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BENFEP, a quantitative database of BENthic Foraminifera from surface sediments of the Eastern Pacific

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Abstract. Foraminifera are important components of the ocean benthos and play a major role in ocean biogeochemistry and ecosystems functioning. Generating ecological baselines for ocean monitoring or biogeographical distributions requires a reference dataset of recent census data. Besides, the information from their modern biogeography can be used to interpret past environmental changes on the sea-floor. In this study, we provide the first comprehensive quantitative BENthic Foraminifera database from surface sediments of the Eastern Pacific (BENFEP). Through the collation of archival census data and its homogenization according to the most recent taxonomic standards, we are able to provide a database with 3093 sediment samples, corresponding to 2572 georeferenced stations of wide geographical coverage (60ºN and 54ºS) and water depths (0-7642 m). The quantitative data includes living, dead, and living and dead assemblages obtained from 47 published and unpublished documents. As well as describing the data collection and subsequent harmonization steps, we provide summarized information of metadata variables, examples of species distribution, potential applications of the database and recommendations for data archiving and publication of benthic foraminiferal data. The database is enriched with meaningful metadata for accessible data management and exploration with R and geospatial software. BENFEP will be upgraded with new records. We complement BENFEP with an additional database integrating metadata and stations geolocation of benthic foraminiferal studies dearth of quantitative data (BENFEPqual).

1 Introduction

The Eastern Pacific extends from the tidewater glaciers at Alaska to the fjords of Chile, encompassing a habitat that integrates eight Large Marine Ecosystems covering 10.7 million of ha (Fig. 1). Tropical and subtropical latitudes harbour exceptional levels of pelagic and benthic biodiversity and the presence of endemic species at macro and microorganism's levels (e.g., Davies et al., 2017; Gooday et al., 2021). Several areas of Eastern Pacific Ocean are at severe risk of species loss (Finnegan et al., 2015; Yasuhara et al., 2020, UNESCO, 2022) and consequently, some of them are under environmental protection figures (Enright et al., 2021).

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The Eastern Pacific is influenced by ocean-atmosphere natural climate variability modes at decadal-to-multidecadal (e.g., El Niño-Southern Oscillation, the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation; Stuecker, 2018), millennial (Pisias et al., 2001) and glacial-interglacial (e.g., Walczak et al., 2020) timescales. These processes resulted in changes in temperature (Liu and Herbert, 2004), salinity (Praetorius et al., 2020) and productivity (Costa et al., 2017) in the surface ocean. In an historical context, the increase in ocean temperatures, ongoing deoxygenation (a decline in oxygen in ocean waters) induced by coastal eutrophication (Helly and Levin, 2004) and global warming are the major threats to shallow and deep-water benthic ecosystems from the Eastern Pacific (Sweetman et al., 2017; Breitburg et al., 2018; Yasuhara et al., 2019).

The Ocean Decade Implementation Plan (2021-2030) (https://www.oceandecade.org/), promoted by the United Nations, establishes several priority objectives for ocean sustainable development and conservation, which include a more profound understanding of benthic ocean ecosystem functioning and a better assessment of the vulnerability of coastal and deep ocean areas to ongoing impacts of anthropogenic activities and climate change. Attaining such targets might be challenged by the scarcity and unevenness of recent benthic organisms' census data that might function as suitable natural baselines (Yasuhara et al., 2012; Kidwell, 2015; Borja et al., 2020). Benthic foraminifera, microscopically-sized and shelled organisms (generally ranging from 63 µm to 1000 µm, Murray, 2006) are major components of the marine benthos. Those whose shells are composed of calcium carbonate, have the potential of being preserved in the marine sediments, providing an ideal natural archive for recording past seafloor conditions.

Benthic foraminifera have been used for decades as past environmental indicators (Jorissen et al., 2007) and, more recently, in environmental monitoring (Alve et al., 2016; Jorissen et al., 2018). For example, in the Eastern Pacific, benthic foraminifera were used as proxies for changes in productivity (e.g., Patarroyo and Martinez, 2015; Diz et al., 2018, Tapia et al, 2021) and intermediate and deep-water oxygenation (e.g., Cannariato and Kennett, 1999; Tetard et al., 2017; Sharon et al., 2020). The proxy value of benthic foraminifera as paleoenvironmental or biomonitoring tools could be hampered if the full scope of current biodiversity patterns, spatial distributions, and species-environmental relations are not fully known or grounded on a limited number of observations. A synthesis effort of recent benthic foraminiferal quantitative occurrences would definitively lead to attain a more complete picture of biogeographical distributions and relationships between environmental parameters and species composition; rendering interpretations based on the more meaningful fossil record.

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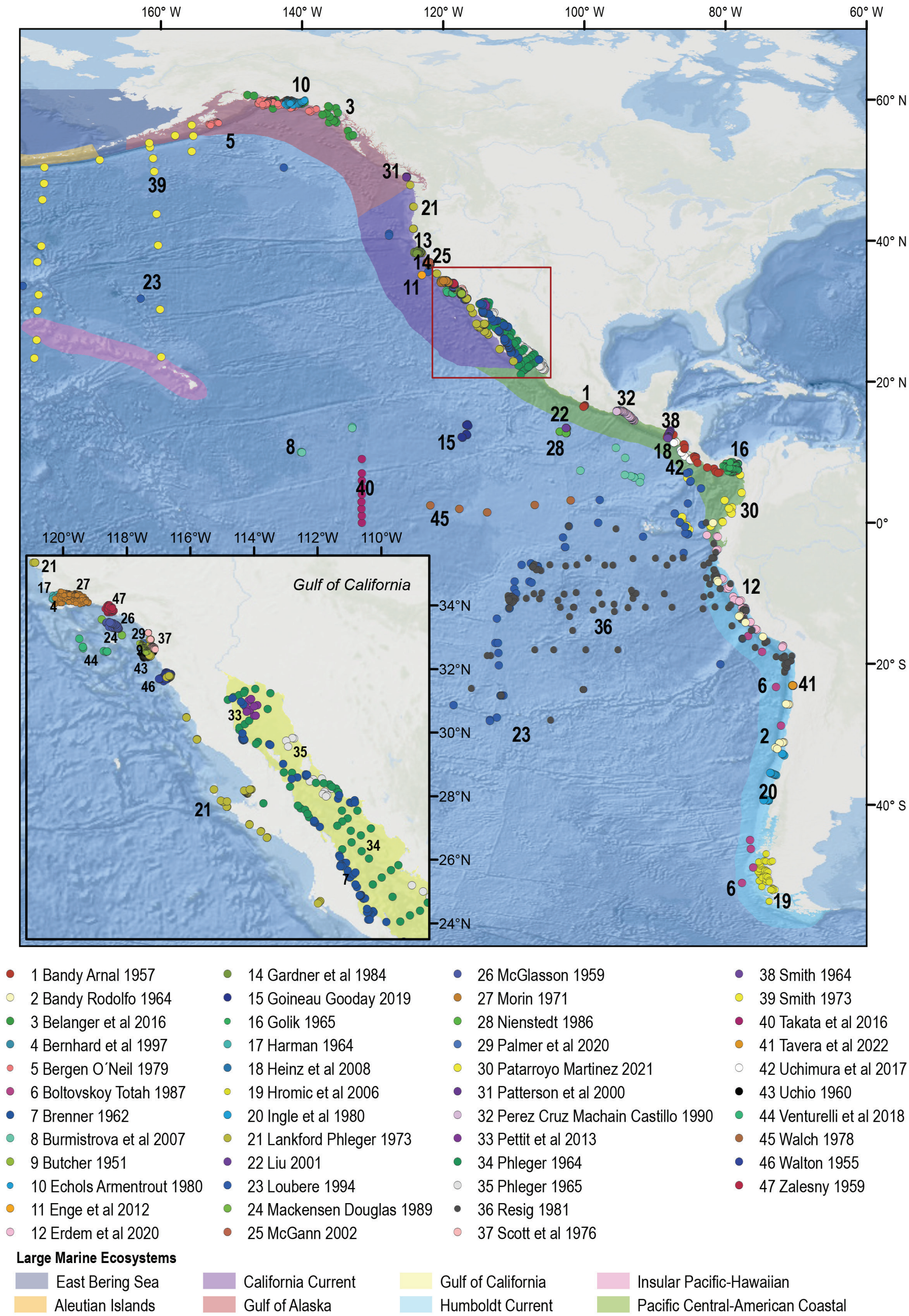

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Figure 1: Spatial distribution of the samples comprising the BENFEP database. The numbers refer to each author´s dataset (see Table A1 for additional information). Colour-shaded areas represent the Large Marine Ecosystems of the Eastern Pacific (data obtained from https://www.sciencebase.gov/catalog/item/55c77722e4b08400b1fd8244, last accessed in August 2022). The map was created using ArcGIS software version 10.8.2 The global relief model integrates land topography and ocean bathymetry (Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributions).

The distribution of different marine microfossils in surface sediments covering large ocean swathes is compiled in several databases developed during the last decades. However, they mainly integrate census data of planktonic organisms dwelling in the first hundred meters of the water column, such as planktic foraminifera (Siccha and Kucera, 2017), dinoflagellates (Marret et al., 2020), radiolarian (Boltovskoy et al., 2010; Hernández-Almeida et al., 2020; Lawler et al., 2021), diatoms (Leblanc et al., 2012) or coccolithophores (Krumhardt et al., 2017). Public databases focused on quantitative surface distribution of benthic microfossils are being developed for ostracods (e.g., Cronin et al., 2021, see also review by Huang et al., 2022). Existing quantitative benthic foraminifera datasets from surface sediments including relatively large number of stations (<300) are restricted to particular ocean sectors, size fractions, or test nature. Examples of these publicly available benthic foraminifera databases are those developed for the Norwegian continental shelf (Sejrup et al., 2004), which includes 298 stations and contains only calcareous foraminifera; the Indian Ocean (De and Gupta, 2010), with 131 core-top samples; or the central Arctic Ocean (Wollenburg and Kuhnt, 2000), with 90 stations. In the East Pacific, the science community performed sporadic research efforts to attain an overview of the quantitative distributions of benthic fauna (e.g., Lankford and Phleger, 1973, n=106; Resig, 1981, n=160; Loubere,1994, n=66, n indicates number of samples, see Table A1). However, the large area to cover and the economic and time-wise efforts required to sample a significant portion of the sea-floor sediments of the entire Eastern Pacific have prevented the construction of a large and consistent database of benthic fauna for this region.

In this paper, we present BENFEP, a quantitative database of BENthic Foraminifera from surface sediments of the Eastern Pacific. It contains a rich collection of metadata (e.g., research vessel, sampling devices, processing methods, etc) and quantitative information (percent, counts, densities) of harmonized taxonomically valid benthic foraminiferal taxa obtained from more than three thousand samples of living, dead and living and dead assemblages gathered from published and unpublished studies. Here, we provide a complete description of the steps to build the database, its limitations, and the potential products for various stakeholders. BENFEP is structured to be analysed with data science and geographic information systems programs. We complement BENFEP with an additional database for the Eastern Pacific containing georeferenced stations obtained from several publications that do not provide raw quantitative data for benthic foraminiferal species, BENFEPqual, a qualitative database of BENthic Foraminifera from surface sediments of the Eastern Pacific.

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2 Methods

2.1 BENFEP briefing

BENFEP integrates metadata and georeferenced quantitative data of benthic foraminifera species (living, dead or living plus dead) from surface sediment samples collated from 47 published and unpublished documents released between 1951 and 2022 (Table A1). The number of samples supplied by each publication to the database varies among authors (see Table A1). The database includes samples ranging from 60ºN to 54ºS (Fig. 1) and localized from intertidal waters (0 m water depth) to the deepest curated sample at 7642 m water depth. BENFEP includes 2572 stations, 3093 samples, and 1072 fully described species plus 391 benthic foraminiferal entities (those classified to genus genera level).

2.2 Data source and selection protocols

The BENFEP database incorporates entries with quantitative data of benthic foraminifera species from the Eastern Pacific surface sediments. A primary source of information for mid to late twentieth century´ entries were the qualitative compilations by Culver and Buzas (1985, 1986, 1987), Ingle and Keller (1980) and the historical references by Finger (2013). For more recent publications, we used the search engines of Scopus, Journal of Foraminiferal Research, JSTOR and PANGAEA (accessed between early 2020 and March 2022), using the keywords “benthic foraminifera” together with geographic terms such as “Eastern Pacific”, or specific geographical terms of this region, such as “California”, “Chile”, “Santa Barbara”, “Alaska”, etc.

A substantial number of entries of BENFEP come from print-only publications including unpublished thesis accessed through universities-interlibrary loans (91%). From these, only 6.8% could be digitized, and the remaining (typewritten or hand-written tables) had to be converted to digital format manually (93.2%). In those cases, entries were doubled or when necessary, tripled checked to minimize errors. BENFEP retains the original format in which census data were published; percentage, counts or densities representing 65.7, 34 and 0.3% of the data respectively. It also includes any non-numeric character used by authors in their original publication to indicate the presence or a semi-quantitative value of a particular species (e.g., “x” represents species percentage lower than 1%, fragments, etc).

2.3. Data geolocation

The samples integrated in BENFEP were georeferenced using the coordinates listed in the original publications. In Smith, (1964) and Walton (1955), coordinates are not indicated in the original publication along with the benthic census data, and they had to be retrieved from another publication that used the same stations (Smith, 1963; Walton, 1954). For 29% of the samples, their location was only shown on maps. In those cases, the maps from the publications were digitized to raster format and georeferenced through ArcGIS software using geographic decimal degrees and World Geodetic System of 1984 (WGS 84 – EPSG:4326). The rasters were then displayed with ArcGIS to extract the sample geolocation by manual digitizing. In those

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cases, when the resolution and precision of the map provided in the publication are clearly insufficient, the present coastline was retrieved using the World Imagery WMS server and the samples´ geolocation was obtained combining both sources of data. It is worth mentioning that the coarse resolution of some hand-drawn maps, in particular from those published in mid-twentieth century surveys, might not be totally accurate. A few samples (11) are not georeferenced because samples´ location is missing from maps (or lists provided by the authors) and other samples (16) are currently located inland.

2.4. Metadata

The metadata for each sample were collated from the original sources, and coded accordingly (see Table B1). The metadata variables include water depth of the surface sediment sample, name of the research vessel used to collect the sample, sampling year, details regarding different sampling methodologies (sampling devices, sampling interval at the seabed), format of data (percent, counts, density), type of assemblage (living, dead or living plus dead), size fraction in which foraminifera were studied and picking, and staining protocols. Additionally, we included as metadata the source of the data (e.g., automatic digitization, manual digitization, or retrieved from repositories), the source of the geographic coordinates (e.g., obtained from tables in the publication or digitized maps), the number of counted individuals in each sample (i.e., equal to or higher than 100, 200 and 300 individuals, or non-counts available) and meaningful annotation regarding the data entry (e.g., presence of symbols -"x"- and their meaning, etc). Metadata aim to provide all the necessary information for users to assess the quality of the faunal dataset and manage the data to their own convenience.

2.5 Taxonomic harmonization

The datasets contributing to BENFEP come from multiple sources published over the last 70 years, and therefore taxonomic inconsistencies between authors are expected. Aiming to harmonize the spectra of genus and species from the original sources, we standardized the original taxonomy using the currently valid taxonomic assignments of the World Foraminifera Database (Hayward et al., 2022), a part of the World Register of Marine Species (WoRMS), accessed between March 2020 and March 2022. The WoRMS species standardized names (including varieties and subspecies) are assigned after consultation of the authors´ species taxonomic list. Species names annotated with "cf." or "aff." are not considered as separated species. The WoRMS search engine was lastly accessed on March 2022 using the package "worms" (Holstein, 2018) through R version 4.2.1 (R Core Team, 2022) to obtain updated scientific names, authorities and URLs that give direct access to WoRMS species ID. This information together with the major adjustments made to the authors´ original assignations are provided in the Supplement.

The species identified to genus level with only one species by one author (e.g., Genus A sp.) were assigned to the column name designed by the genera followed by "spp." (e.g., Genus A spp.). However, if an author indicates two or more "sp." species for the same genus (e.g., Genus B sp1, Genus B sp2), a column name with the undetermined species followed by a shortened author identification is used (e.g., Genus B sp1Gol, Gol refers to the data set of Golik). The columns named

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"Indeterminate calcareous" and "Indeterminate agglutinated" include individuals not identified at the genus or species level in the original publication and included in more general categories such as "other calcareous", "miliolids", "lagenids", or "other agglutinated", respectively. When authors do not provide information about the test nature (e.g., agglutinated, calcareous), census data of the non-identified forms are placed under the variable "Indeterminate calcareous".

2.6 Structure of the database

The BENFEP database consists of 3093 rows and 1533 columns. Each row contains data of one surface sample distributed in metadata (columns 1 to 23) and benthic foraminifera species census (one taxon per column in columns 24 to 1526) in their original published format (percent, counts or density). The species names are described in full, including species authority (see Supplement for full species description). A column representing the sum of rows containing species census (percentages, counts, or densities) was added at the end of the species census data (column: Total, see also column: Format). Following the variable Total, there are six new columns; three columns coding the ranked abundance of individuals in each sample (N100, N200, N300) and the remaining three host meaningful remarks about the sample (see Table B1 for explanations of column codes).

The whole database can be managed using R version 4.2.1 (R Core Team, 2022). It can be uploaded and managed with geographic information system software such as QGIS and ArcGIS after changing the table format from wide to long.

3 Results and discussion

3.1 Samples distribution

The sample distribution in BENFEP is dictated by the availability of, and access to, benthic foraminifera quantitative datasets. The geographic range of samples varies between 60ºN and 54ºS and from 70ºW to 179ºW. The largest density of quantitative data occurs between 40 and 30ºN followed by groups of stations centred at 60ºN and between 10ºN and 17ºN (Fig. 1, see also Video Supplement). There are some spatial gaps in benthic foraminifera census data, such as the regions between 17 and 21ºN and several narrow latitudinal intervals in the Southern Hemisphere (40-45, 36-39, 33-35, 29-31ºS). The water depths range from tidal (0 m) to 7642 m, but 50% of stations are collected between 37 and 550 m of water depth (Fig. 2). From Fig. 1 and Fig. 2, it remains clear that the Eastern Pacific in ocean areas deeper than 1000 m (i.e., bathypelagic, mesopelagic and abyssal-hadalpelagic bathymetric zones, following Costello and Breyer, 2017) are noticeably understudied and that far more studies are needed to obtain a full overview of benthic foraminiferal distributional patterns in those ocean regions. Indeed, the highest number of samples in hadalpelagic environments (deeper than 4000 m, Fig. 2) are from the South Pacific and they come from expeditions carried out during the 60's and 70's (Bandy and Rodolfo, 1964; Resig, 1981).

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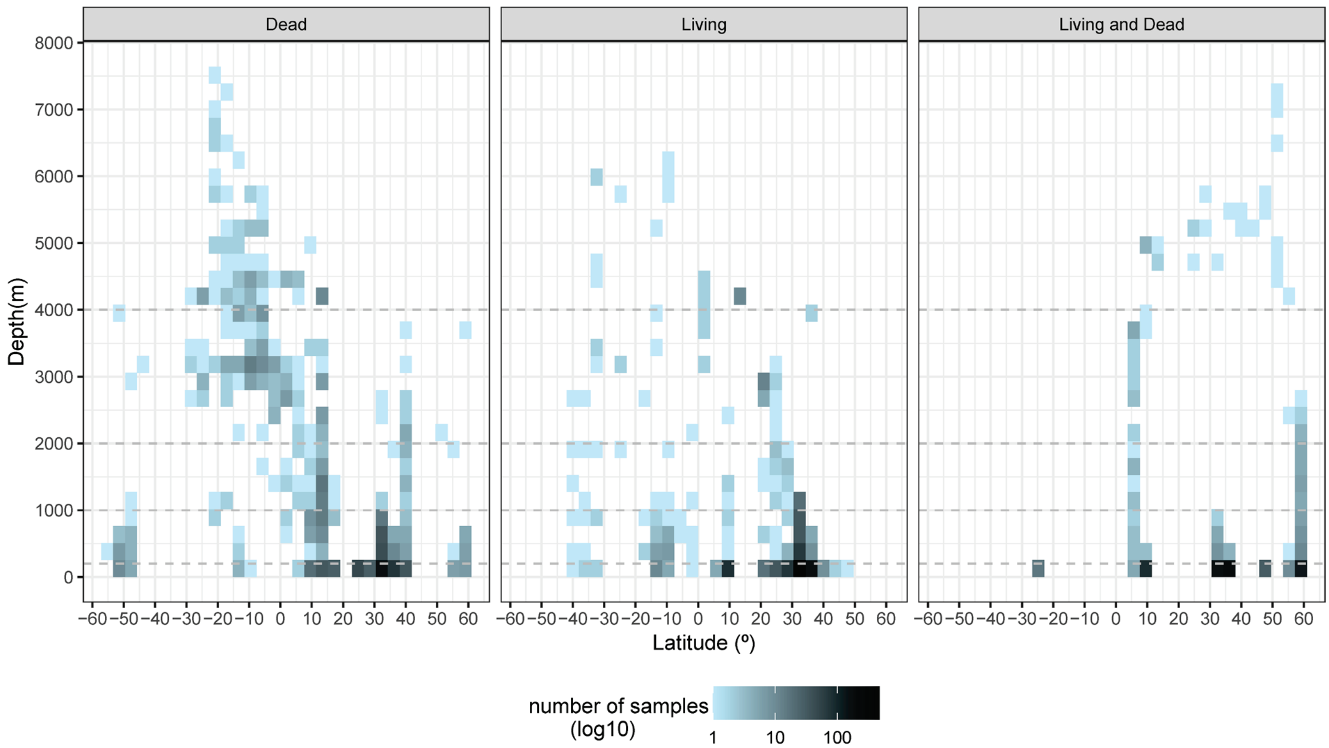

Figure 2: Distribution of samples with water depth and latitude. Horizontal dashed lines separate the epipelagic (0-200 m), the mesopelagic zone (200-1000 m), the bathypelagic (1000-2000 m), the abyssopelagic (2000-4000 m) and the hadalpelagic (>4000 m) zones following bathymetric divisions of Costello and Breyer (2017). The graphs were elaborated with the package "tidyverse" (Wickham et al., 2019) using R version 4.2.1 (R Core Team, 2022).

3.2 Research vessels, sampling devices and sampling intervals

Research expeditions were carried out on board of different Research Vessels, being *Velero IV*, *Spencer F. Baird, McArthur, Yaquina, Golden West*, *Atlantics II, Puritan, Horizon, Meteor* some of the 25 cited research vessels. Alternatively, some samples were provided by miscellanea collections from Scripps Institution of Oceanography and Allan Hancock Foundation.

Samples were collected using a variety of devices (at least 18 different samplers, Table B1), but most of samples were taken using a gravity corer (22%) and Hayward orange peel grabs, Box corer, Phleger corer and miscellanea tools (mostly in shallow water depths), with percentages around 15-10% each (Fig. 3). The most common sediment sampling interval below the seafloor is 0-1 cm (41.2%), where benthic foraminifera are distributed between dead (10.2%), living (23.5%) and living plus dead (7.5%) assemblages. Deeper sampling intervals (e.g., 0-2 and 0-3 cm) represent 34% of the samples in the database (Fig. 3) and 66.6% of those correspond to living and living plus dead assemblages. There are 21% of the samples classified as "surface

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samples", representing authors´ generic assignations to the uppermost centimetre of the sediment (e.g., "surface", "core-top", "uppermost centimetres of the sediment").

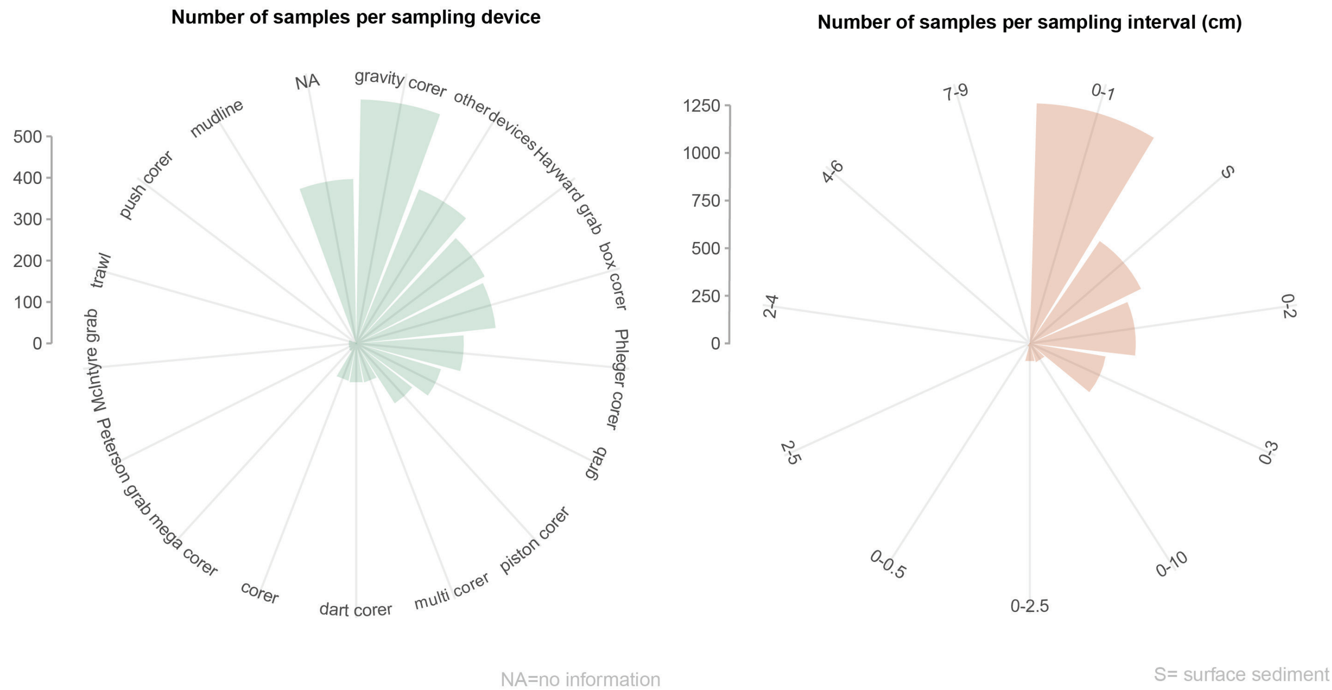

Figure 3: Sampling devices and sampling intervals in BENFEP. The distribution of sampling devices is calculated using the Device_1 column (see Table B1 for more information). The graphs were elaborated with the package "tidyverse" (Wickham et al., 2019) using R version 4.2.1 (R Core Team, 2022).

3.3 Benthic foraminiferal assemblages

The BENFEP database reports data of living (39.6%), dead (33.3%) and living and dead (27.1%) benthic foraminifera (Fig. 4). The Rose Bengal staining (Walton, 1952) is the only method used by authors to distinguish dead from living foraminifera. The "vital" stain is mixed with different solvents, being the most used formaldehyde (58%), followed by alcohol (15%) and others, which include seawater and distilled water (27%). Samples were mainly dry picked after flotation (46%) with a density liquid (mostly Cl_4C), which was a common practice between 1951 and 1980 (Fig. 4).

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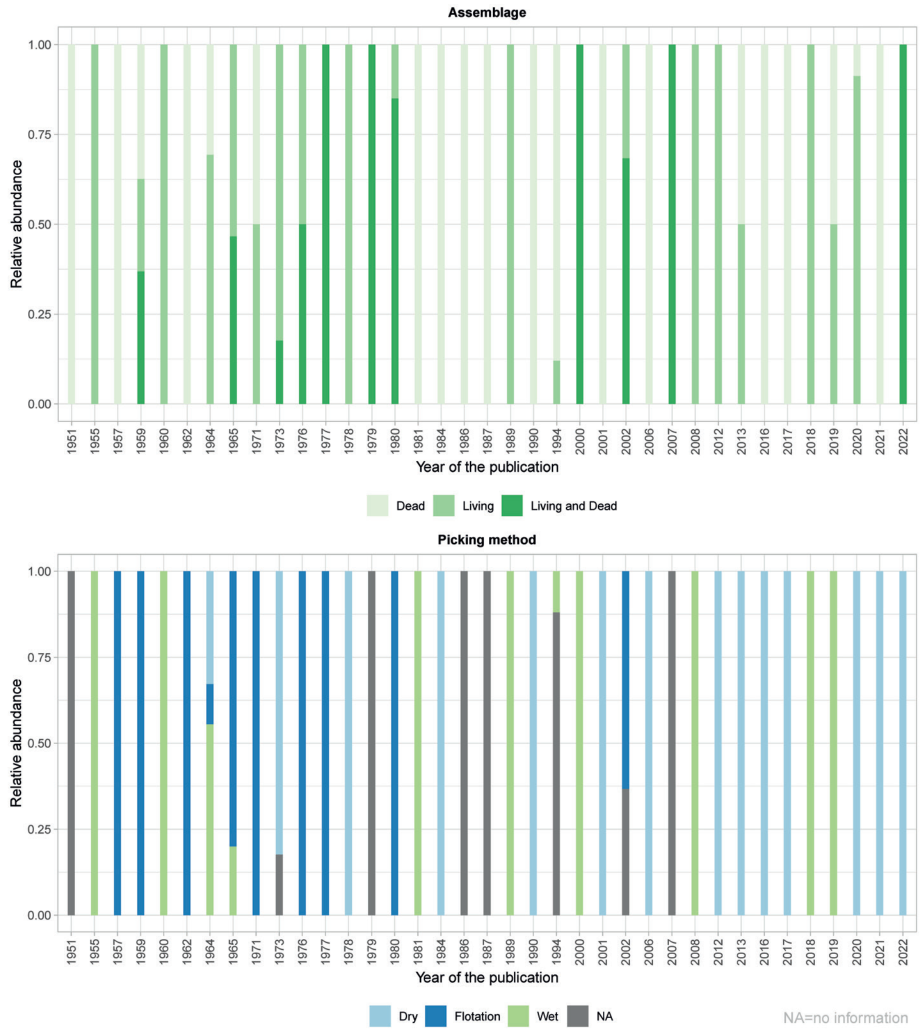

Figure 4: Temporal evolution of the type of assemblage and picking methods. The year in the x-axis corresponds to the year of the publication. The graphs were elaborated with the package "tidyverse" (Wickham et al., 2019) using R version 4.2.1 (R Core Team, 2022).

Most of benthic foraminiferal assemblages were analysed in the smallest size fraction commonly used in benthic foraminiferal studies. For example, 62.5% of the samples were analysed in the >61-74 µm size fraction, 6% in the > 88-106 µm size fraction and 10.5% in the > 125-150 µm size fraction. The size fraction used for foraminiferal analysis is not reported in 11.7% of the publications (Table A1 and Fig. 5), which correspond to four entries; Phleger (1965), Landford and Phleger (1973), Bergen and O´Neil (1979) and the historical data reported by McGann (2002).

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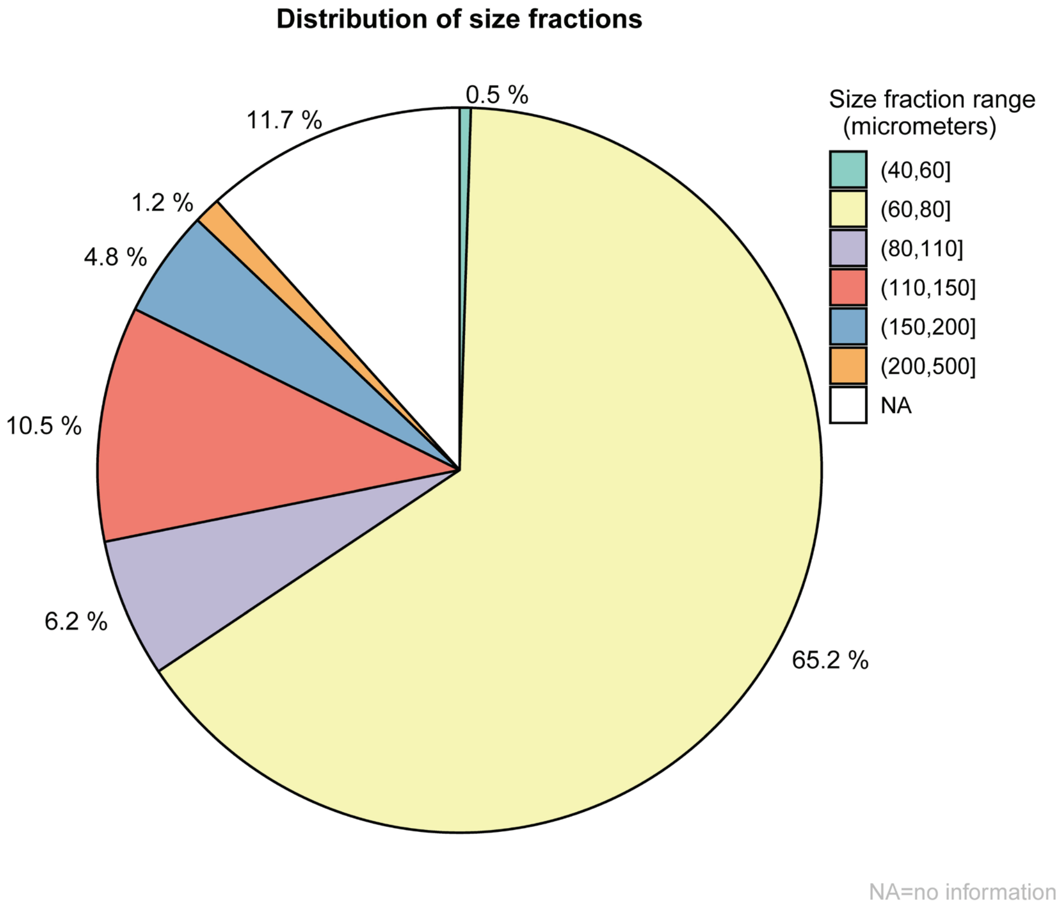

230 **Figure 5:** Distribution of the size fractions used in the benthic foraminiferal studies included in BENFEP. The graph was elaborated with the packages "ggforce" (Pedersen, 2019) and "tidyverse" (Wickham et al., 2019) using R version 4.2.1 (R Core Team, 2022).

3.4 Benthic foraminiferal species

The BENFEP dataset includes a total of 1071 valid taxa (see Supplement) corresponding to 370 genera belonging to the classes Globothalamea (64%), Tubothalamea (11.6%), Nodosariata (19.4%) and Monothalamea (4.7%). In addition to the accepted taxonomic entities, the database contains 394 benthic foraminifera individuals identified as genera level (i.e., "spps"). The genera with the largest number of valid species are *Bolivina* (53) followed- in decreasing order- by *Quinqueloculina*, *Uvigerina*, *Fissurina*, *Lagena*, *Bulimina*, *Reophax* (20-32 species, Fig. 6).

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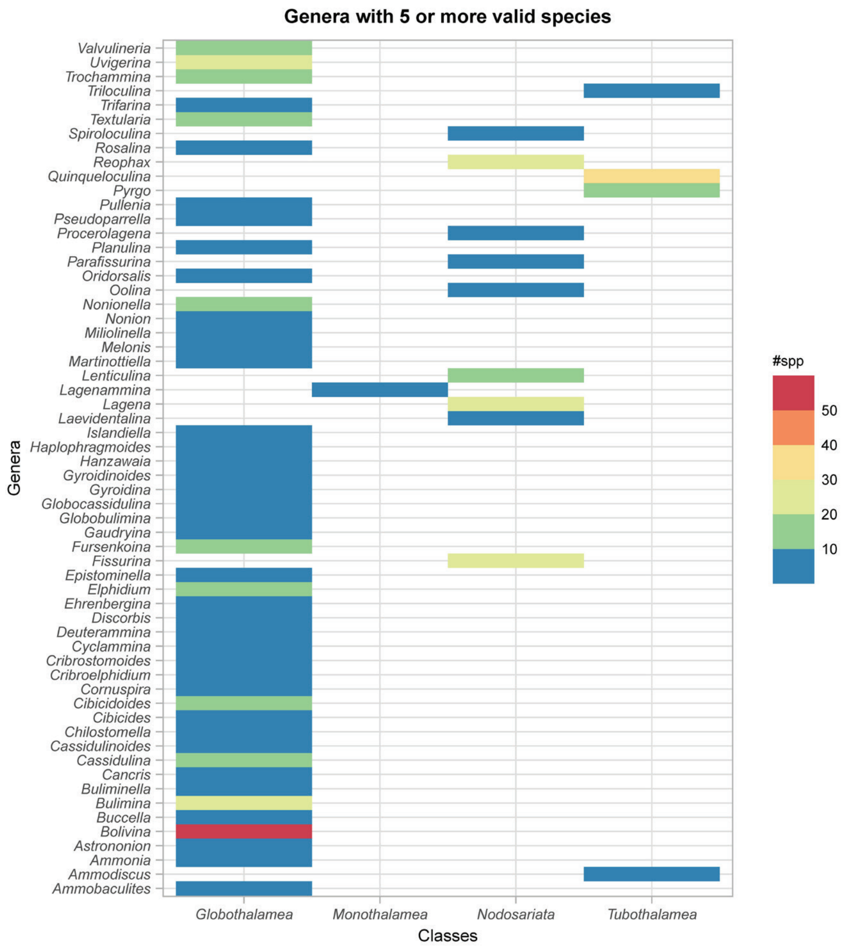

Figure 6: Number of species per foraminifera genus and its distribution among classes. Only genera with 5 or more species are represented in the figure. The graph was elaborated with the package "tidyverse" (Wickham et al., 2019) using R version 4.2.1 (R Core Team, 2022).

From the taxonomically valid species, 504 were only identified by a single author (e.g., *Cassidulina smechovi*, *Arbor multiplex*) and 174 by only two authors (e.g., *Poritextularia mexicana*, *Siphonaperta sabulosa*). The BENFEP database contains 404 species that can be considered rare, with a mean relative contribution lower than 1% (Murray, 2013; calculation based on samples with counts above 100 individuals and taking into account the >42-88 µm fraction). Furthermore, the highest number of species (90) is found in a station studying living individuals located in the South Pacific at 1800 water depth (Ingle et al., 1980, Fig. 7D). BENFEP integrates quantitative data across a variety of marine environments, thus, the relative abundance of particular species varies geographically and with water depth (Fig. 7). For example, *Textularia mariae*, *Elphidium excavatum* subsp. *clavatum* and *Globocassidulina crassa* are frequent in epipelagic zone while *Nodulina dentaliniformis* and *Nutallides umbonifer* characterize the abyssopelagic and hadalpelagic zones (Fig. 7E).

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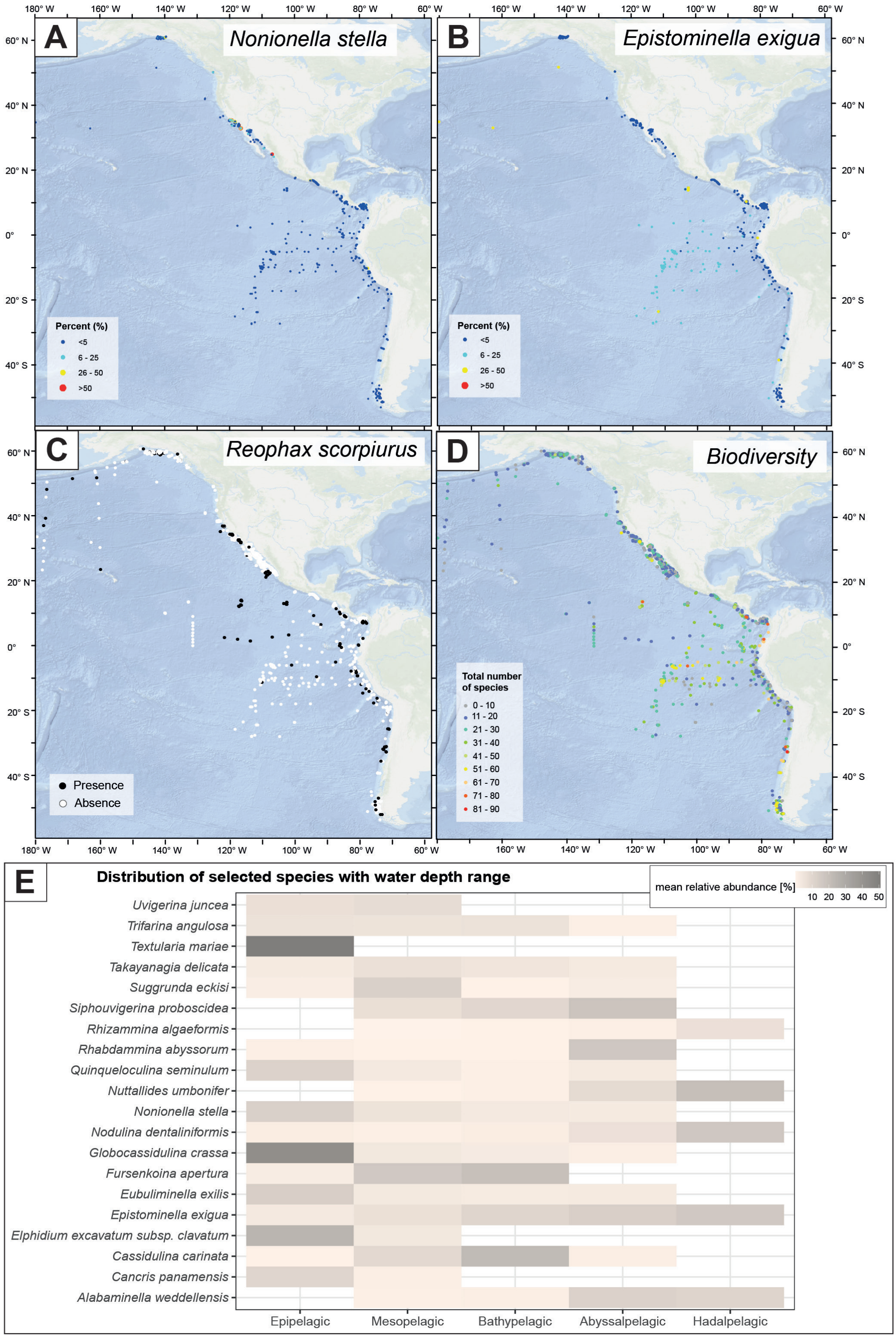

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Figure 7: Geospatial representation of relative abundance (A, B) and presence-absence (C) of selected species, total number of species (D) and selected species distribution with water depth (E). The relative abundance of species in figure A and B and the heatmap of figure E are calculated from a percentage matrix that integrates samples with counts of more than 100 individuals and size fraction ranging between 61 and 88 µm. The presence-absence representation (C) and species richness (D) are calculated from raw data and integrating semi-quantitative information provided by authors. The maps of A-D were created using ArcGIS software version 10.8.2. The global relief model integrates land topography and ocean bathymetry (Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributions). The graph in E was elaborated with the package "tidyverse" (Wickham et al., 2019) using R version 4.2.1 (R Core Team, 2022).

3.5 Potential applications of BENFEP

The high number of stations with benthic foraminifera census data collated from surface sediments of the Eastern Pacific together with the metadata provided, make the BENFEP database a reference one for a specialized community working on present and past benthic foraminiferal distributions. The database could be integrated in global open-access data systems (e.g., Ocean Biodiversity Information System), thus serving as a source of ecological information (e.g., biodiversity, ecosystem functioning) for deep-sea monitoring, management, and conservation (Danovaro et al., 2020). Figure 7 displays some of the potential applications of BENFEP ranging from the relationship between species and a particular environmental variable (i.e., water depth, Fig. 7E) which can be extended to another, externally accessed environmental variable, the geographic distribution of the relative abundance of species (Fig. 7A, B) to the species occurrences (Fig. 7C).

3.6 Limitations of the database

3.6.1 Taxonomic concepts

The species-level taxonomy of benthic foraminifera is mainly based on morphological traits, whose identification criteria might differ among authors. Despite the effort to harmonize the taxonomy, it is likely that incorporating data from different authors, while portraying data in their original form, could have artificially increased the number of species. This limitation is shared among global or regional databases curating other modern marine microfossil groups (Leblanc et al., 2012; Siccha and Kucera, 2017; Hernández-Almeida et al., 2020). However, the effect of diversified taxonomic concepts might be augmented in benthic foraminifera, whose modern taxa (2400 living species, Murray, 2007) outnumber other marine microorganisms' groups with fossilizing potential, such as planktonic foraminifera (n=50 living species, Brummer and Kucera 2022), coccolithophores (n=200 extant species, Young et al., 2003) or radiolarian, with at least 900 species (Biard, 2022).

3.6.2 Data originally sourced in percentage

The data provided in percentage do not generally add to 100%. There are several explanations for this. Firstly, the presence of symbols (such as x, -, <0.1) indicating semi-quantitative census data (i.e., "species representing less than 1%") or incomplete assemblage description (e.g., datasets including only species representing a particular percentage of the assemblage) necessarily preclude that the sum of the relative contribution of species reaches 100%. Secondly, rounding of decimals to entire numbers in the original sources might have led to percentages over 100%. A few samples contain more than 100%, and they are probably the result of typing errors in the original sources. In any case, we decide to retain quantitative data in their unabridged form because there are potential applications of the database insensitiveness to percentages such as species occurrences.

3.6.3 The representativeness of the surface sediment assemblages as recent analogues

One of the purported applications of BENFEP is to provide a quantitative estimate of recent benthic foraminiferal assemblages that could be later used in paleoenvironmental interpretations (e.g., Fig. 7). The database integrates census data obtained from oceanic regions with different sedimentation rates, over different sampling years and using sampling devices that might result in diversion from recent conditions. For example, dead benthic foraminifera obtained from surface sediments might not be representative of the surface if the sampling device fails to recover the sediment-water interface or sedimentation rates are very low. Besides, the benthic foraminifera quantitative data include living, dead and living plus dead assemblages whose significance for building recent analogues is still discussed. It might be argued that only living foraminifera should be used to consider baseline studies, as suggested by Schönfeld (2012). However, it might also be considered that living assemblages represent the conditions at the specific time of sampling and do not hold the time-averaged representativeness of the dead assemblages (Murray, 2000). BENFEP incorporates suitable tools for the final users to evaluate data quality as well as to tailor the final output to their specific criteria.

4 Complementary information to BENFEP: BENFEPqual

In the process of building BENFEP (section 2.2), we found numerous publications that, despite of dealing with a quantitative or semi-quantitative census of benthic foraminifera, raw data were not made available in the publication. We collated metadata and georeferences of 1262 stations taken from 31 studies dealing with benthic foraminifera from surface sediments of the Eastern Pacific and published between 1929 and 2019. This complementary and qualitative database (BENFEPqual) incorporates information of studies where: 1) absolute or relative abundance data of benthic foraminiferal species are represented exclusively in graphs (76.5%), and 2) ranked abundances or presence-absence data of species are presented on tables (23.5% of the data). The procedure for stations´ georeferencing and column coding of metadata follows the indications of sections 2.3 and 2.4, respectively. Information about water depth, size fraction and sampling interval was absent for 63%, 43% and 35% of the stations, respectively. Figure C1 represents the geolocation of stations in BENFEPqual. More than 50% of the samples are concentrated between 27 ºN and 37.5ºN. The BENFEPqual database constitutes a valuable source of information to identify further benthic foraminiferal surveys.

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5 Recommendations for archiving benthic foraminifera quantitative data

Data sharing in easily accessible formats and public repositories should be the core of the commitment of scientists, universities and research institutions to open science. Data reusing is not only precluded by lack of data sharing but also by incomplete or lacking metadata, taxonomic information, etc, which are essential to provide the single user or the synthesiser with the information to evaluate the quality of data. In the process of building this database, we have found several issues that we raise as recommendations aiming to encourage best practices in data reporting.

-*Data sharing*. Encouraging authors (and publishers) to share their published data in a readily accessible format and in public repositories to avoid the irreversible loss of valuable quantitative data. In the best scenario, machine and manual digitalization are a time-consuming process.

-*Raw data*. Ensuring reproducibility, quality checking and further use of data require raw data, that is, species counts and total counts per each sample. It has been a common practice to provide data in species percent with generic information about the number of individuals counted by sample. As mentioned before, this format is prone to error and hinders, at least, data reusing for some diversity calculations (e.g., rarefaction).

-*Metadata*. Providing detailed information about each station´s sampling device, sampling interval, geographic coordinates, picking and staining protocols, research vessel, sampling year, etc. It is not recommended It would be avoidable to describe samples´ metadata using unspecific generalizations.

-*Taxonomy.* Providing full taxonomic references of all species. That might seem time-consuming and undervalued outside the specialized foraminifera community, however, it is a crucial element for reliable taxonomic harmonization and further use of the data.

6 Data availability and future plans

The BENFEP database can be accessed from https://doi.pangaea.de/10.1594/PANGAEA.947086 (Diz et al., 2022a). This database is conceived as a springboard to store future quantitative data of benthic foraminifera in the East Pacific and make them available to the scientific community. It can be enlarged with new records as they are being generated or after the authors request, therefore providing an ongoing live resource. Any changes to add, correct, or update taxonomic categories to an existing version will be indicated in PANGAEA. We also encourage users of the BENFEP database to quote original data sources.

BENFEPqual is available to download from https://doi.pangaea.de/10.1594/PANGAEA.947114 (Diz et al., 2022b) and it could also be updated. Both databases are distributed under the CC-BY: Creative Commons Attribution 4.0 International.

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7 Conclusions

We present the BENFEP database, the largest open-access database of quantitative data of benthic foraminifera from surface sediments compiled up to date. It contains harmonized census counts of 1071 taxonomically valid species of living, dead, living, and dead benthic foraminifera from 3093 sediment samples, corresponding to 2572 georeferenced stations of the Eastern Pacific. It also contains a rich collection of metadata gathered from 47 documental sources spanning the last 70 years. BENFEP prospective is to function as an alive repository for new entries and a reference database for paleoenvironmental reconstructions, as well as biogeography and biomonitoring studies. The database is friendly coded and can be accessed using different software, aiming to a broad spectrum of users and tailoring needs. Complemental information about benthic foraminiferal studies in the Eastern Pacific can be found in the qualitative database, BENFEPqual.

Appendices

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Appendix A

Table A1. Number of samples per contributor and type of assemblage

Author(s)	Dead	Living	Living and Dead	Fraction (>µm)
Bandy and Arnal, 1957	36			61
Bandy and Rodolfo, 1964		19		500
Belanger et al., 2016	27			63 (3), 125 (24)
Bernhard et al., 1997		9		63
Bergen and O´Neil, 1979			95	NA
Boltovskoy and Totah, 1987	8			63
Brenner, 1962	81			200
Burmistrova et al., 2007			16	42
Butcher, 1951	78			200
Echols and Armentrout, 1980			102	62
Enge et al., 2012		2		63
Erdem et al., 2020		52		63
Erskian and Lipps, 1977			44	200
Gardner et al., 1984	70			149
Goineau and Gooday, 2019	11	11		63
Golik, 1965		89	124	63
Harman, 1964	26			61
Heinz et al., 2008		7		63
Hromic et al., 2006	35			63
Ingle et al., 1980		18		61
Lankford and Phleger, 1973		103		NA
Liu, 2001	37			63
Loubere, 1994	66			63
Mackensen and Douglas, 1989		3		125
McGann, 2002		95	205	110 (NA), 190(150)
McGlasson, 1959	71	49		62
Morin, 1971	166	166		62
Nienstedt, 1986	45			63
Palmer et al., 2020	5			63
Patarroyo and Martinez, 2021	22			63
Patterson et al., 2000			31	63
Perez-Cruz and Machain-Castillo, 1990	48			63
Pettit et al., 2013	9	9		63
Phleger, 1964		76		62
Phleger, 1965		53		NA
Resig, 1981	140			63
Scott et al., 1976		112	112	63
Smith, 1964	16			150
Smith, 1973			22	200
Takata et al., 2016	9			105
Tavera et al., 2022			17	212
Uchimura et al., 2017	24			63
Uchio, 1960		151		77(63), 74(74)
Venturelli et., al 2018		9		63
Walch, 1978		10		62
Walton, 1955		182		88
Zalesny, 1959			70	61

NA, no information

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Appendix B

Table B1. Explanatory notes on column names and column codes of BENFEP

Column name	Explanatory notes	Codes in column	Codes explanation
Authors	Identification code for author or authors of the publication followed by year		See References for a full identification of the publication
Year	Year of the publication		
Source	Source of the data in the database	R	Tables in digital repository including an open access repository or a supplementary file in a journal
		D	Printed tables in thesis, publications or journal repositories. The tables were machine digitized
		MD	Printed tables in publication or journal repository. The tables were manually digitized
		Author	Provided by authors
Source_doi	doi of the data source when hosted in an open access repository		
RVessel_1	Research Vessel number 1. This is the main column filled when samples are collected aboard a single research vessel.	Mis	Miscellanea collections. This applies when the publication does not indicate the Research Vessel but collection of samples from various sources (Scripps Institution of Oceanography, Allan Hancock Foundation, oil company)
RVessel_2	Research Vessel number 2. This column is filled when samples are collected aboard an additional Research Vessel, different from Rvessel_1		Applies the same codes as in RVessel_1
YRVessel_1	Sampling year of RVessel_1. This is the main column filled when data are from RVessel_1		
YRVessel_2	Sampling year of RVessel_2 or different sampling year from YRVessel_1		
YRVessel_3	Different sampling year from YRVessel_2		
Device_1	Sampling device used to collect the sediment samples	BC	Box corer
	When several devices are indicated (see Device_2, Device_3),	C	Unspecific type of corer
	"Device_1" refers to the most frequent, according to the text	DartC	Dart corer
		FF	Free fall corer
		G	Unspecific type of grab
		GC	Gravity corer
		HayG	Hayward orange peel grab, or orange peel grab
		MC	Multi corer
		McG	Smith McIntyre grab
		MegaC	Mega corer
		Mudline	Mudline corer
		PC	Piston corer
		PG	Peterson grab
		PhC	Phleger corer
		PiC	Pilot corer
		PushC	Push corer
		TC	Trigger corer
		Trawl	Menzies trawl
		Other	By hand, dredges, skin driving, scoopfish, snapper, tube dragged over the seafloor, Phleger tube
Device_2	When filled, it indicates that the authors do not specify the type of the device for each station but they generally indicate the use of two different devices in their data set		It applies the same codes as in Device_1
Device_3	When filled, it indicates that the authors do not specify the type of the device for each station but they generally indicate the use of three different devices in their data set		It applies the same codes as in Device_1

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Column name	Explanatory notes	Codes in column	Codes explanation
Interval	Interval of studied sediment, in centimeters	S	When indicated, it refers to a generic designation refering to the surface sediment such as "surface" or "upper few centimetres or "bottom samples", "modern".
Fraction	Size fraction studied for benthic foraminifera (>micrometers) When necesary, the USA Tyler mesh screen is converted to micrometers		
Assemblage	Type of benthic foraminiferal assemblage	L	Living assemblage
		D	Dead assemblage
		LD	Living and dead assemblage
RoseBengal		Alcohol	Rose Bengal in an alcohol solution (ethanol, ethyl alcohol, methanol, isopropyl alcohol, unspecific alcohol)
	All living assemblages in the database are studied using the Rose Bengal staining method mixed with different solvents	Formaldehyde	Rose Bengal in (buffered) formaldehyde
		Other	Rose Bengal in a solution with other solvent (seawater, glutaraldehyde, distilled water)
Picking	Method of picking the foraminifera	Dry	Dry picking after sieving
		Wet	Wet picking after sieving
		Flotation	Dry picking after using the Cl_4C flotation method
Format	Format in which the original data are provided	Percent	Percentage
		Counts	Counts
		Density	Counts per volume unit
S_Coord	Source of the geographic coordinates	Listed	Listed in the publication or in a secondary reference
		Map	Extracted from the digitized maps provided in publication
Station	Station identification. For stations described by a number, we added the abbreviated name of the author ahead of the station name		
Long	Longitude in degrees from 0 to 180(-180) with positive (negative) values indicating east (west)		
Lat	Latitude in degrees from 0 to 90(-90), positive (negative) indicates latitude north (south)		
Depth	Water depth in meters		When necessary, fathoms or feet are converted to meters by multiplying by 1.8288 or dividing by 0.3048, respectively
	Columns 24-1526 benthic foraminifera species or foraminiferal entities		
Total	Sum of colums from 24-1526		See Format column
N100	It indicates whether sample counts are equal to or higher than 100 individuals	Yes	Sample counts are equal to or higher than 100 individuals
		No	Sample counts are lower than 100 individuals
		NC	The counts per sample are not indicated, however the authors indicate in the publication that samples contain more than 100 individuals
N200	It indicates whether sample counts are equal to or higher than 100 individuals	Yes	Sample counts are equal to or higher than 200 individuals
		No	Sample counts are lower than 200 individuals
		NC	The counts per sample are not indicated, however the authors indicate in the publication that samples contain more than 200 individuals
N300	It indicates whether sample counts are equal to or higher than 100 individuals	Yes	Sample counts are equal to or higher than 300 individuals
		No	Sample counts are lower than 300 individuals
		NC	The counts per sample are not indicated, however the authors indicate in the publication that samples contain more than 300 individuals
Remark_1	Relevant additional information regarding the author´s dataset		
Remark_2	Relevant additional information regarding the author´s dataset		
Remark_3	Relevant additional information regarding the author´s dataset		

An unfilled field, indicates no information available. It applies to any column

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Appendix C

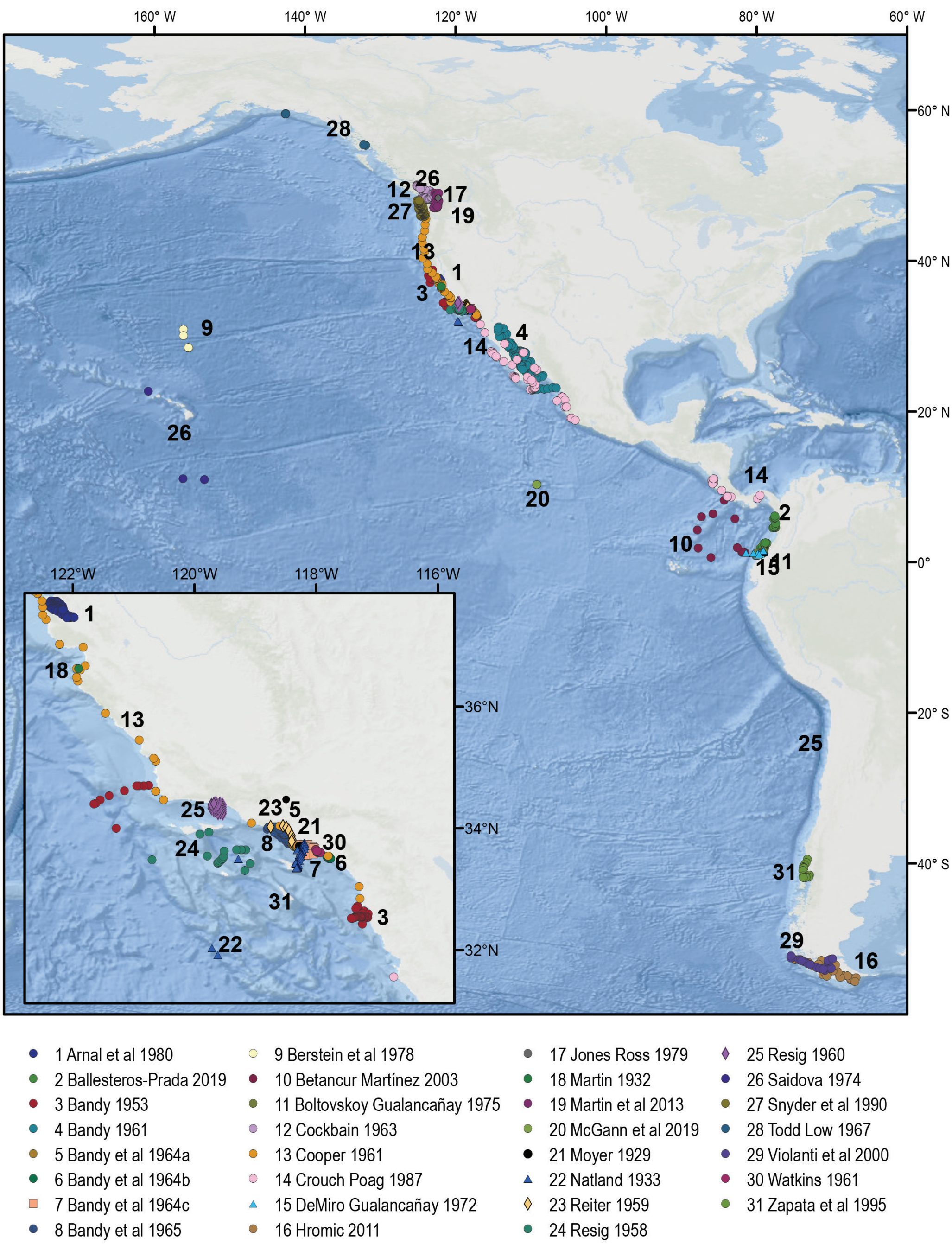

Figure C1. Spatial distribution of the samples comprising the BENFEPqual database. The numbers refer to each author's dataset. The map was created using ArcGIS software version 10.8.2. The global relief model integrates land topography and ocean bathymetry (Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributions).

Video supplement. Accumulative timeline heatmap showing the geographic distribution of samples´ density (in qualitative scale) in BENFEP. The type of assemblage (dead, living, or living and dead) is identified using crossed, filled circles, and asterisks, respectively. The global relief model integrates land topography and ocean bathymetry (Sources: Esri, Garmin, GEBCO, NOAA NGDC, and other contributions). The slides for the video are created using QGIS software and the video assembly is performed with Adobe Premiere software.

Supplement1. File indicating the systematics of benthic foraminiferal valid species names in BENFEP following the concepts of the World Foraminifera Database (Hayward et al., 2022, last accessed in March 2022).

Author contributions. IHA conceptualized the study. PD was responsible for metadata collating, benthic foraminifera curation and species harmonization. PD and VGG cross-validated entries of manually digitized data carried out by VGG. RGV and AO were responsible for georeferencing stations and geographic data visualizations while PD was involved in the organizing quantitative data for figures and statistics. All authors contributed to designing the structure of the database and actively participated in organizing the manuscript outline, writing and editing the manuscript at its various stages.

Competing interests. The authors declare that they have no conflict of interest.

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