lAppendix 1 - Supplementary material for

**Changes in the particulate organic carbon pump efficiency since the Last Glacial Maximum in the northwestern Philippine Sea**

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# X-ray fluorescence ratios

The Mn/Fe is based on the sensitivity of these elements to redox processes: under anoxic conditions, Mn is more rapidly reduced than Fe, resulting in preferential Mn release into the water and therefore in a decrease of Mn/Fe ratio in the sediment. On the contrary, under oxic conditions, Fe oxidizes faster than Mn. Fe therefore accumulates first in the sediment, followed by Mn if there is still oxygen available for the reaction. As oxygen increases, Mn accumulates in the sediment, causing the increase of the Mn/Fe ratio (Naeher et al., 2013).

The Br/Ti is based on the low concentration of Br in the terrestrial environment but is particularly abundant in marine environments due to the synthesis of organic bromine-laden compounds by marine producers, especially microalgae (Croudace and Rothwell, 2015; Dirksen et al., 2019; Gribble, 1998; Harvey, 1980; Mayer et al., 2007; Ziegler et al., 2008). The Ti/K is usually used to qualitatively estimate changes in chemical weathering intensity and is based on the greater mobility of K in water than Ti during mineral breakdown. (Clift et al., 2014; Gebregiorgis et al., 2020). However, Taiwan is under the influence of an intense rainfall regime, which leads to very strong physical erosion and prevents the development of chemical weathering (Li et al., 2012; Nayak et al., 2022; Selvaraj and Chen, 2006). Analysis of illite crystallinity in core MD18-3532 from the Ryukyu Arc accretionary prism shows that this dominance of physical erosion has persisted over the last 26,000 years, despite climatic variations during the last glacial-interglacial period (Fenies et al., 2023). As a result, using the Ti/K ratio as a proxy for chemical weathering intensity is not appropriate. Instead, K is enriched in clay minerals, notably illite, which is the main component of Taiwanese clays (Diekmann et al., 2008; Fenies et al., 2023; Nayak et al., 2022), and is concentrated in the finer fraction, while Ti is sourced from heavy minerals, such as rutile, ilmenite or titanite (Meinhold, 2010), and is more enriched in the coarser fraction (Bertrand et al., 2024).

# Characterisation of the nature of particulate organic carbon

In Taiwan, the Total Organic Carbon (TOC) can originate from primary productivity and/or continental input. The organic carbon isotopic signature and TOC/TN ratio of bedrocks and particles suspended in Taiwan's rivers are extremely close to those of marine organic matter complicating the characterization of the nature of the organic matter in marine sediments (Hilton et al., 2010; Meyers, 1997; Ogrinc et al., 2005). Therefore, we opted for a comparison with the Br/Ti and Ti/K ratios to distinguish marine organic matter from the terrestrial input.

# Multivariate analyses of benthic foraminiferal assemblages

### Hierarchical cluster analysis

The hierarchical cluster analysis was performed using the Euclidian distance based Ward’s method using the ward.D2 method of the hclust function of the R programming package “vegan” (Oksanen et al., 2022). In order to validate the quality of the dendogram obtained, the cophenetic correlation coefficient has been calculated using the cophenetic function of the R programming package “stats” (R Core Team, 2013).

### Detrended correspondence analysis (DCA) and distance-based redundancy analysis (db-RDA)

The detrended correspondence analysis (DCA) was performed using the decorana function in the R programming package “vegan” (Oksanen et al., 2022). The db-RDA was performed using the capscale function in the R programming package “vegan” (Oksanen et al., 2022). Environmental variables were defined to reflect possible environmental influences on the benthic foraminiferal community: Br/Ti for marine organic matter, Mn/Fe for bottom – pore water oxygenation, and Ti/K for terrestrial inputs by turbidity current activity (and in consequence, the post mortem transport of benthic foraminifera). The environmental variables were z-scores transformed prior to analysis using to prevent a potential scale effect. The analysis only includes samples that have data available for all variables that are constraining. The inflation factor variances of all the constraining variables were measured using the vif function in the R programming package “vegan” in order to potentially remove environmental variables with a value greater than 5 to prevent a multicollinearity effect from impacting the analysis (Oksanen et al., 2022). The significance of the model, the relationships between constraining and explanatory variables, and the axes were then tested using the anova function in the R programming package “vegan” (Oksanen et al., 2022).

# Transfer functions to quantitatively reconstruct bottom – pore water oxygenation changes

Transfer functions integrating benthic foraminifera species or genus abundances (Kaiho, 1994; Kranner et al., 2022; Ohkushi et al., 2013; Schmiedl et al., 2003) have been widely used to quantitatively or semi-quantitatively study changes in combined bottom – pore water oxygenation through time (Aksu et al., 2002; Bulian et al., 2022; Du et al., 2022; Jain et al., 2007; Ohkushi et al., 2013; Ovsepyan et al., 2021; Palmer et al., 2022; Pérez-Asensio et al., 2014; Schmiedl et al., 2003, 2010, 2023; Sharon et al., 2021; Tetard et al., 2017, 2021a; Thena et al., 2021; Wang et al., 2018). To this end, various equations and methods of using these equations have been proposed, however not all them can be used in this study. For instance, those of Kaiho (1994), Schmiedl et al. (2003) and Ohkushi et al. (2013) exclude agglutinated benthic foraminifera. In our record, the agglutinated benthic foraminifera shows a median of 2.82% and an interquartile range of 0.00 – 11.45%, making these methods unsuitable for use. Recently, Sharon et al. (2021) showed that the use of a Detrended Correspondence Analysis (DCA), in cases where the faunal distribution throughout the core was mainly related to an oxygenation gradient, allowed the number of taxa usable for the Behl Dissolved Oxygen (Ohkushi et al., 2013) to be extended, notably enabling the inclusion of agglutinated benthic foraminifera. However, in our record, at least 3 environmental parameters (oxygenation, food and transport) can strongly affect the distribution of taxa throughout the core, preventing the observation of a sufficiently clear oxygenation gradient along Axis 1 of the DCA to apply this method (Fig. XXX).

The transfer function proposed by Tetard et al. (2021) overcome these problems. The Benthic Foraminiferal Assemblage (BFA) index includes agglutinated foraminifera and is designed for reconstructing changes in bottom – pore water oxygenation in oxygen-depleted environments such as the Oxygen Minimum Zone. Consequently, it can only reconstruct oxygen concentration from 0 to 1.5 ml L-1. Considering the changes in taxa observed during the assemblage study and modern observations from the World Ocean Atlas (Fig. 2d), we expect significant variations in oxygenation and values exceeding 1.5 mL L-1. Therefore, we also used the Enhanced Benthic Foraminifera Oxygen Index (EBFOI), proposed recently by Kranner et al. (2022), an update of the Benthic Foraminifera Oxygen Index of Kaiho (1994) that includes agglutinated benthic foraminifera and allows reconstruction of the bottom – pore water oxygenation from 0 to 6 ml L-1. This transfer function was then adjusted by Schmiedl et al. (2023) to correct an error in the equation 3 that led to aberrant bottom – pore water oxygen concentration values. The combined use of these two transfer functions should provide a more accurate estimate of changes in bottom – pore water oxygenation over the last 20,000 years, regardless of whether the period was dysoxic or highly oxygenated.

# Quantitative reconstruction of benthic foraminifera primary productivity

The Benthic Foraminifera Accumulation Rate is an estimate of the benthic foraminifera abundance in the sediment taking into account the sedimentation rate and dry bulk sediment density:

$$BFAR=NbBF ×LSR×D\_{dry}$$

Dry bulk density (Ddry) was calculated following the equation:

$$D\_{dry}=\frac{2.65×\left(1.024-D\_{wet}\right)}{\left(1.024-2.65\right)}$$

where wet bulk density (Dwet) is calculated as:

$$D\_{wet}=0.8247×Gamma Density+0.0948$$

Gamma density was measured on board using a GEOTEC Standard multi-sensor core logger (MSCL) system considering that the density of pore water is 1.024 g cm-3 and the average density of sediment is 2.65 g cm-3 (Auffret et al., 2002).

# Detailed description of the benthic foraminifera ecology present in the biofacies based on the scientific literature and results of the db-RDA

In the db-RDA triplot (Fig. 5), five of the seven taxa of biofacies A (*C*. *ovoidea*, *G.* *altiformis*, *Nonionella* sp., shelf miliolids and *R*. *rotundatus*) are positively correlated with the supply of the terrestrial material and terrestrial organic matter by turbidity currents (Ti/K) and negatively with the inputs of marine organic matter from the primary productivity (Br/Ti) and the oxygenation of the bottom – pore water (Mn/Fe). These observations are consistent with ecology of the taxa. Both *C*. *ovoidea* and *R*. *rotundatus* are infaunal species favoured by eutrophic environment, marked by suboxic to dysoxic bottom – pore water oxygenation and high organic matter inputs, possibly associated with turbidite (Bernhard et al., 1997; Cannariato et al., 1999; Hess et al., 2005; Mojtahid et al., 2009; Rathburn et al., 1996; Rathburn and Corliss, 1994; Schmiedl et al., 2000). The three others taxa all originate from higher up the slope, *G.* *altiformis* is usually associated with the bathyal zone (Barbieri, 1991; Culver, 1988), *Quinqueloculina* spp. and *Triloculina* spp. (grouped under the heading shelf miliolids) with the shelf (Murray, 2006; Polonia et al., 2023; Smith et al., 2001; Smith and Gallagher, 2003) and *Nonionella* sp. with the shelf to the upper bathyal (Duchemin et al., 2007; Fiorini, 2015; McGann et al., 2003).

The two remaining taxa in biofacies A show differences (Fig. 5). *M*. *affinis* shares the negative correlation with Mn/Fe, but seems to be more affected by the availability of marine organic matter (Br/Ti) than by the supply of terrestrial material and organic matter (Ti/K). This can be explained by the species' reactivity to high organic matter flux and its ability to feed in the nitrate reduction zone on phytoplankton organic matter degraded by bacterial activities (Caralp, 1989; De and Gupta, 2010; Fontanier et al., 2003; Koho et al., 2008; Zarriess and Mackensen, 2010) and its wide bathymetric distribution (Hayward et al., 2001). *G. affinis* is positively correlated to Mn/Fe and Ti/K and negatively to Br/Ti, which could be explained by a stronger affinity for oxic bottom water oxygenation (Tetard et al., 2021b), despite being deep infaunal and favored by dysoxic oxygenation of pore waters and sulphate-reducing conditions (Koho et al., 2008; Zarriess and Mackensen, 2010), a low competitive ability against species favored by high inputs of labile organic matter (fresh phytoplankton) (Fontanier et al., 2002), but a capacity to feed on degraded organic matter and a strong response to high flows of organic matter to the sea floor (Glock, 2023; Nomaki et al., 2006; Schmiedl et al., 2000, 1997; Schonfeld, 2001; Zarriess and Mackensen, 2010), notably resulting from turbidite sedimentation (Rathburn et al., 1996; Rathburn and Corliss, 1994).

The three taxa of the biofacies B (Fig. 4) are positively correlated to the supply of marine organic matter by the marine primary productivity (Br/Ti), negatively correlated to the bottom – pore water oxygenation (Mn/Fe) and to the erosion of Taiwan, the supply of terrigenous organic matter and material, and the hydro-sedimentary activity of the canyon (Ti/K) (Fig. 5). This is consistent with the ecology of this species as the three of them are dysoxic species adapted to significant inputs of fresh/labile marine organic matter from phytoplankton (Caralp, 1989; Caulle et al., 2014; Goineau et al., 2015, 2011; Ohkushi et al., 2018; Zarriess and Mackensen, 2010). It also indicate negligible influence of post mortem transport on these taxa.

Most of the taxa (16 on 20) of the biofacies C show positive correlation with the bottom – pore oxygenation (Mn/Fe), very weak positive to negative correlation with supply of marine organic matter (Br/Ti) and negative correlation to the supply of terrestrial organic matter and material by turbidity currents (Ti/K) (Fig. 5). Among those, eleven on seventeen (*Cibicidoides* spp., *L*. *wuellerstorfi*, *P*. *irregularis*, *O*. *umbonatus*, *E*. *exigua*, *Psammosiphonella* spp., *M*. *pompilioides*, *M*. *sphaeroides*, *E*. *bradyi*, *Textularia* spp. and *S*. *schlumbergeri*) are opportunistic and oligotrophic species that take advantage under oxic or suboxic conditions of sporadic or seasonal inputs of fresh organic matter (Altenbach et al., 1999; Chauhan et al., 2016; De and Gupta, 2010; Enge et al., 2012; Gooday, 1988; Jorissen and Wittling, 1999; Kitazato et al., 2000; Kuhnt et al., 1996; Langlet et al., 2014; Linke and Lutze, 1993; Lutze and Thiel, 1989; Mackensen et al., 1995; Ohga and Kitazato, 1997; Rathburn et al., 1996; Rathburn and Corliss, 1994; Schmiedl et al., 1997; Sousa et al., 2006; Vicente et al., 2021; Zarriess and Mackensen, 2010). Among the five remaining taxa, the genus *Fissurina* spp. and *Lagena* spp. have unclear ecology but they are believed to be either ecto-parasites or suspension feeders (Collen and Newell, 1999; Haynes, 1981; Ranju et al., 2022) and thriving in oxic bottom – pore water conditions (Kurtarkar et al., 2024; Rathburn and Corliss, 1994 and Tetard's personal communication). They are therefore consistent with the ecological characteristics of the above-mentioned species. In a similar way, the ecology of *Reophax* spp. is still not perfectly understood but the genus has been often find under oxic bottom water conditions (Enge et al., 2012; Fontanier et al., 2005; Ohkushi and Natori, 2001; Schonfeld, 2001; Szarek et al., 2007) and seems to thrive under strong supply of degraded organic matter to the seafloor (Sousa et al., 2024; Vicente et al., 2021; Yamashita et al., 2019). This latter ecological characteristic contrasts with its negative correlation with Ti/K (Fig. 5), but may be explained by the poor resistance of the tests to fragmentation during burial (Murray and Pudsey, 2004).

The two least consistent species in the group of taxa correlating positively with Mn/Fe in biofacies C are *Eu*. *bradyi* and *G. pacifica* (Fig. 5). Theyare both deep infaunal species favoured by dysoxic pore water conditions and high organic matter concentration in sediments (Das et al., 2017; Mazumder and Nigam, 2014). However they are usually find under suboxic bottom water conditions (Fontanier et al., 2014; Kaithwar et al., 2020; Keating-Bitonti and Payne, 2017; Tetard et al., 2021b), which might explain the correlation with Mn/Fe. Together they represent on average only 4.14% of all benthic foraminifera specimens in the samples in which they occur, and 3.08% of all samples, therefore, they do not represent a major contribution to the ecological significance of this biofacies.

Among the forth remaining taxa of the biofacies, C are *H*. *elegans* and *C*. *carinata* correlate positively with Mn/Fe and negatively with Br/Ti, but differ from the biofacies C taxa presented above in correlating positively with Ti/K (Fig. 5). As *H*. *elegans* is characteristic of deep environments, it is unlikely that this correlation can be explained by post-mortem transport of the tests (Dessandier et al., 2015; Duros et al., 2011; Mojtahid et al., 2010). On the other hand, *H*. *elegans* is known to be oxic and tolerate variable organic matter fluxes and inputs of degraded organic matter (Altenbach et al., 1999; Dessandier et al., 2015), providing a competitive advantage in the case of inputs of more refractory continental organic matter via turbidity currents. Regarding *C*. *carinata*, the species is suboxic and and can be found in water depths of up to 3500 m (Uchimura et al., 2017), therefore post-mortem transport is rather unlikely, and its correlation with inputs of continental material and organic matter by turbidity currents seems to be more related to its preference for strong fluxes of organic matter on the ocean floor (De Rijk et al., 2000) and its pioneering role in recolonization after turbidite deposition (Hess et al., 2005).

Finally, the last two taxa of the biofacies C are *Pyrgo* spp. and *U*. *peregrina*. They both show negative correlation to Mn/Fe and Br/Ti and positive correlation to Ti/K (Fig. 5). These correlations are coherent with the ecology of *U*. *peregrina*, a suboxic species (Cannariato et al., 1999; Rathburn and Corliss, 1994; Uchimura et al., 2017) adapted to high organic matter fluxes (De Rijk et al., 2000; Mackensen et al., 1995; Schmiedl et al., 1997; Zarriess and Mackensen, 2010). However, they are inconsistent with *Pyrgo* spp. which thrives in oxic conditions (Caulle et al., 2014; Geslin et al., 2004; Ohkushi et al., 2013; Schonfeld, 2001) and reduced food availability (De and Gupta, 2010; Murgese and De Deckker, 2005). It is therefore possible that, despite its wide distribution in water depths (up to 4 000 m) (Burkett et al., 2020), *Pyrgo* spp. may have been partly affected by post-mortem transport.

# Supplementary figures



*Figure S1: Detrended correspondence analysis (DCA) species score from the 30 taxa with abundance greater than 5% in at least 2 samples. The colors correspond to the biofacies identified by the hierarchical cluster analysis (Fig. 4) with rose corresponding to the biofacies A, yellow corresponding to the biofacies B and purple corresponding to the biofacies C. The shape. The different geometric shapes indicate the oxygenation conditions associated with the taxa, with a circle for dysoxic conditions, a triangle for suboxic conditions and a diamond for oxic conditions.*

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