analyses of the microbial consortia  
592 directly attached to them (*i.e.* their phycosphere). A surprising result was that *A. fusiformis* was not identified  
593 as a central taxa in the networks despite being the main component of the microbial communities owing to  
594 its biomass. This highlight a potential limitation of the network approach due to the fact that the permanence  
595 of this species at high biomass did not allow the identification of co-variations with other taxa. As most of

596 microorganisms from the lake are not cultivated yet due to the difficulty to reproduce its harsh environmental  
597 conditions, the use of genome resolved metagenomics approaches should provide greater insights into the  
598 genomic abilities of these uncultivated microorganisms. Nonetheless, the relative “simplicity” of this system  
599 with the two contrasted ecological zones and a purely microbial and low diversity biocenose allowed us to  
600 provide a deep and multiscale analysis of the microbial networks (global properties, modules composition,  
601 nodes and links characteristics). Doing so, we were able to get a deeper understanding of this ecosystem  
602 functioning (synthesized in Box 1) and such approach should be further deployed in other microbial systems.

603

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607

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610 Indien, due to the fact that Dziani Dzaha lake is currently a protected water body with free public access but  
611 restricted activities, under the control of the French agency for littoral ecosystems conservation  
612 (<http://www.conservatoire-du-littoral.fr/>).

613

#### 614 **Conflicts of interest**

615 The authors declare no conflict of interest related to this work.

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621 **BOX 1 – What did we learned from network analysis of Dziani Dzaha lake microbial communities ?**

622

623 In this section, we present an interpreted synthesis of our results that translate the observed networks  
624 characteristics into biological and ecological insights. The main results are graphically synthesized in Figure  
625 5.

626 First of all, we confirmed the presence of two ecologically contrasted zones in the Dziani Dzaha lake  
627 and the low diversity of its microbial communities. In addition, we found that the two zones shared 91% of  
628 the OTUs and mostly differed in terms of OTUs relative abundances, illustrating the Baas-Becking theory  
629 (De Wit and Bouvier 2006).

630 Then, we found that in the surface zone the two main primary producers *Arthrospira fusiformis*  
631 (Cyanobacteria) and *Picocystis salinarum* (Chlorophyta) were associated with different microbial consortia  
632 (*i.e.* modules and direct associations). As modules are often interpreted as putative functional groups (Faust  
633 2021), the differences in the taxonomic composition of primary producers modules suggest that they might  
634 play a different functional role in the system. In addition, the number of OTUs was lower in *A. fusiformis* (n  
635 = 22) module than in *P. salinarum* (n = 115) one, and we hypothesize that this counterintuitive result  
636 considering the size difference between these two taxa (Seymour *et al.* 2017) was likely the result of their  
637 different lifestyle, with *A. fusiformis* constituting a large particle and *P. salinarum* being part of the free  
638 living community.

639 Taxa centrality within the network is often considered as an indicator of their importance within the  
640 system and higher influence on the realized functions (notion of hub or keystone taxa). Here, we were  
641 surprised that both primary producers were not central according to centrality metrics (*e.g.* degree,  
642 betweenness, hub score), but the majority of central OTUs in the surface network were part of *P. salinarum*  
643 module (72%). This suggests that the free living assemblage realizes the main biogeochemical processes in  
644 the surface zone, which likely correspond to syntrophic metabolic processes that transform organic substrates  
645 released by primary producers, into dissolved nutrients. Contrarily, OTUs from *A. fusiformis* module were  
646 not central, which might reflect their specialization toward a phycosphere associated lifestyle. In addition,  
647 Protozoa were found to be more central in the network than expected considering their number, which likely  
648 represents their role as predator of Bacteria and Archaea. Despite these differences in associations between  
649 the two primary producers, they were both associated with Woesearchaeota, which supports the fact that this  
650 group is known to depend on the release of organisms substrates by other taxa as a result of its reduced  
651 genomic repertoire.

652 In a second time, the cells produced in the surface zone sink in deeper layers of the lake, where they

653 encounter anoxic, aphotic and  $\text{H}_2\text{S}/\text{HS}^-$  rich environmental conditions that results in the lysis and

654 degradation of primary producers that decrease in abundance (especially *A. fusiformis*). The sinking speed

655 estimated for the two phytoplanktonic taxa were quite low, and this likely allowed the shift in their functional  
656 role in the system, from harvester of solar energy in the surface layer and redistributors of organic molecules  
657 to a diversified organic matter pool that fuel fermentative processes in the bottom zone. This was reflected in  
658 the disappearance of association with Woesearchaeota and the replacement of this group by anaerobic  
659 fermenter (*e.g.* Rhodobacteraceae, ML635J-40 aquatic group).

660

661           If we shift the focus from the primary producers to the whole network, we observed that the bottom  
662 zone network contained more modules, which might indicate a higher diversity of functional groups that  
663 occupy a wider diversity of ecological zones. The bottom network also appeared more complex, with more  
664 OTUs, more connections between them, a higher density of links and a shorter distance between nodes  
665 (number of steps to link any pair of OTUs). All these indices could be the sign of a higher interdependence of  
666 microorganisms for the realization of the collective degradation of the different types of organic matters  
667 resulting from the degradation of primary producers (mostly *A. fusiformis* and its EPS). Central nodes from  
668 the bottom network were different from the surface ones, with notably the replacement of archaeal OTUs by  
669 Firmicutes and Chloroflexi, which constitutes another sign of the reorganization of the network toward a  
670 different functional state.

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864 **Table 1: Environmental conditions in the two environmental niches observed in Lake Dziani**  
 865 **Dzaha**

866 Differences between the two niches were tested using Wilcoxon rank sum test and the p-values  
 867 were adjusted using the Bonferroni correction. Presented values are mean±sd. Wilcoxon rank sum  
 868 test: \*\*\* : p values < 0.001, \*\* : pvalue < 0.01, \* : pvalue < 0.05.  
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	Surface	Bottom	
Temperature (°C)	30.88 ± 1.09	30.00 ± 0.25	
pH	9.33 ± 0.30	9.12 ± 0.24	
O <sub>2</sub> (% saturation)	79.16 ± 128.74	0.38 ± 0.75	
Salinity (psu)	55.71 ± 12.25	66.34 ± 3.19	***
Eh (mV)	-53.63 ± 147.46	-324.41 ± 56.81	***
H <sub>2</sub> S/HS <sup>-</sup> (μmol.L <sup>-1</sup> )	99.79 ± 100.90	3051.58 ± 1962.88	***
Chl a (μg.L <sup>-1</sup> )	556.34 ± 168.50	206.80 ± 143.53	***

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**Table 2: Comparison of the composition and structure of microbial communities from the two environmental niches observed in Lake Dziani Dzaha**

Differences between the two niches were tested PERMANOVA.

	Composition (Jaccard)						Structure (Bray-Curtis)				
	Df	MeanSqs	F	R <sup>2</sup>	p-value		MeanSqs	F	R <sup>2</sup>	p-value	
All domains	1	1.44	10.96	0.30	0.001	***	1.09	15.87	0.38	0.001	***
	26	0.13	-	0.70	-		0.07	-	0.62	-	
Archaea	1	1.55	9.21	0.26	0.001	***	1.23	12.78	0.33	0.001	***
	26	0.17	-	0.74	-		0.10	-	0.67	-	
Bacteria	1	1.73	11.55	0.31	0.001	***	1.50	16.60	0.39	0.001	***
	26	0.15	-	0.69	-		0.09	-	0.61	-	
Eukaryota	1	0.13	2.93	0.10	0.025	*	0.05	2.98	0.10	0.03	*
	26	0.05	-	0.90	-		0.02	-	0.90	-	

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900 **Table 3: Comparison of global networks characteristics**  
 901 Average metrics values estimated across networks from each niche. Wilcoxon rank sum test: \*\*\* : p  
 902 values < 0.001, \*\* : pvalue < 0.01, \* : pvalue < 0.05.  
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Network characteristic	Niche		t-test		
	Surface	Bottom	t	p-value	
Number of nodes	272	310	3.2	0.004	**
Number of links	790	1099	5.1	0.000	***
Network diameter	8.5	6.9	-5.0	0.000	***
Network density	2.9	3.5	7.2	0.000	***
Average inter-node distance	3.8	3.4	-6.4	0.000	***
Centralized degree	1641	1893	2.3	0.032	*
Centralized betweenness	253668	246414	-0.5	0.648	
Centralized closeness	13.7	14.1	0.5	0.624	
Hub score	43.5	65.3	9.4	0.000	***

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 906 **Table 4: Direct association of dominant taxa in both niches**  
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Dominant taxa	Niche	Linked OTU	Domain	Phylum	Class	Order	Family	Link type
<i>A. fusiformis</i>	<b>Surface</b>	Bac_OTU_14	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Negative
		Bac_OTU_44	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Negative
		Bac_OTU_69	Bacteria	Deinococcus-Thermus	Deinococci	Deinococcales	Trueperaceae	Positive
		Bac_OTU_179	Bacteria	Firmicutes	Clostridia	Clostridiales	Syntrophomonadaceae	Negative
		Bac_OTU_307	Bacteria	Firmicutes	Clostridia	Halanaerobiales	ODP1230B8.23	Positive
		Arc_OTU_8	Archaea	Woesearchaeota(DHVEG-6)	Unknown class	Unknown order	Unknown family	Positive
		Arc_OTU_61	Archaea	Woesearchaeota(DHVEG-6)	Unknown class	Unknown order	Unknown family	Negative
	<b>Bottom</b>	Bac_OTU_29	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Negative
		Bac_OTU_32	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Negative
		Bac_OTU_127	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Negative
		Bac_OTU_130	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Negative
		Bac_OTU_195	Bacteria	Elusimicrobia	Elusimicrobia	Rs-M47	Unknown family	Negative
		Bac_OTU_196	Bacteria	Firmicutes	Clostridia	Halanaerobiales	ODP1230B8.23	Negative
		Bac_OTU_199	Bacteria	Proteobacteria	Alphaproteobacteria	Rhodospirillales	Rhodospirillaceae	Positive
Bac_OTU_201	Bacteria	Proteobacteria	Alphaproteobacteria	Rhodobacterales	Rhodobacteraceae	Positive		
Bac_OTU_271	Bacteria	Firmicutes	Clostridia	Clostridiales	Syntrophomonadaceae	Negative		
<i>P. salinarum</i>	<b>Surface</b>	Bac_OTU_11	Bacteria	Bacteroidetes	Sphingobacteriia	Sphingobacteriales	Lentimicrobiaceae	Negative
		Bac_OTU_189	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	ML635J-40aquaticgroup	Positive
		Bac_OTU_237	Bacteria	Bacteroidetes	BacteroidetesIncertainSedis	OrderIII	ML310M-34	Negative
		Arc_OTU_50	Archaea	Euryarchaeota	Methanomicrobia	Methanosarcinales	Methanosarcinaceae	Positive
		Arc_OTU_81	Archaea	Euryarchaeota	Thermoplasmata	Thermoplasmatales	MarineBenthicGroupDandDHVEG-1	Positive
		Arc_OTU_107	Archaea	Bathyarchaeota	Unknown class	Unknown order	Unknown family	Positive
		Euk_OTU_149	Eukaryota	Ciliophora	Intramacronucleata	Spirotrichea	Hypotrichia	Negative
	<b>Bottom</b>	Bac_OTU_73	Bacteria	Actinobacteria	Nitriliruptoria	Euzebyales	Euzebyaceae	Positive
		Bac_OTU_77	Bacteria	Firmicutes	Clostridia	M55-D21	Unknown family	Positive
		Bac_OTU_169	Bacteria	Firmicutes	Clostridia	Clostridiales	Syntrophomonadaceae	Positive
		Bac_OTU_264	Bacteria	Synergistetes	Synergistia	Synergistales	Synergistaceae	Positive
		Arc_OTU_116	Archaea	Woesearchaeota(DHVEG-6)	Unknown class	Unknown order	Unknown family	Positive
		Euk_OTU_3	Eukaryota	Ancyromonadida	Unknown class	Unknown order	Unknown family	Negative
		Euk_OTU_45	Eukaryota	Stramenopile	Placididea	Unknown order	Unknown family	Positive

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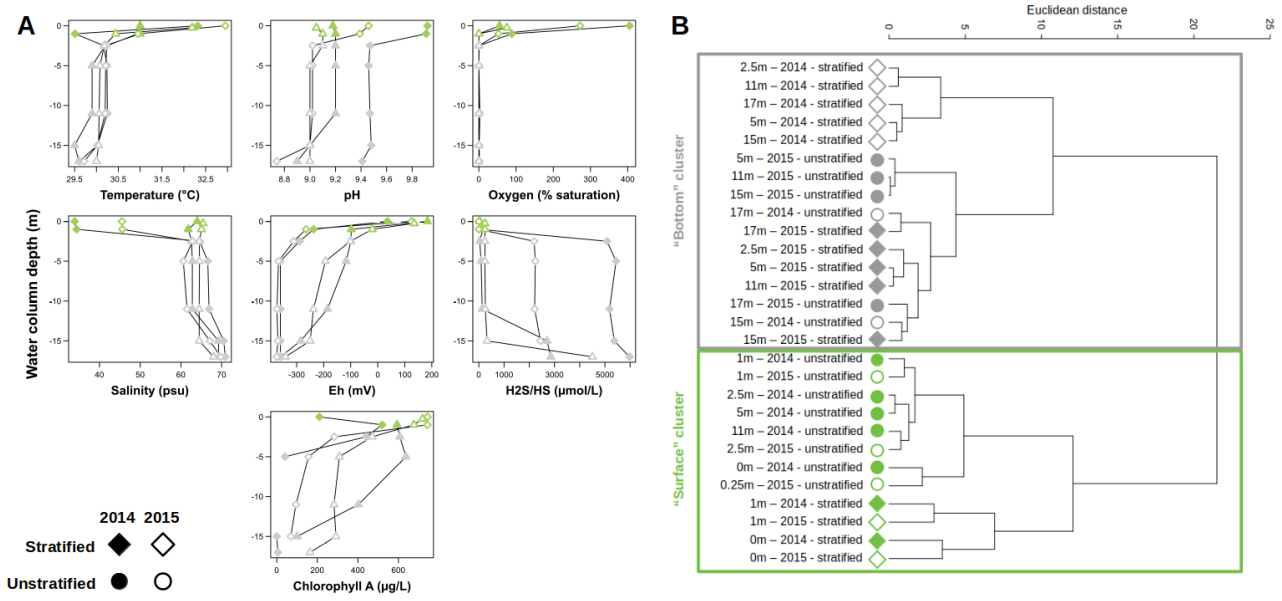
913 **Figure 1: Delineation of two contrasted ecological zones in the Dziani Dzaha lake**

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915 A: Physico-chemical characteristics of the studied samples. Diamonds and circles correspond to stratified  
916 and unstratified seasons, respectively, while filled and empty dots correspond to 2014 and 2015 surveys,  
917 respectively. For each variable the samples are colored according to the ecological zone they belong to  
918 (surface or bottom cluster in B).

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920 B: Dendrogram representing the separation of samples in two clusters, based on euclidean distance between  
921 samples computed using the seven variables presented in A.



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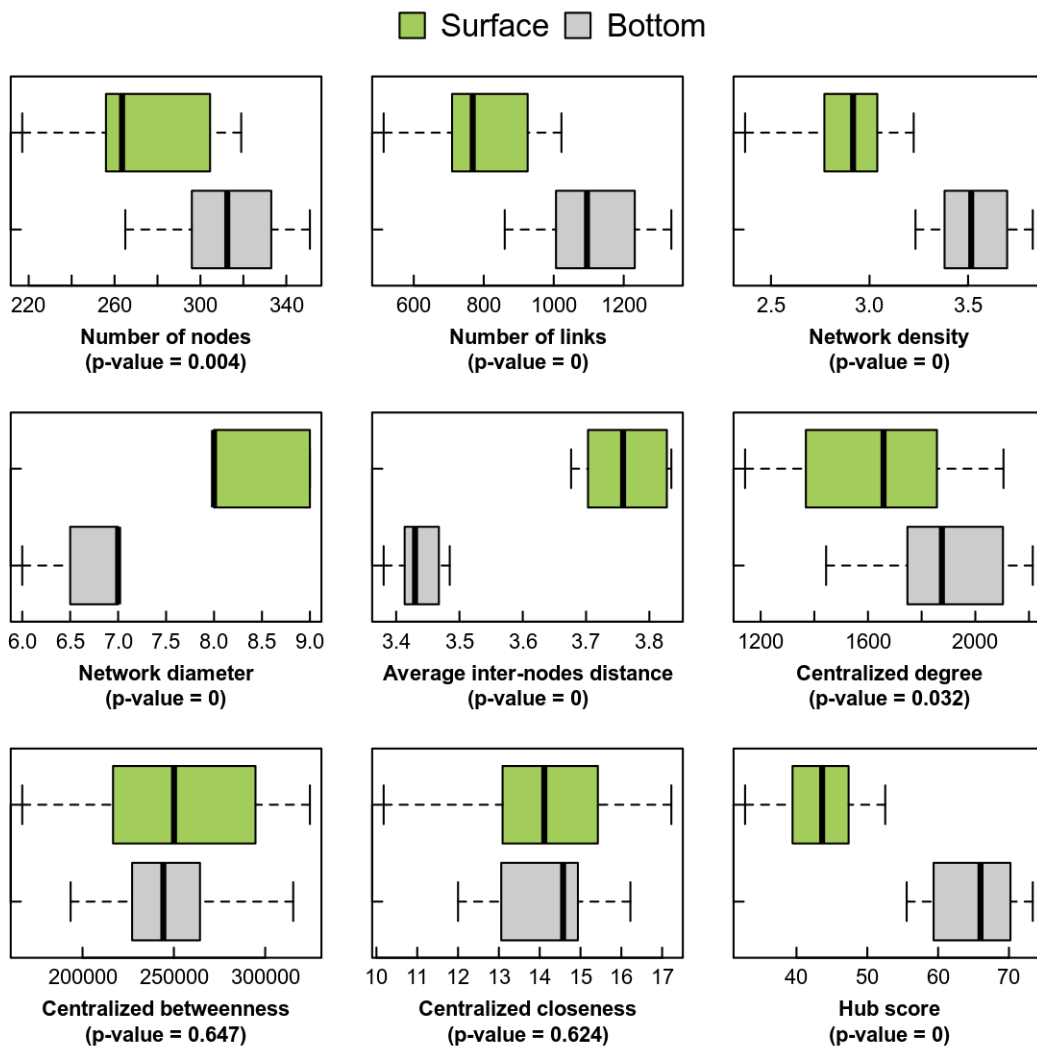
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**Figure 2: Global characteristics of association networks in each environmental niche**

Each boxplot represents the distribution of values observed across the networks from each separated community (n = 12 and 16 for surface and bottom, respectively). The p-values of the Wilcoxon rank sum test comparing the two niches are presented below each subplot.

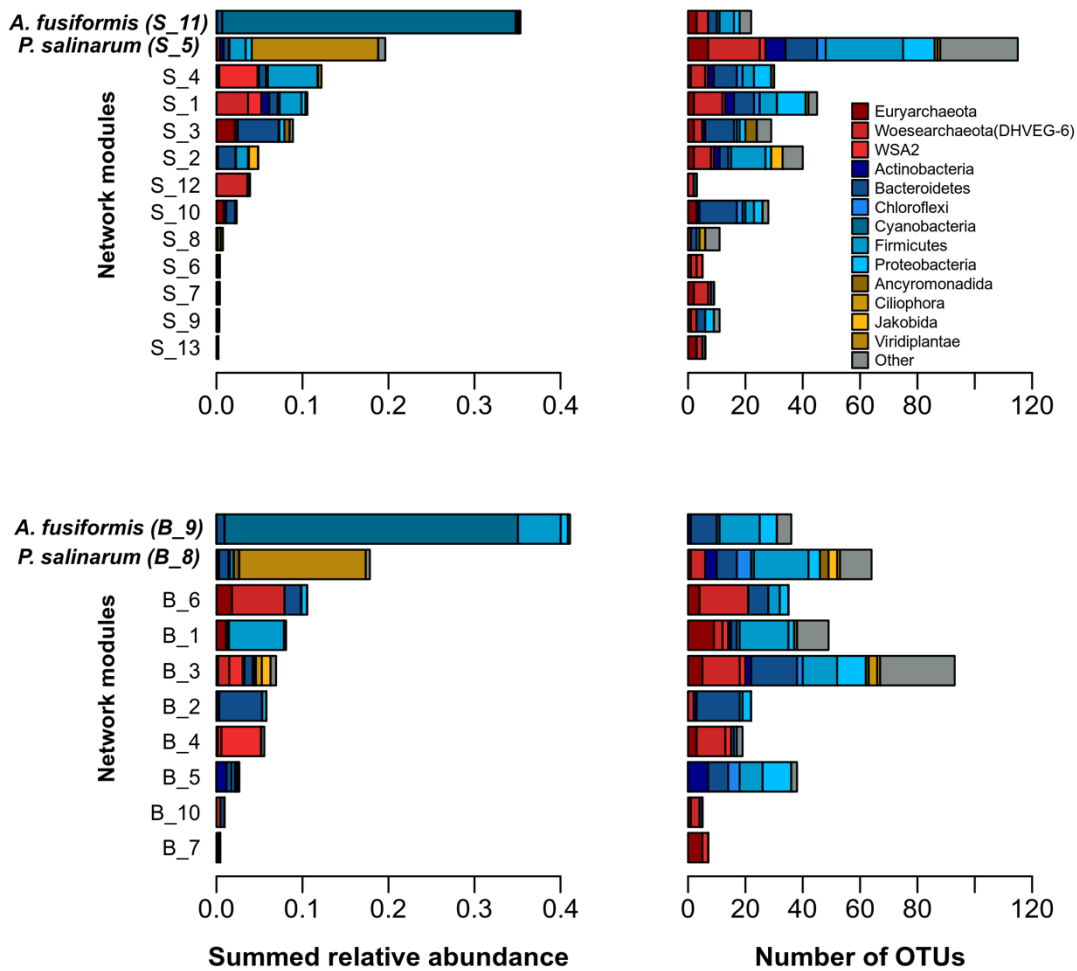


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**Figure 3: Taxonomic composition of modules in both niches**

This figure corresponds to the modules identified using the walktrap clustering algorithm. Archaea phyla are in nuances of red, Bacteria in nuances of blue and Eukaryota in nuances of brown. *A. fusiformis* was detected in modules S\_11 and B\_9 while *P. salinarum* was detected in modules S\_5 and B\_

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1005 **Figure 4: Taxonomy of peripheral and central nodes in both niches**

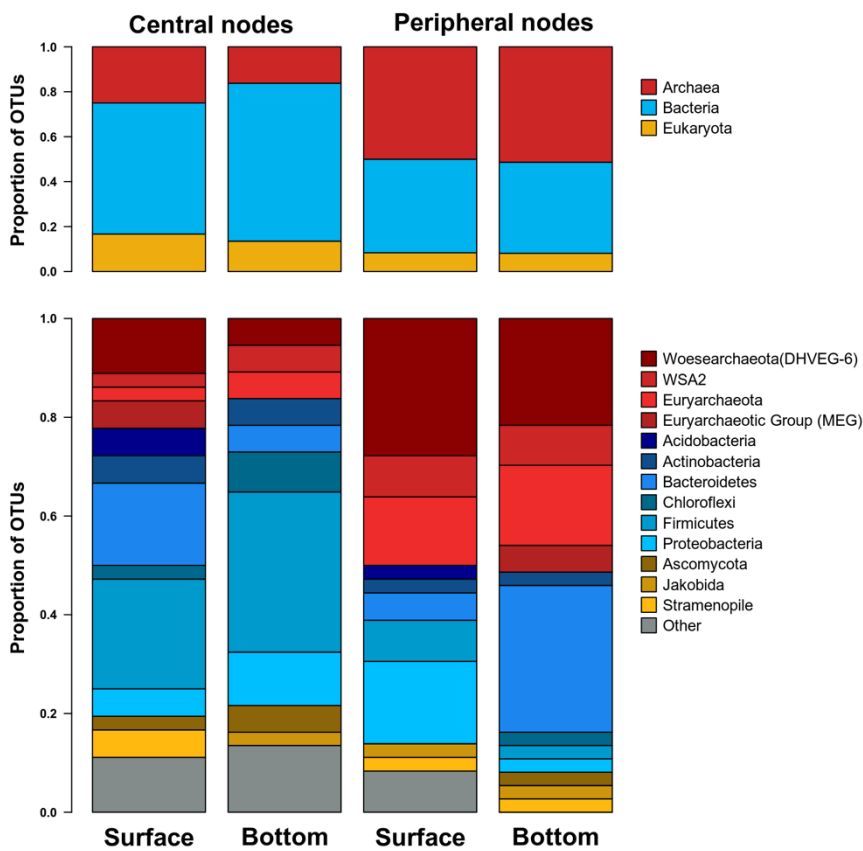
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1007 Peripheral and central nodes (*i.e.* OTUs) were identified as the one with an average centrality rank falling  
1008 within the first and tenth decile, respectively (cf. Figure S6, n = 36 and 37 in surface and bottom niches,  
1009 respectively). Top plot corresponds to taxonomic classification at the Domain level while bottom plot  
1010 corresponds to Phylum level.

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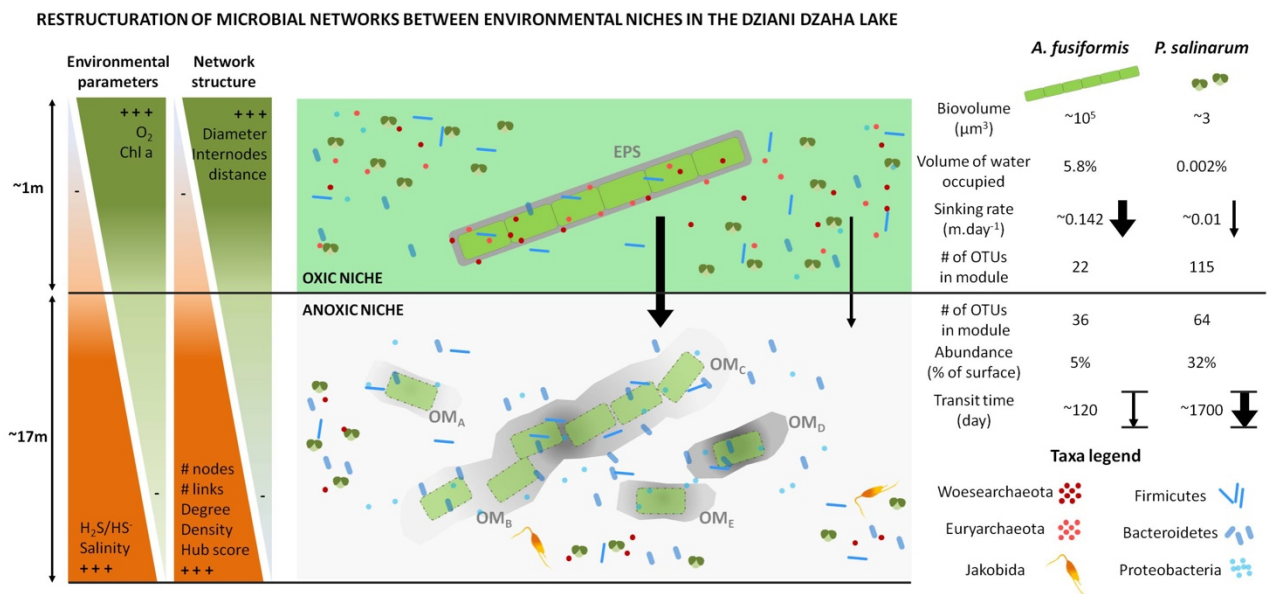
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**Figure 5: Conceptual model of the functioning of Lake Dziani Dzaha ecosystem**

This figure presents a conceptual model of the Lake Dziani Dzaha functioning, centered around the two main primary producers. The left part of the figure represents the change in environmental parameters and network characteristics between the two niches. The right part represents the characteristics of the two main primary producers. The central part represents the spatial organization of the primary producers and of the main taxonomic groups in both niches. The decomposition of *A. fusiformis* and its surrounding exopolysaccharides (EPS) into different organic matter pools (OM) is figured with the shading of the EPS matrix around lysed cells.



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