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1 PFR²: a curated database of planktonic foraminifera 18S ribosomal DNA as a resource for studies
2 of plankton ecology, biogeography, and evolution.

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37 **Abstract**

38 Planktonic foraminifera (Rhizaria) are ubiquitous marine pelagic protists producing
39 calcareous shells with conspicuous morphology. They play an important role in the marine
40 carbon cycle and their exceptional fossil record serves as the basis for biochronostratigraphy and
41 past climate reconstructions. A major worldwide sampling effort over the last two decades has
42 resulted in the establishment of multiple large collections of cryopreserved individual planktonic

43 foraminifera samples. Thousands of 18S rDNA partial sequences have been generated,
44 representing all major known morphological taxa across their worldwide oceanic range. This
45 comprehensive data coverage provides an opportunity to assess patterns of molecular ecology
46 and evolution in a holistic way for an entire group of planktonic protists. We combined all
47 available published and unpublished genetic data to build PFR², the *Planktonic Foraminifera*
48 *Ribosomal Reference* database. The first version of the database includes 3,322 reference 18S
49 rDNA sequences belonging to 32 out of the 47 known morphospecies of extant planktonic
50 Foraminifera, collected from 460 oceanic stations. All sequences have been rigorously
51 taxonomically curated using a six-rank annotation system fully resolved to the morphological
52 species level and linked to a series of metadata. The PFR² website, available at [http://pfr2.sb-](http://pfr2.sb-roscoff.fr)
53 [roscoff.fr](http://pfr2.sb-roscoff.fr), allows downloading the entire database or specific sections, as well as the
54 identification of new planktonic foraminiferal sequences. Its novel, fully documented curation
55 process integrates advances in morphological and molecular taxonomy. It allows for an increase
56 in its taxonomic resolution and assures that integrity is maintained by including a complete
57 contingency tracking of annotations and assuring that the annotations remain internally
58 consistent.

59 **Introduction**

60 Despite their ubiquity and the critical role they play in global biogeochemical cycles,
61 unicellular eukaryotes (protists) remain the most poorly known domain of life (e. g., Pawlowski
62 et al., 2012). Because of their extreme morphological and behavioral diversity, the study of even
63 relatively narrow lineages requires a high degree of taxonomic expertise (e. g., Guillou et al.,
64 2012, Pawlowski and Holzmann, 2014). As a result, the knowledge of protistan ecology and
65 evolution is limited by the small number of taxonomists, resulting in scarcity of taxonomically

66 well-resolved ecological data. As an alternative approach, numerous studies have demonstrated
67 the potential of identification of protists by means of short DNA sequences or barcodes (e. g.,
68 Saunders, 2005; Sherwood et al., 2007; Hollingsworth et al., 2009; Nossonova et al., 2010;
69 Pawlowski and Lecroq, 2010; Hamsher et al., 2011; Stern et al., 2010; Schoch et al., 2012), both
70 at the single-cell and metacommunity levels (e. g., Sogin et al., 2006; Logares et al., 2014). Such
71 barcoding/metabarcoding approaches critically rely on the fidelity of the marker gene with
72 respect to specificity (avoiding ambiguity in identification), comprehensiveness (assuring all taxa
73 in the studied group are represented in the reference barcode database) and accuracy (assuring
74 that barcode assignments are consistent with a coherent, phenotypic taxonomic framework; e. g.,
75 Zimmermann et al., 2014)). These three pre-requisites are rarely found in protists, where
76 classical morphological taxonomy is often challenging, DNA extraction and sequencing from a
77 single cell is prone to contamination, and a large portion of the diversity in many groups remains
78 unknown (e. g., Mora et al., 2011). In this respect, planktonic foraminifera represent a rare
79 exception.

80 Planktonic foraminifera are ubiquitous pelagic marine protists with reticulated
81 pseudopods, clustering within the Rhizaria (Nikolaev et al., 2004). The group is marked by a
82 rather low number of extant morphospecies (47; Hemleben et al., 1989), which can be
83 distinguished using structural characteristics of their calcite shells. Their global geographic
84 distribution, seasonal dynamics, vertical habitats and trophic behavior have been thoroughly
85 documented by analyses of plankton hauls (e.g., Bé and Hudson, 1977), sediment trap series
86 (e.g., Zaric et al., 2005) and thousands of surface sediment samples across the world oceans (e.g.,
87 Kucera et al., 2005). Their outstanding preservation in marine sediments resulted in arguably the
88 most complete fossil record, allowing comprehensive reconstruction of the evolutionary history

89 of the group (Aze et al., 2011). Over the last two decades, the morpho-taxonomy and phylogeny
90 of the group have been largely confirmed by molecular genetic analyses (e.g., Aurahs et al.,
91 2009a) based on the highly informative, ~1,000 bp fragment at the 3' end of the 18S rDNA gene.
92 These analyses confirmed that the morphological characters used to differentiate planktonic
93 foraminifera taxa are phylogenetically valid both at the level of morphological species and at the
94 level of higher taxa. The studied gene fragment contains six hypervariable expansion segments,
95 some unique to foraminifera, providing excellent taxonomic resolution (Pawlowski and Lecroq,
96 2010). Analyses of this fragment revealed the existence of genetically distinct lineages within
97 most of the morphospecies, which likely represent reproductively isolated units (Darling et al.,
98 1996, 1997, 1999, 2000, 2003, 2004, 2006, 2007, 2009; Darling and Wade, 2008; Wade et al.,
99 1996; de Vargas et al., 1997, 1999, 2001, 2002, de Vargas and Pawlowski, 1998; Stewart et al.,
100 2001; Aurahs et al., 2009b, 2011; Ujiié and Lipps, 2009; Ujiié et al., 2008, 2012; Morard et al.,
101 2009, 2011, 2013; Seears et al., 2012; Quillévéré et al., 2013; Weiner et al., 2012, 2014; André et
102 al., 2014). In order to assess the ecology and biogeography of such cryptic species, large
103 numbers of rDNA sequences from single-cell extractions collected across the world oceans have
104 been generated for most morphospecies (Figure 1). Due to this extensive single-cell rDNA
105 sequencing, the genetic and morphological diversity of planktonic foraminifera have been linked
106 together to a degree that now allows for transfer of taxonomic expertise. The knowledge of the
107 genetic and morphological taxonomy of the group allows the establishment of an exceptionally
108 comprehensive reference genetic database that can be further used to interpret complex data from
109 plankton metagenomic studies with a high level of taxonomic resolution. Because planktonic
110 foraminifera are subject to the same ecological forcing as other microplankton, including the
111 dominance of passive transport in a relatively unstructured environment, huge population sizes,

112 and basin-scale distribution of species, they can potentially serve as a model for the study of
113 global ecological patterns in other groups of pelagic protists, whose diversity remains largely
114 undiscovered (Mora et al., 2011).

115 By early 2014, 1,787 partial 18S rDNA sequences from single-cell extractions of
116 planktonic foraminifera were available in public databases. However, their NCBI taxonomy is
117 often inconsistent, lacking standardization. It includes (and retains) obvious identification errors,
118 as discussed by Aurahs et al. (2009a) and André et al. (2014), and their annotation lacks critical
119 metadata. In addition, an equivalent number of rDNA sequences not deposited in public
120 databases have been generated by the co-authors of the present study. Collectively, the existing
121 rDNA sequences from single cells collected throughout the world oceans cover the entire
122 geographic and taxonomic range of planktonic foraminifera. This collection unites the current
123 morphological, genetic, ecological, and biogeographic knowledge of the group and may serve as
124 a *Rosetta Stone/Philae Obelisk* for interpreting metabarcoding data (Pawlowski et al., 2014). To
125 pave the way for future exploitation of this resource, we combined all published and unpublished
126 planktonic foraminifera rDNA sequence data and curated the resulting database with a semi-
127 automated bioinformatics pipeline. The resulting *Planktonic Foraminifera Ribosomal Reference*
128 database (PFR²) is a highly resolved, fully annotated and internally entirely consistent collection
129 of 18S rDNA sequences of planktonic foraminifera, aligned and evaluated in a way that
130 facilitates, among others, direct assessment of barcoding markers.

131 **Material and Methods**

132 *Primary database assembly*

133 A total of 1,787 18S rDNA sequences of planktonic foraminifera were downloaded from the
134 GenBank query portal (<http://www.ncbi.nlm.nih.gov/>; release 201) on the 14th of May 2014. The
135 taxonomic path and metadata for these sequences were extracted from NCBI and supplemented
136 by information in original papers when available. The metadata associated to each sequence
137 consisted of: (i) their organismal origin (specimen voucher, taxonomic path, infra specific
138 genetic type assignment), (ii) their methodological origin (direct sequencing or cloning), and (iii)
139 their spatio-temporal origin (geographic coordinates, depth, and time of collection). Metadata
140 were described using standard vocabularies and data formats. For 47 sequences, the coordinates
141 of the collection site could not be recovered, in which case the locality was described in words
142 (Supplementary Material 1).

143 We next compiled all unpublished 18S rDNA sequences generated by the co-authors of this
144 paper and linked them with the same suite of metadata. These sequences originate from single-
145 cell extractions of planktonic foraminifera collected by stratified or non-stratified plankton net
146 hauls, in-situ water pumping, as well as SCUBA diving. After collection, the specimens were
147 individually picked under a stereomicroscope, cleaned, taxonomically identified and transferred
148 into DNA extraction buffer or air-dried on cardboard slides and stored at -20°C or -80°C. DNA
149 extractions were performed following the DOC (Holzmann & Pawlowski, 1996), the GITC*
150 (Morard et al., 2009), or the Urea (Weiner et al., 2014) protocols. Sequences located at the 3' end
151 of the 18S rDNA were obtained following the methodology described in de Darling et al. (1996,
152 1997), de Vargas et al. (1997), Aurahs et al. (2009b), Morard et al. (2011) and Weiner et al.,
153 (2014). A total of 820 new planktonic foraminiferal sequences were analyzed and annotated for
154 this study. In addition, 925 unpublished sequences analyzed in Darling et al. (2000, 2003, 2004,
155 2006, 2007), Darling and Wade (2008), Sears et al. (2012), and Weiner et al. (2014) were also

156 included. All unpublished sequences, except 177 sequences shorter than 200 bp, were deposited
157 in GenBank under the accession numbers KM19301 to KM194582. Overall, PFR² contains data
158 from 460 sites sampled during 54 oceanographic cruises and 15 near shore collection campaigns
159 between 1993 and 2013. It covers all oceanic basins, all seasons, and water depths ranging
160 between the surface and 700 meters (Figure 1; Supplementary Material 1).

161 *Taxonomy*

162 Morphological taxonomy

163 As the first step in the curation process, the primary taxonomic annotations of all 3,532 18S
164 rDNA sequences gathered from NCBI and our internal databases were harmonized. The
165 identification of planktonic foraminifera is challenging especially for juvenile individuals, which
166 often lack diagnostic characters (Brummer et al., 1986). Thus, many of the published and
167 unpublished 18S rDNA sequences were mislabeled or left in open nomenclature. In some cases
168 the same taxon has been recorded under different names, reflecting inconsistent use of generic
169 names, synonyms and misspelling. To harmonize the taxonomy, we first carried out a manual
170 curation of the original annotations to remove the most obvious taxonomic conflicts in the
171 primary database. To this end, the sequence annotations were aligned with a catalog of 47
172 species names based on the taxonomy used in Hemleben et al. (1989), but adding
173 *Globigerinoides elongatus* following Aurahs et al. (2011) and treating *Neogloboquadrina*
174 *incompta* following Darling et al. (2006). Thus, the 109 sequences labelled as *Globigerinoides*
175 *ruber* (pink) and the 63 labelled as *Globigerinoides ruber* (white) were renamed as
176 *Globigerinoides ruber*. The 113 sequences of *Globigerinoides ruber* and *Globigerinoides ruber*
177 (white) attributed to the genotype II were renamed *Globigerinoides elongatus* following Aurahs

178 et al. (2011). The 12 sequences labelled *Globigerinella aequilateralis* were renamed
179 *Globigerinella siphonifera* following Hemleben et al. (1989). The 7 sequences corresponding to
180 the right-coiled morphotype of *Neogloboquadrina pachyderma* were renamed *Neogloboquadrina*
181 *incompta* following Darling et al. (2006). All taxonomic reassignments were checked by
182 sequence similarity analyses to the members of the new group. Next, we attempted to resolve the
183 attribution of sequences with unresolved taxonomy and searched manually for obviously
184 misattributed sequences. This refers to sequences that are highly divergent from other members
185 of their group but identical to sequences of other well-resolved taxa. Overall, these first steps of
186 manual curation led to the taxonomic reassignment of 124 sequences. All corrections and their
187 justification are documented in the Supplementary Material 1.

188 Annotation of genetic types

189 In order to preserve the information on the attribution of 18S rDNA sequences to genetic types
190 (potential cryptic species), we harmonized the existing attributions at this level for species where
191 extensive surveys have been carried out and published. A total of 1,356 sequences downloaded
192 from NCBI were associated with a genetic type label, which was always retained. In addition, 19
193 sequences labelled as *Globigerinoides ruber*, 15 as *Globigerinoides sacculifer*, 36 as
194 *Globigerinita glutinata*, 6 as *Globigerinita uvula*, 9 as *Globorotalia inflata*, 10 as
195 *Neogloboquadrina incompta*, 6 as *Neogloboquadrina pachyderma*, 5 as *Orbulina universa*, 5 as
196 *Pulleniatina obliquiloculata*, 30 as *Hastigerina pelagica*, and 32 as *Globigerinella siphonifera*
197 have been analyzed after their first release in the public domain by Aurahs et al. (2009), Ujiié et
198 al. (2012), Weiner et al. (2012, 2014), and André et al. (2013, 2014), and were attributed to a
199 genetic type by these authors. These attributions differ from those in the NCBI label, but were
200 retained in the PFR² database. In case of multiple attributions of the same sequence to different

201 genetic types by several authors, we retained the molecular taxonomy that was based on the
202 study presenting the most resolved and comprehensive attribution. In addition, 877 unpublished
203 sequences belonging to *Orbulina universa*, *Globigerina bulloides*, *Neogloboquadrina incompta*,
204 *Neogloboquadrina dutertrei*, *Neogloboquadrina pachyderma*, and *Turborotalita quinqueloba*
205 received a genotypic attribution following de Vargas et al. (1999) and Darling et al. (2004, 2006,
206 2007, 2008). Most of these sequences have been produced and identified within earlier studies,
207 but were not originally deposited on NCBI. Their PFR² genotypic assignment is therefore
208 entirely consistent with the attribution of the representative sequences of the same genetic type
209 that were deposited on NCBI.

210 PFR² final taxonomic framework

211 As a result of the first manual curation and annotation to the genetic type level, the original 3,532
212 18S rDNA sequences were re-assigned to 33 species names and 2,276 sequences were annotated
213 to the level of genetic types (Supplementary Material 1). For all sequences, we established a
214 ranked taxonomy with six levels: 1- Morphogroup, 2-Genus, 3-Species, 4-Genetic type level 1,
215 5-Genetic type level 2, 6-Genetic type 3. For the “Morphogroup” rank we used the taxonomical
216 framework of Hemleben et al. (1989), dividing the extant planktonic foraminifera species into
217 five clades based on the ultrastructure of the calcareous shell: Spinose, Non-spinose,
218 Microperforate, Monolamellar and Non-spiral. The “Genus” and “Species” ranks follow the
219 primary annotation as described above. For the “Genetic type level 1”, “Genetic type level 2”
220 and “Genetic type level 3” ranks, we used the hierarchical levels presented in the labels of the
221 genetic types of *Globigerinoides ruber*, *Globigerinoides elongatus*, *Globigerinella siphonifera*,
222 *Globigerinella calida*, *Hastigerina pelagica*, *Globigerina bulloides*, *Neogloboquadrina dutertrei*,
223 *Pulleniatina obliquiloculata*, and *Turborotalita quinqueloba*. Genetic type attributions lacking

224 hierarchical structure were reported in the rank “Genetic type level 1”. After this step, the
225 Primary Reference Database (Figure 2) of 3,532 sequences contained 113 different taxonomic
226 paths (Supplementary Material 1).

227 *Sequences partitioning into conserved and variable regions*

228 Because PFR² is a resource not only for taxonomic assignment but also for ecological and
229 biogeographical studies, all planktonic foraminiferal 18S rDNA sequences were included
230 irrespective of length, as long as they contained taxonomically relevant information. As a result,
231 the length of the sequences included in the annotated primary database ranges between 33 and
232 3,412 bp. To evaluate their coverage and information content, all sequences were manually
233 aligned using Seaview 4 (Gouy et al., 2010) to the borders of each variable region of the 18S
234 rDNA fragment. The positions of the borders were determined according to the SSU rDNA
235 secondary structure of the monothalamous foraminifera *Micrometula hyalostera* presented by
236 Pawlowski and Lecroq (2010), except for the region 37/f where a strict homology was difficult to
237 establish for all sequences. Instead, we defined the end of this region by the occurrence of a
238 pattern homologous to the series of nucleotides “CUUUCACAUGA” located at the 3’ end of
239 Helix 37. We also noticed that the short conserved fragment located between the variable regions
240 45/e and 47/f was difficult to identify across all sequences. We thus merged the regions 45/e, 46
241 and 47/f into a single region that we named 45E-47F (Table1). As a result, the position and
242 length of six conserved (32-37, 37-41, 39-43, 44-45, 47-49, 50) and five variable (37F, 41F, 43E,
243 45E-47F, 49E) regions were identified for all sequences (Figure 2). The remaining part of the
244 18S rDNA sequence, only present in sequences EU199447, EU199448 and EU199449 and
245 located before the motive “AAGGGCACCACAAGA” has not been analyzed in this way. All
246 regions fully covered in a sequence and containing sequence motives observed at least twice in

247 the whole dataset were labelled as “complete”. Regions fully covered but containing a sequence
248 motive that was observed only once in the whole dataset were labelled as “poor”. This is because
249 we consider sequencing/PCR errors as the most likely cause for the occurrence of such unique
250 sequence motives. We realize that using this procedure, even genuine unique sequences may be
251 discarded from the analysis, but this would be the case only if such sequences deviated in all
252 regions. In all other cases, the regions were labelled as “partial” when only a part of the region
253 was present or “not available” if they did not contain any fragment of the sequence. As a result
254 we obtain the Partitioned Primary Reference Database (Figure 2). The coverage of each
255 individual region in the Partitioned Primary Reference Database is given in Supplementary
256 Material 1, and all sequence partitions are given in Supplementary Material 2.

257 *Semi-automated iterative curation pipeline for optimal taxonomic assignment*

258 The consistency of taxonomic assignments within the annotated database of partitioned
259 sequences was assessed using a semi-automated process (Figures 2 and 3). All “complete”
260 regions of sequences with the same taxonomic assignment at the morphospecies level were
261 automatically aligned using global pairwise alignment (Needleman & Wunsch 1970), as
262 implemented in the software *needle* from the Emboss suite of bioinformatics tools (Rice et al.,
263 2000). To detect annotation inconsistencies, mean pairwise similarities were computed for each
264 “complete” region of each sequence against all other sequences with the same taxonomic
265 assignment from the finest annotation level “Genetic type level 3” up to the “Species level” rank.
266 Results are provided in Supplementary Material 1 and were visualized using R (R Development
267 Core Team, 2014) and the ggplot2 library (Wickham, 2009). The resulting plots are given in
268 Supplementary Material 3. If all annotations are consistent and there is no variation within taxa,
269 each sequence within the analyzed taxon should only find an exact match and the mean pairwise

270 similarity for that taxon should be 1. However, beyond sequencing/PCR errors introducing
271 spurious sequence differences, there are several reasons why the mean pairwise similarity within
272 a taxon may be lower. First, if a sequence has been assigned the wrong name, its similarity to all
273 other sequences labelled with that name will be low, thus decreasing the resulting mean pairwise
274 similarity. Second, if a sequence has been assigned to the correct taxon, but the taxon comprises
275 multiple sequence motives, that sequence will find a perfect match within the taxon but the mean
276 pairwise similarity will also be lower than 1.

277 In order to deconvolve the different sources of sequence variability within taxa, we followed a
278 three-step iterative approach, which was repeated for each of the 11 "complete" regions of the
279 analyzed SSU rDNA fragment. First, we considered the distribution of mean pairwise similarities
280 for all sequences within each region assigned to one taxon at the finest rank of "Genetic type
281 level 3". Assuming that misidentifications are rare and result in large pairwise distances, we
282 manually searched for sequences whose mean pairwise similarity deviates substantially from the
283 rest of the sequences within the taxon. Such sequences were initially "invalidated", whereas all
284 other sequences analyzed at this level were "validated". We then repeated the same procedure for
285 the higher ranks of "Genetic type level 2", "Genetic type level 1" and finally "Species level",
286 always starting with the full database (Figures 2 and 3A). Thus, at each level, we expected a
287 misidentified sequence to have a pairwise similarity markedly lower than the mean of pairwise
288 similarities between correctly assigned sequences (Figure 3B). This procedure had to be repeated
289 for every rank, because not all sequences in the database are assigned to all ranks. Nevertheless,
290 once "validated", a sequence cannot be "invalidated" during analyses of higher rank taxa,
291 because it represents an accepted variability within that taxon. In taxa where all sequences within

292 a region show low mean pairwise similarities all attributions are initially invalidated (this would
293 be typically the case for a “wastebasket taxa”; Figure 3C).

294 In the second step, all sequences invalidated during step 1 were reconsidered based on their
295 pairwise similarities with ‘validated’ sequences from the same region. The main goal of the
296 curated taxonomy being to achieve correct taxonomic assignment at the species level, the
297 pairwise comparison was carried out at this rank. If the best match is a ”validated” sequence with
298 the same initial species attribution as the invalidated sequence, this sequence is “validated” at the
299 species level and its assignment at the “genetic type” level is then deleted. Such a situation can
300 only occur when the sequence was initially assigned to the wrong genetic type within the correct
301 species. If the pairwise comparisons of all regions analyzed match sequences with different (but
302 consistent) species attributions than the invalidated sequence, the sequence is reattributed to that
303 species. If the pairwise comparisons indicate that the analyzed sequence has no close relative in
304 the validated part of the database, the initial attribution is retained, provided that the initial
305 attribution is not yet in the validated dataset. This case occurs when all sequences of one species
306 have been initially invalidated because the same species name was associated with highly
307 divergent sequences. When the sequence has no close relative but its initial attribution is
308 represented in the validated part of the dataset, the initial attribution is discarded and the
309 sequence receives an artificial attribution derived from the nearest higher rank that matches the
310 pairwise comparisons. In all cases, the erroneous attributions are replaced by the corrected ones
311 in the database (Figure 2, Supplementary Material 1).

312 In the third step, sequences that received new attributions were reanalyzed as described in step 1.
313 If inconsistencies in the distribution of mean pairwise similarities remain, steps 2 and 3 are
314 repeated until no inconsistency is observed.

315 As a final diagnosis we performed leave-one-out analyses to evaluate the robustness and
316 potential limitations of the curated taxonomy, as well as a monophyly validation by Neighbor-
317 Joining using only sequences that are covering the 6 conserved and 5 variable regions of the 5'
318 end fragment. First, each individual sequence included in the first version of PFR² was blasted
319 against the remaining part of the database including n-1 sequences using SWIPE (Rognes, 2011).
320 The sequences among the “n-1 PFR² database” returning the highest score were retrieved and
321 their taxonomic attribution compared to the one of the blasted sequence (Supplementary Material
322 1). Second, we retrieved all sequences covering the 5 variable and 6 conserved regions and
323 divided them according to their assignment to higher taxa (here simplified by the morphogroups
324 Monolamellar, Non-Spinose, Spinose, and Microperforates + Benthic). Each subset was
325 automatically aligned using MAFFT v.7 (Kato and Standley., 2013) and the subsequent
326 alignments were trimmed off on the edges to conserve only homologous position, finally leading
327 to 41, 583, 271, and 100 analyzed sequences for the Monolamellar, Non-Spinose, Spinose, and
328 Microperforates + Non-spiral morphogroups, respectively. For each alignment, a tree was
329 inferred using a Neighbor-Joining approach with Juke and Cantor distance while taking into
330 account gap sites as implemented in SEAVIEW 4 (Supplementary Material 4) with 100 pseudo-
331 replicates. The scripts used to perform the different curation steps are available as Supplementary
332 Material 5.

333 **Results**

334 Of the 3,532 planktonic foraminiferal 18S rDNA partial sequences analyzed, 3,347 (94.8%)
335 contained at least one “complete” gene region making possible the curation process. The
336 remaining 185 sequences included 33 singletons (rare motives or poor quality sequences) and
337 152 sequences that were too short to cover at least one region (Supplementary Material 1).

338 Amongst the 3,347 curated sequences, the taxonomic assignment of 84 was initially invalidated.
339 Of these, 3 represent cases where the morphospecies attribution was correct, but the attribution to
340 a genetic type was erroneous. In 46 cases, the invalidated sequences found a perfect match with a
341 different taxon and thus their taxonomic assignment was changed. In all of these cases, the novel
342 taxonomic assignment corresponded to a morphologically similar morphospecies, explaining the
343 original misidentification of the sequenced specimen. In 14 cases, the original assignment was
344 retained because the sequences did not find any match and their original attribution did not
345 appear in the validated part of the dataset. All of these sequences were labelled as *Hastigerinella*
346 *digitata*. This species name had been entirely invalidated in the first step because of inconsistent
347 use of the homonymous species name *Beella digitata*. Finally, 17 sequences received an
348 unresolved artificial assignment. These represent six different sequence motives diverging
349 substantially from all sequences in the validated part of the database and also between each
350 other. Because the original attribution upon collection was obviously wrong, we could not
351 reassign these sequences to the species level. In two cases, we could identify the most likely
352 generic attribution, but four sequences are left with an entirely unresolved path. Finally, our
353 procedure captured one sequence with a spelling error in its path and three sequences that appear
354 to have been attributed correctly but represent small variants within species. After resolution of
355 the 84 conflicts described above, the re-annotated dataset was subjected to a second round of the
356 curation process for verification. All sequences were validated.

357 Based on this internally consistent taxonomic annotation for all 3,347 18S rDNA sequences from
358 individual planktonic foraminifera, we generated the *Planktonic Foraminiferal Ribosomal*
359 *Reference* or PFR² database. Of the 3,347 sequences, 25 were shorter than 200 bp, and could not
360 be deposited in NCBI (see Supplementary Material 1). The PFR²1.0 database thus includes 3,322

361 reference sequences assigned to 32 morphospecies and 6 taxa with unresolved taxonomy (Figure
362 2), and contains 119 unique taxonomic paths when including all three levels of genetic types.

363 The leave-one-out BLAST evaluation applied on the first version of PFR² to assess its robustness
364 returned an identical taxonomic path for 2,509 sequences. For 614 sequences, the BLAST-
365 determined taxonomic paths were identical between the “morphogroup” and “species” rank but
366 displayed a different resolution between the ranks “genetic type level 1” and “genetic type level
367 3”. This reflects a situation where some sequences belonging to one species are annotated to the
368 level of a genetic type, whereas others are not. Finally, 19 sequences were assigned to the correct
369 species but to a different genetic type. This illustrates the case of genetic types represented by
370 only one sequence in the database, which were logically assigned to the closest genetic type
371 within the same species by the leave-one-out procedure. Thus, 94.5 % of the sequences in the
372 PFR² database find a nearest neighbor with a correct taxonomic assignment at the species target
373 level. For the remaining 180 sequences, the returned taxonomic path was inconsistent at the
374 species level. In two cases, the sequences were assigned to a morphologically and
375 phylogenetically close sister species (*Globorotalia ungulata* and *Globorotalia tumida*), reflecting
376 insufficient coverage in the database for these species. Two cases involved singleton sequences
377 with unresolved taxonomy, which find no obvious nearest neighbor. Finally, 176 cases of
378 inconsistent identification refer to sequences of *Globigerinella calida* and *Globigerinella*
379 *siphonifera*, whose species names have been used interchangeably in the literature (Weiner et al.,
380 2014) and the clade has been shown to be in need of a taxonomic revision (Weiner et al., 2015).
381 The leave-one-out evaluation thus reveals excellent coverage of PFR² and confirms that the
382 curated taxonomy is internally entirely consistent.

383 To further confirm the validity of morphospecies level taxonomy, we constructed NJ trees for the
384 five clades including only the long sequences (Supplementary Material 4). This analysis
385 confirmed the monophyly of all morphospecies, except the *Globigerinella calida*/*Globigerinella*
386 *siphonifera* plexus. All clades were strongly supported except for the sister species *Globorotalia*
387 *tumida* and *Globorotalia ungulata* and the monolamellar species *Hastigerina pelagica* and
388 *Hastigerinella digitata*. In the first case, the poor support reflects the lack of differentiation
389 between these two species in the conserved region of the gene, thus decreasing the bootstrap
390 score; in the second case the extreme divergence of two genetic lineages of *Hastigerina pelagica*
391 renders the phylogenetic reconstruction difficult (Weiner et al., 2012).

392 An analysis of the taxonomic annotations retained in PFR² reveals that the database covers at
393 least 70-80% of the traditionally recognized planktonic foraminiferal species in each clade. The
394 species represented in PFR² constitute the dominant part of planktonic foraminifera assemblages
395 in the world oceans. Compared with a global database of census counts from surface sediments
396 (MARGO database, Kucera et al., 2005), the species covered by PFR² account for >90% of tests
397 larger than 150 µm found in surface sediments (Figure 4). In cold and temperate provinces, PFR²
398 species account for almost the entire assemblages, while in warmer subtropical and tropical
399 waters, only up to 4% of the sedimentary assemblages are not represented in PFR². Evidently,
400 PFR² reference sequences cover most of the ecologically relevant portion of the morphological
401 diversity and the taxa that are not yet represented in PFR² are small, rare or taxonomically
402 obscure. It is possible that some of these taxa may correspond to the six sequences with still
403 unresolved taxonomy. If so, PFR² may be considered to cover up to 38 of the 47 recognized
404 species.

405 Finally, for each species present in PFR², we evaluated the ecological coverage of the global
406 sampling effort (Figure 4). Morphospecies of planktonic foraminifera are known to be
407 distributed zonally across the world oceans, reflecting the latitudinal distribution of sea surface
408 temperature (e. g., Bé and Tolderlund, 1971). A comparison between the temperature range of
409 each species as indicated by their relative abundance in surface sediment samples (Kucera et al.,
410 2005) and the temperatures measured at sampling localities shows that a large portion of the
411 ecological range of the species is covered by the reference sequences in PFR² (Figure 4).

412 *The PFR² web interface*

413 To facilitate data download and comparative sequence analyses, PFR² has been implemented into
414 a dedicated web interface, available at <http://pfr2.sb-roscoff.fr>. The website provides:

- 415 (1) a search/browse module, which allows the user to download parts of the database either by
416 taxonomic rank (morphogroup name, genus name, species name), geographic region (e. g.,
417 North Atlantic, Mediterranean Sea, Indian Ocean) or collection (cruise name) ;
- 418 (2) a classical BLAST/Similarity module that facilitates identification of unknown sequences;
- 419 (3) a map module displaying the localities for all sequences present in PFR² and facilitating
420 download of all data from each single locality;
- 421 (4) a download section with direct access to all data included in PFR². All sequences and
422 sequence partitions are available in FASTA format and the metadata are available in a
423 tabulated file.

424 **Discussion**

425 Comprehensive databases of ribosomal RNA sequences with curated taxonomy are available for
426 Protists (Protist ribosomal reference database, PR²; Guillou et al., 2013) and for the major

427 domains of life (SILVA; Yilmaz et al., 2013). These databases include sequences of planktonic
428 foraminifera. However, they are used mainly as benchmarks to annotate complex environmental
429 datasets (e.g., Logares et al., 2014) at the morphological species level. In contrast, PFR² has been
430 designed and implemented in a way that facilitates other applications.

431 First, because of structural limitations PR² contains “only” 402 sequences of planktonic
432 foraminifera (based on Released 203 of GenBank, October 2014), compared to PFR², which
433 contains for now 3,322 SSU rDNA sequences. Second, 2276 of the sequences present in PFR²
434 have an assignation to the genetic type level and as far as possible, the sequences are associated
435 with metadata related to the origin of each specimen and the conditions where it was collected,
436 thus forming a basis for ecological modelling. Third, most importantly, using planktonic
437 foraminifera as a case study, we propose and implement an annotation scheme with unmatched
438 accuracy and full tracking of changes. This is only possible because of the narrower focus of
439 PFR² combined with high-level expert knowledge of their taxonomy. The fidelity of the
440 annotations will facilitate a qualitatively entirely different level of analysis of eDNA libraries.

441 For example, the design of PFR² allows to incorporate advances in classical and molecular
442 taxonomy, particularly at the level of genetic types (e.g., André et al., 2014), which can be re-
443 evaluated depending of the criteria used to delineate molecular OTUs. Further, by retaining
444 information on clone attribution to specimens (vouchers), PFR² allows to evaluate intra-genomic
445 polymorphism, which offers excellent opportunity to identify the taxonomically relevant level of
446 variability (Weber and Pawlowski, 2014). Finally, the modular structure of PFR² (i.e., its
447 partitioning into variable and conserved regions) is particularly suitable for the evaluation of
448 existing barcodes or the design of new barcoding systems needed to capture total or partial
449 planktonic foraminiferal diversity within complex plankton assemblages. Indeed, an examination

450 of the length polymorphism in the 11 regions of the 18S rDNA fragment that have been aligned
451 for all PFR² sequences reveals that next to the variable 37/f region identified as a barcode for
452 benthic foraminifera (Pawlowski and Lecroq, 2010), several other regions may be suitable as
453 targets for barcoding of planktonic foraminifera (Figure 5).

454 The main difference between PFR² and classical databases is in the association of sequence data
455 with environmental and collection data. Such level of annotation is not feasible in large
456 databases, which have to rely on the completeness and level of metadata details provided in
457 GenBank. The association of metadata to PFR² sequences facilitates an assessment of
458 biogeography and ecology of genetic types (potential cryptic species). This is significant for
459 studies of evolutionary processes in the open ocean such as speciation and gene flow at basin
460 scale, but also for paleoceanography, which exploits ecological preferences of planktonic
461 Foraminiferal species to reconstruct climate history of the Earth (e.g., Kucera et al., 2005).
462 Modeling studies showed that the integration of cryptic diversity into paleoceanographic studies
463 will improve their accuracy (Kucera and Darling, 2002; Morard et al., 2013). Together with the
464 MARGO database (Kucera et al., 2005), which records the occurrence of morphospecies of
465 planktonic foraminifera in surface sediments and the CHRONOS/NEPTUNE database (Spencer-
466 Cervato et al., 1994; <http://www.chronos.org/>), which records their occurrence through
467 geological time, PFR² represents the cornerstone to connect genetic diversity to the fossil record
468 in an entire group of pelagic protists.

469 **Conclusion and perspectives**

470 The PFR² database represents the first geographically and taxonomically comprehensive
471 reference barcoding system for an entire group of pelagic protists. It constitutes a pivotal tool to

472 investigate the diversity, ecology, biogeography, and evolution in planktonic foraminifera as a
473 model system for pelagic protists. In addition, the database constitutes an important resource
474 allowing reinterpretation and refinement of the use of foraminifera as markers for stratigraphy
475 and paleoceanography. In particular, PFR² can be used to: (i) annotate and classify newly
476 generated 18S rDNA sequences from single individuals; (ii) study the biogeography of cryptic
477 genetic types; (iii) design rank-specific primers and probes to target any group of planktonic
478 foraminifera in natural communities; and (iv) assign accurate taxonomy to environmental
479 sequences from metabarcoding or metagenomic datasets. This last point is particularly worth
480 noting. Indeed, future global metabarcoding of planktonic foraminifera covering comprehensive
481 spatio-temporal scales will likely reveal the full extent and complexity of species diversity and
482 ecology in this group, serving as a model system for studies of the evolutionary dynamics of the
483 plankton and its interaction with the Earth system.

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676

677 **Author contribution**

678 KFD, CdV, YU, RM, TdG, AKMW, HAS, MK, AA, MS participated in sample collection, CdV,
679 MK, KFD, CMW, CJD, FQ, GE, TdG provided laboratory infrastructure, KFD, YU, RM,
680 AKMW, AA, HAS participated in laboratory work. FM and RM conceived and designed the
681 bioinformatics pipeline, FM performed the computational work, SA built the website. RM wrote
682 the manuscript with help from MK and CdV. All authors read, edited and approved the final
683 manuscript.

684 **Data Accessibility**

685 Sequences, NCBI accession numbers and metadata are available in Supplementary Material 1
686 and 2 and on the PFR² website at <http://pfr2.sb-roscoff.fr>. The custom scripts used to perform the
687 curation procedure are available in Supplementary Material 5; the results of the curation process
688 are given in Supplementary Material 1 and 2.

689 **Figures**

690 Figure 1

691 **Sampling Map.** Location of the 460 oceanic stations sampled over 20 years for single-cell
692 genetic studies of planktonic foraminifera. Each symbol corresponds to a scientific cruise or near
693 shore collection site. Cruise names and dates of the collection expeditions are indicated in the
694 legend. Grey shading shows ocean bathymetry.

695 Figure 2

696 **Workflow to constitute PFR².** In step I the sequences, metadata and taxonomic information are
697 retrieved from public databases and literature or from the internal databases of the co-authors to
698 constitute the Primary Reference Database. In step II, the coverage of each sequence is evaluated
699 by alignment with structural regions of the 18S RNA secondary structure derived for the species
700 *Micrometula hyalostera* (Pawlowski and Lecroq, 2010). In step III, the consistency of the
701 annotation is checked from the most exclusive level of annotation “genetic type 3” up to the
702 species level (Phase 1) to detect annotation inconsistencies (See Figure 3). Sequences with
703 wrong annotation are invalidated, compared to the validated part of the dataset (Phase 2) and re-
704 annotated depending on the best hit out of the valid dataset. The consistency of all annotations is
705 then checked again following the same procedure as in Phase 1 (Phase 3), to ensure that no
706 taxonomic inconsistency remains. In step IV, all sequences which have been subjected to the
707 curation process are integrated in the *Planktonic Foraminifera Ribosomal Reference* database
708 (PFR²). The results of all steps are given in Supplementary Material 1.

709 Figure 3

710 **Annotation inconsistency detection.** The procedure followed to identify annotation
711 inconsistencies is exemplified by three cases. Each graph represents variability in pairwise
712 similarities observed across each region of all sequences sharing the same annotation level. The
713 names of the taxon and annotation level are given above the plot with the number of sequences
714 in parenthesis. Each vertical line represents one region with the variability represented as box
715 plot, the number of “complete” regions is given at the bottom of the line. The case “A” describes
716 the annotation validation process starting from the most exclusive rank of “genetic type level 3”
717 to the “species” rank. After the validation at one rank level, the sequences with valid annotation
718 are merged into a taxonomic unit of a higher rank, this now including multiple sequence motifs
719 which decreases the average similarity level of each region, thus leading to higher variability in
720 higher ranks. Case “B” represents the occurrence of obvious outliers at the species level, which
721 are invalidated. Case “C” represents the co-occurrence of divergent sequences under the same
722 taxonomic attribution, which are consequently all invalidated. Box plots for all ranks can be
723 found in Supplementary Material 3 and the pairwise similarities calculated for each taxonomic
724 level are given in Supplementary Material 1.

725 Figure 4

726 **Taxonomic and ecological coverage of PFR².** For each morphogroup (Spinose, Non-Spinose,
727 Microperforates, Monolamellar and Non-Spiral) the number of species included in PFR² is given
728 in the filled bar while the number of species not present is indicated in the adjacent open bar. The
729 relative abundance in the sediments of each species included in PFR² is given in a log-scale
730 value against mean Sea Surface Temperature (SST) at the sampling station. Relative abundances
731 in sediments are derived from the MARGO database (Kucera et al., 2005) and the mean annual
732 SST (MODIS Aqua, NASA, Greenbelt, MD, USA). The grey dots highlight the mean annual
733 SST at the location where the living planktonic foraminifera yielding sequences were sampled.
734 The number of sequences available for each species as well as the number of taxonomic paths
735 above the species level is shown next to the graphs. Also shown is the cumulative mean relative
736 abundance in the sediments of all species included in PFR² plotted against the mean annual SST
737 in discrete 1°C intervals. Vertical bars represent 95% confidence intervals for each 1°C bin.

738 Figure 5

739 **Length polymorphism.** Each rectangle represents the length polymorphism within each region
740 of the analyzed 18S rDNA fragment across all resolved taxonomic units in PFR². The regions are
741 based on the rRNA secondary structure and are named following Pawlowski and Lecroq (2010).

742 **Supplementary Material.**

743 Supplementary Material 1

744 Information on all consecutive steps followed to constitute the PFR². All fields are explained in
745 the file.

746 Supplementary Material 2

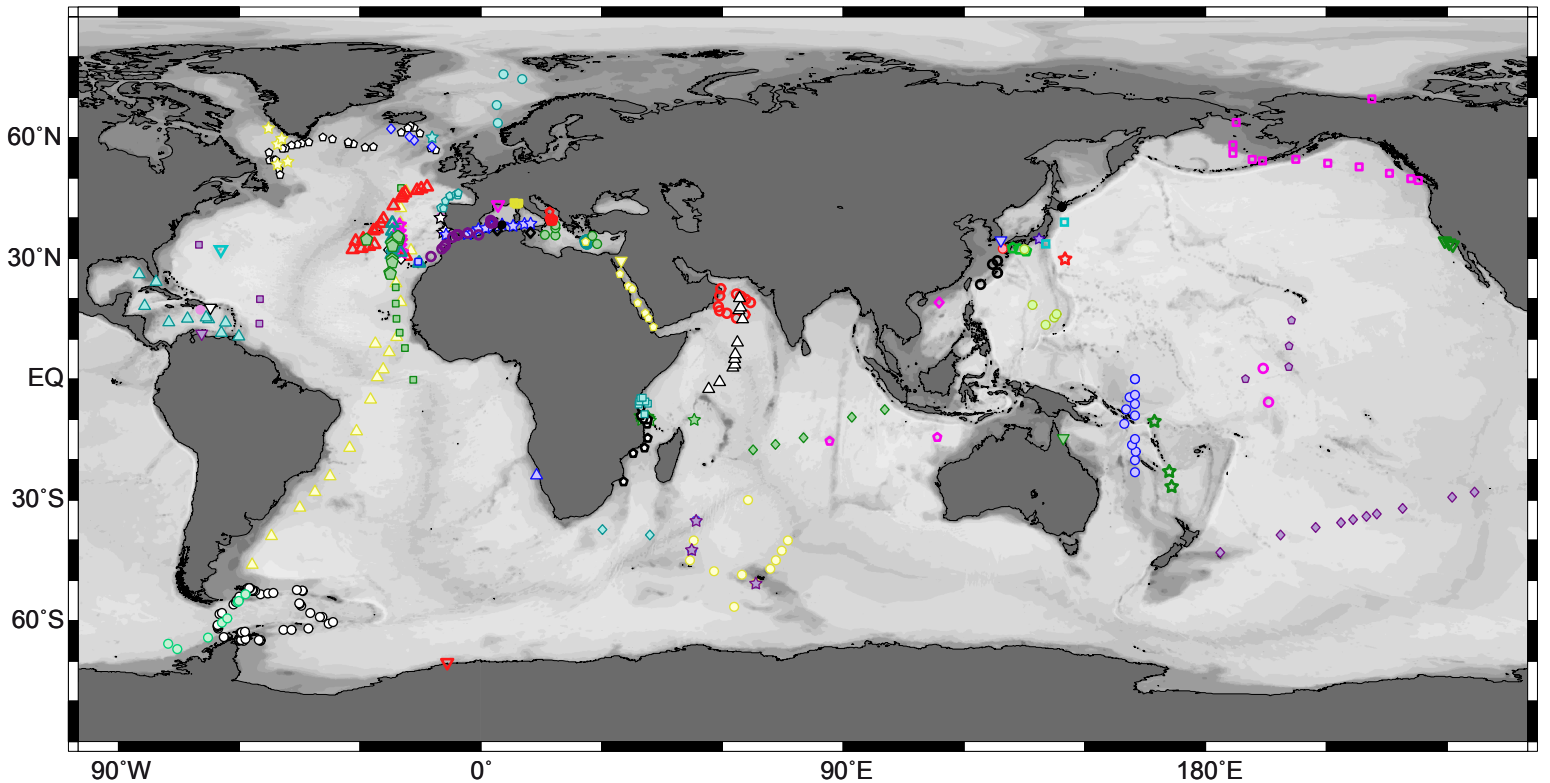
747 FASTA files of sequences used to build the PFR². FASTA files are provided for the full
748 sequences and individual partitions.

- 749 Supplementary Material 3
- 750 Box plots showing pairwise similarities for each taxonomic level. See Figure 3 for explanations
751 of the content of the plots.
- 752 Supplementary Material 4
- 753 Neighbor-joining trees showing the monophyly of each morphospecies present in PFR².
- 754 Supplementary Material 5
- 755 Custom scripts used to perform the different curation steps.

Table 1. Flanking conserved sequences of the 5 variable regions in planktonic foraminifera. The minimum and maximum length of each region are given as well as their coverage in the database (See details in the text).

Region	Specificity	Beginning	End	Min length	Max length	Not available	Partial	Poor	Complete
32-37	Eukaryotes	-	-	-	-	949	2583	0	0
37F	Foraminifera	5'-GGAUUGACA	CUUUCACAUGA-3'	38	132	800	272	249	2211
37-41	Eukaryotes	-	-	68	72	547	403	138	2444
41F	Foraminifera	5'-AAUUGCG	GCAACGAA-3'	58	322	349	346	282	2555
39-43	Eukaryotes	-	-	27	29	460	34	57	2981
43E	Eukaryotes	5'-CUUGUU	AACUAGAGGG-3'	33	195	401	263	265	2603
44-45	Eukaryotes	-	-	113	123	487	1288	136	1621
45E-47F	Euk - Forams	5'-CAGUGAG	GGUGGGG-3'	179	312	1660	187	386	1299
47-49	Eukaryotes	-	-	140	148	1827	425	152	1128
49E	Eukaryotes	5'-GUGAG	CGAACAG-3'	27	127	2251	130	125	1026
50	Eukaryotes	-	-	-	-	2389	1143	0	0

Figure 1. Sampling Map. Location of the 460 oceanic stations sampled over 20 years for single-cell genetic studies of planktonic Foraminifera. Each symbol corresponds to a scientific cruise or near shore collection site. Cruise names and dates of the collection expeditions are indicated in the legend. Grey shading shows ocean bathymetry.



Scientific cruise

- Alis, GYRAFOR-A (Jun 2008)
- △ Charles Darwin, CD148 (July 2003)
- ◇ Charles Darwin, CD159 (July 2004)
- ◇ Discovery, D262 (Apr 2002)
- ◇ Discovery, D286 (Dec 2005, Jan 2006)
- ☆ Garcia del Cid, Iberia-Forams (Sept 2012)
- Hakuho-maru, KH04-2 (Jun-Jul 2009)
- Hakuho-maru, KH10-4 (Aug 2011)
- △ James Clark Ross, AMT-5 (Sept-Oct 1997)
- James Clark Ross, AMT-8 (Apr Jun 1999)
- James Clark Ross, JR 19 (Mar 1997)
- James Clark Ross, JR 48 (Feb-Mar, 2000)
- ☆ Maria S. Merian, MSM09-2 (Aug-Sep 2008)
- ◇ Maria S. Merian, MSM15-5 (Jul 2010)
- ◇ Marion Dufresne, GYRAFOR-B (Jul-Aug 2007)
- ☆ Marion Dufresne, OISO2011 (Jan 2011)
- Marion Dufresne, OISO-4 (Jan-Feb 2000)
- Melville, Melville (June 2003)
- Meteor, M37-2a (Apr 1997)
- Meteor, M69-1 (Aug 2006)
- Meteor, M71-2 (Dec 2006 - Jan 2007)
- Meteor, M71-3 (Jan-Feb 2007)
- Meteor, M74-1a (Sep 2007)
- Meteor, M74-1b (Sep-Oct 2007)
- Meteor, M75-2 (Feb 2008)
- △ Meteor, M78-1 (Feb-March 2008)
- ◇ Mirai, MR02-K01 (Jan 2002)
- ☆ Mirai, MR10-06 (Nov 2010)
- ☆ Pelagia, 64PE303 - GLOW (Feb-Mar 2009)
- Pelagia, 65PE304 (Mar 2009)
- Polarstern, Arktis XV/1-2 (Jun 1999)
- △ Poseidon, P247 (Jan 1999)
- Poseidon, P283-2 (Feb-Mar 2002)
- Poseidon, P308 (Mar 2004)
- ◇ Poseidon, P321 (May 2005)
- ◇ Poseidon, P334 (Mar-Apr 2006)
- ☆ Poseidon, P349 (Apr 2007)
- Poseidon, P411 (Apr 2011)
- Poseidon, P413 (May 2011)
- ☆ Professor Logachev, Denmark Strait (Sept 1997)
- ◇ Roger Revelle, Revelle (Jan 2001)
- Ron Brown, CMarZ (April 2006)
- Sarmiento de Gamboa, FORCLIM-7 (Apr 2009)

- Seriora, Amakusa (Sep 2009)
- Sir Wilfried Laurier, CCGS (July 2007)
- ◇ Sonne, SO-221 (May 2012)
- ☆ Sonne, SO-226 (Mar 2013)
- Tansai-maru, KT02-15 (Oct 2002)
- ◇ Tansai-maru, KT07-14 (Jun 2007)
- Tansai-maru, KT06-11 (Jun 2006)
- ☆ Tansai-maru, KT06-30 (Nov 2006)
- △ Welwitschia, NatMIRC (Nov 2001)

Near-Shore Collection

- ▽ Bermuda (Apr 1996)
- ▽ Curaçao (Feb 1993)
- ▽ Eilat (Feb 2011)
- ▽ Ekstrom Ice Shelf-Atka Bay (Jan 2001)
- ▽ Lizard Island, GBR (Aug 1993, Sep 1997)
- ▽ Puerto Rico (Mar 1995)
- ▽ Santa Barbara Chanel (Feb 1998, Jan-Sep 1999)
- ▽ Tsugaru strait
- ▽ Villefranche sur Mer (Dec 1995)

Figure 2. Workflow to constitute PFR². In step I the sequences, metadata and taxonomic information are retrieved from public databases and literature or from the internal databases of the co-authors to constitute the Primary Reference Database. In step II, the coverage of each sequence is evaluated by alignment with structural regions of the 18S RNA secondary structure derived for the species *Micrometula hyalostera* (Pawlowski and Lecroq, 2010). In step III, the consistency of the annotation is checked from the most exclusive level of annotation “genetic type 3” up to the species level (Phase 1) to detect annotation inconsistencies (See Figure 3). Sequences with wrong annotation are invalidated, compared to the validated part of the dataset (Phase 2) and re-annotated depending on the best hit out of the valid dataset. The consistency of all annotations is then checked again following the same procedure as in Phase 1 (Phase 3), to ensure that no taxonomic inconsistency remains. In step IV, all sequences which have been subjected to the curation process are integrated in the *Planktonic Foraminifera Ribosomal Reference* database (PFR²). The results of all steps are given in Supplementary Material 1.

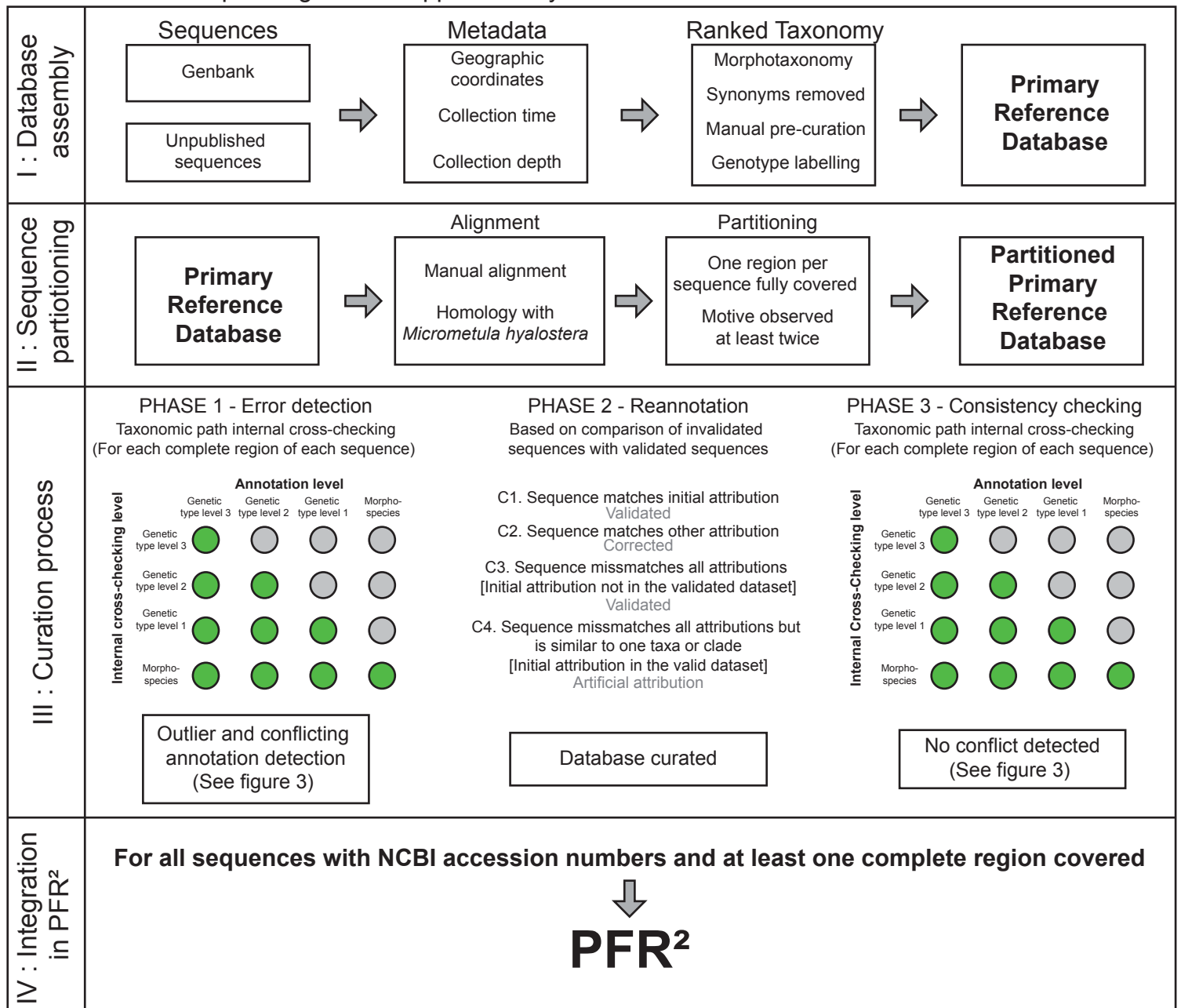


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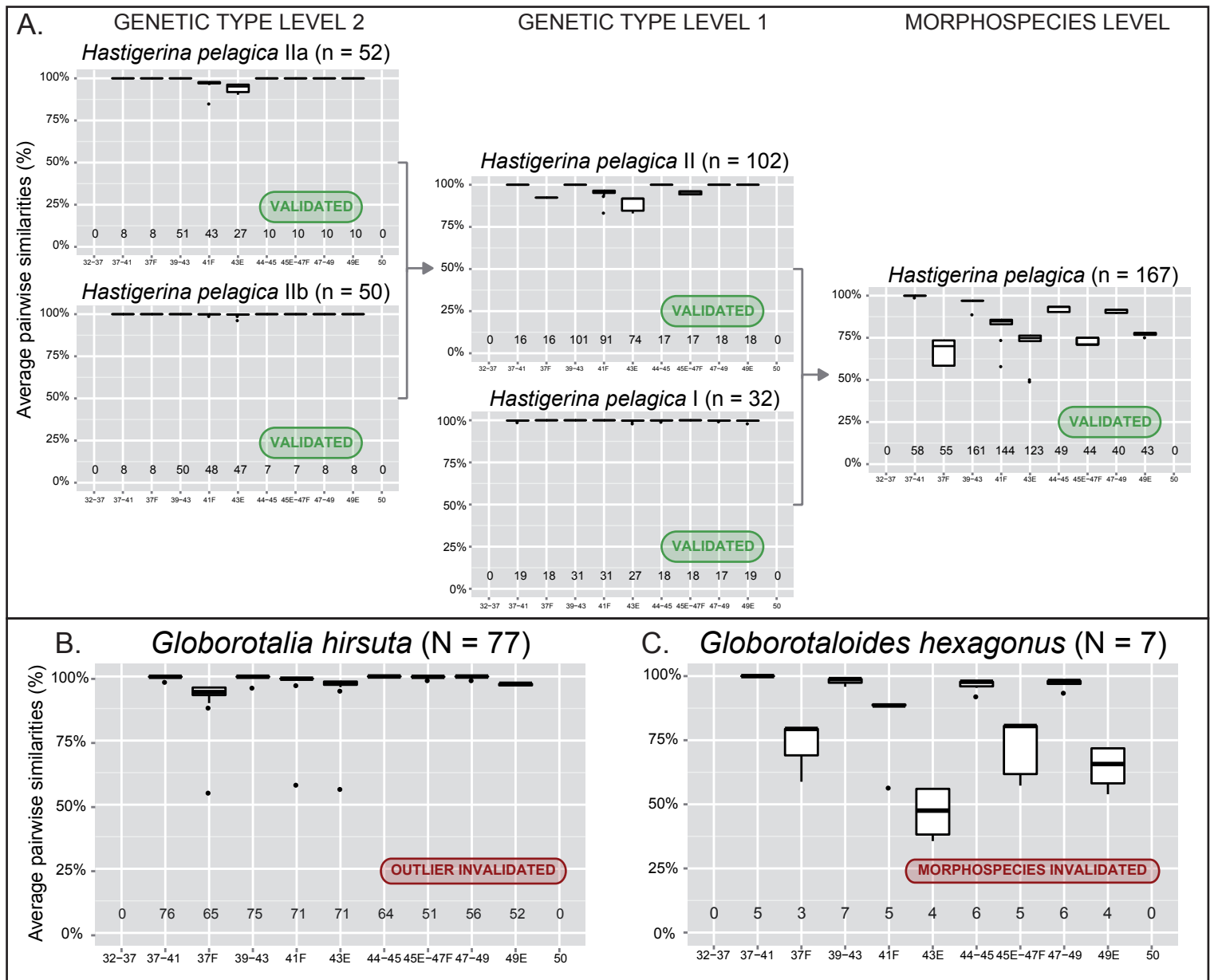


Figure 4. Taxonomic and ecological coverage of PFR². For each morphogroup (Spinose, Non-Spinose, Microperforates, Monolamellar and Non-Spiral) the number of species included in PFR² is given in the filled bar while the number of species not present is indicated in the adjacent open bar. The relative abundance in the sediments of each species included in PFR² is given in a log-scale value against mean Sea Surface Temperature (SST) at the sampling station. Relative abundances in sediments are derived from the MARGO database (Kucera et al., 2005) and the mean annual SST from the World Ocean Atlas (Locarnini, 2005). The grey dots highlight the mean annual SST at the location where the living planktonic Foraminifera yielding sequences were sampled. The number of sequences available for each species as well as the number of taxonomic paths above the species level is shown next to the graphs. Also shown is the cumulative mean relative abundance in the sediments of all species included in PFR² plotted against the mean annual SST in discrete 1°C intervals. Vertical bars represent 95% confidence intervals for each 1°C bin.

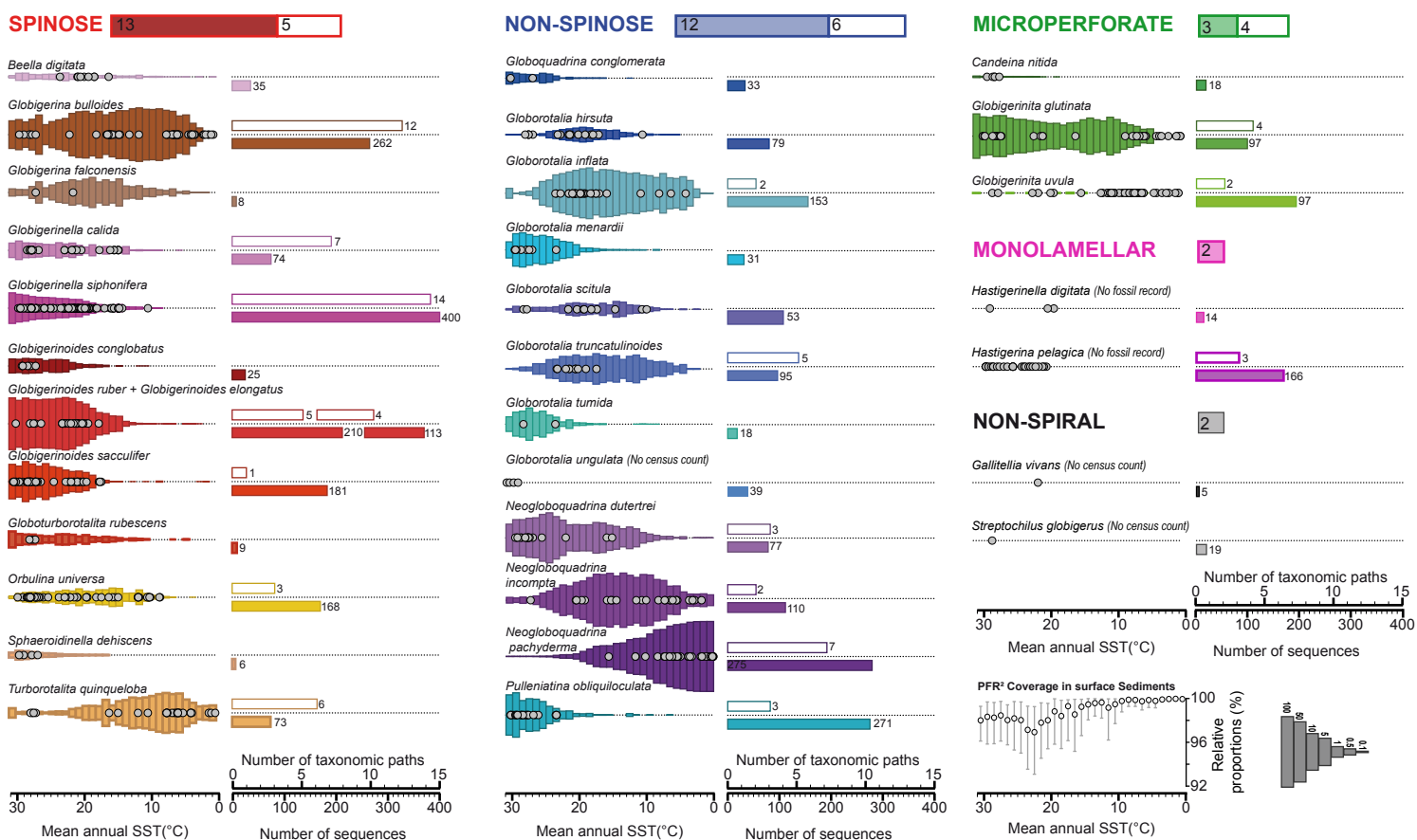


Figure 5. **Length polymorphism.** Each rectangle represents the length polymorphism within each region of the analyzed 18S rDNA fragment across all resolved taxonomic units in PFR². The regions are based on the rRNA secondary structure and are named following Pawlowski and Lecroq (2010).

