Calcium carbonate dissolution triggered by high productivity during the last glacial-interglacial interval at the deep western South Atlantic

Jaime Y. Suárez-Ibarra\textsuperscript{1}, Cristiane Fraga Frozza\textsuperscript{2}, Sandro Monticelli Petró\textsuperscript{3}, Pamela Lara Palhano\textsuperscript{2}, and Maria Alejandra Gomez Pivel\textsuperscript{2}

\textsuperscript{1}Univerzita Karlova
\textsuperscript{2}Universidade Federal do Rio Grande do Sul
\textsuperscript{3}Universidade do Vale do Rio dos Sinos - UNISINOS

November 28, 2022

Abstract

Studies reconstructing surface paleoproductivity and benthic conditions allow us to measure the effectiveness of the biological pump, an important mechanism in the global climate system. In order to assess surface productivity changes and their effect on the seafloor, we studied the core SAT-048A, recovered from the continental slope of the southernmost Brazilian continental margin, in the western South Atlantic. We assessed the sea surface productivity, the organic matter flux to the seafloor and the dissolution effects, based on micropaleontological (benthic and planktonic foraminifers, ostracods), geochemical (benthic and planktonic $\delta^{13}C$ isotopes) and sedimentological data (carbonate and bulk sand content). Superimposed on the climate-induced changes related to the last glacial-interglacial transition, the reconstruction indicates paleoproductivity changes synchronized with the precessional cycle. From the reconstructed data, it was possible to identify high (low) surface productivity, high (low) organic matter flux to the seafloor, and high (low) dissolution rates of planktonic Foraminifera tests during the glacial (postglacial). Furthermore, within the glacial, enhanced productivity was associated with higher insolation values, explained by increased NE summer winds that promoted meandering and upwelling of the nutrient-rich South Atlantic Central Water. Changes in the Atlantic Meridional Overturning Circulation and the reorganization of bottom water masses could also have changed the CO$_3^{2-}$ saturation levels and have influenced the carbonate preservation. However, changes in the Uvigerina spp. $\delta^{13}C$ values are very likely linked to the organic matter flux and not to the sea bottom dissolved inorganic matter $\delta^{13}C$ values.
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J.Y. SUÁREZ-IBARRA$^{1,2}$, C.F. FROZZA$^1$, S.M. PETRÓ$^3$, P.L. PALHANO$^4$, M.A.G. PIVEL$^4$

$^2$Ústav Geologie a Paleontologie, Přírodovědecká fakulta, Univerzita Karlova, Albertov 6, Praha 2, 12843, Czech Republic, present address.
$^3$ITT FOSSIL - Instituto Tecnológico de Micropaleontologia, Universidade do Vale do Rio dos Sinos, Av. UNISINOS, 950, 93022-750, São Leopoldo, RS, Brazil.
$^4$Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, Cx. P. 15001, 91501-970, Porto Alegre, RS, Brazil.

Key Points:

• High summer insolation induced high glacial productivity in the study area.
• High surface productivity led to high organic matter flux to the seafloor.
• Seafloor dissolution was caused by surface conditions rather than water masses changes.

Corresponding author: J.Y. SUÁREZ-IBARRA, jysuarezibarra@gmail.com
Abstract

Studies reconstructing surface paleoproductivity and benthic conditions allow us to measure the effectiveness of the biological pump, an important mechanism in the global climate system. In order to assess surface productivity changes and their effect on the seafloor, we studied the core SAT-048A, recovered from the continental slope of the southernmost Brazilian continental margin, in the western South Atlantic. We assessed the sea surface productivity, the organic matter flux to the seafloor and the dissolution effects, based on micropaleontological (benthic and planktonic foraminifers, ostracods), geochemical (benthic and planktonic δ13C isotopes) and sedimentological data (carbonate and bulk sand content). Superimposed on the climate-induced changes related to the last glacial-interglacial transition, the reconstruction indicates paleoproductivity changes synchronized with the precessional cycle. From the reconstructed data, it was possible to identify high (low) surface productivity, high (low) organic matter flux to the seafloor, and high (low) dissolution rates of planktonic Foraminifera tests during the glacial (postglacial). Furthermore, within the glacial, enhanced productivity was associated with higher insolation values, explained by increased NE summer winds that promoted meandering and upwelling of the nutrient-rich South Atlantic Central Water. Changes in the Atlantic Meridional Overturning Circulation and the reorganization of bottom water masses could also have changed the CO$_2^-$ saturation levels and have influenced the carbonate preservation. However, changes in the Uvigerina spp.$\delta^{13}$C values are very likely linked to the organic matter flux and not to the sea bottom dissolved inorganic matter $\delta^{13}$C values.

Keywords: Planktonic Foraminifera, Stable isotopes, Atlantic Meridional Overturning Circulation, Upper Circumpolar Deep Water, North Atlantic Deep Water.

1 Introduction

The Late Quaternary climate is characterized by orbit-related glacial-interglacial fluctuations (EPICA Community Members, 2004; Jouzel et al., 2007) associated to CO$_2$ variations (Petit et al., 1999; Shakun et al., 2012). Nevertheless, the orbital forcing per se is not strong enough to induce such temperature changes, and thus, feedbacks in the Earth’s climate system are expected to amplify (or reduce) the primary signal (Lorius et al., 1990; Shackleton, 2000). An intensified biological pump in the oceans, and therefore an increase of exported biogenic carbon—along with biogenic carbonate—burial in the sediments (Brummer & van Eijden, 1992), is expected during glacial times as a mechanism to remove atmospheric CO$_2$. Since planktonic Foraminifera are important contributors of pelagic calcium carbonate flux (Milliman et al., 1999; Schiebel, 2002; Kučera, 2007) they represent an important piece in the global climate system, due to their capacity to remove CO$_2$ and contribute to its storage in the marine sediments.

However, high biological surface productivity can also: i) boost the benthic communities (Cronin et al., 1999), leading to the remineralization of higher percentages of organic matter (OM) and decreasing the biologic carbon burial; and ii) release more CO$_2$ (e.g., due to respiration processes; Hales, 2003) and dissolve larger quantities of biogenic carbonate, (e.g., planktonic Foraminifera tests; Schiebel, 2002). Therefore, the export of organic matter to the seafloor can have a contrary effect (e.g., Zamelczyk et al., 2012; Naik et al., 2014) regarding the biogenic carbonate burial.

The western South Atlantic is an ideal setting to study the effects of high OM fluxes to the seafloor given its well-documented high glacial productivity (Gu et al., 2017; Pereira et al., 2018; Portilho-Ramos et al., 2019). Therefore, this study reconstructs the past sea surface and bottom oceanographic conditions in this region, in terms of productivity, using a multiproxy analysis (micropaleontological, geochemical and sedimentological data), in order to improve the understanding of the benthic-pelagic dynamic during the last glacial-interglacial interval at the western South Atlantic.
Figure 1. Location of core SAT-048A and other mentioned-cores (Supplementary material), plan view and latitudinal cross section. Seasonal variation of average sea surface salinity in the study area for the months of (a) January-March and (b) July-September, according to the World Ocean Atlas 2013 (WOA13, Zweng et al., 2013). The isohalines 32, 34 and 36 psu (dashed lines) highlight the less saline water intrusion from the south during the austral winter according to the wind regime. Present Río de la Plata Estuary (RdIPE) and Patos-Mirim Lagoon System (PMLS) represent important continental nutrient sources to the study area. The isolines (c) (dotted curves) of dissolved oxygen concentrations (µmol/kg) from a section of the South American continental margin showing the South Atlantic water masses that circulate in the region: Tropical Water (TW), South Atlantic Central Water (SACW), Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW).
2 Regional setting

The studied core was recovered off Santa Marta Cape, at the Pelotas Basin slope, western South Atlantic (Figure 1a, b). The proximal portion of the continental shelf of the Pelotas Basin represents a submerged coastal plain (Martins, 1984) that was exposed during the last Pleistocene regression (Marine Isotope Stage 2) and dissected by drainage networks from fluvial systems (Weschenfelder et al., 2014), contributing with larger inputs of nutrients from continental outflows compared to the Holocene.

Surface circulation in the shelf portion of the study area is dominated by the northward Brazil Coastal Current, which carries the Coastal Water (CW), a mixture of oceanic and continental drainage waters. Offshore, the Brazil Current (BC) transports southward the warm (temperature, \( T > 20^\circ C \)) and salty (salinity, \( S > 36 \) psu) Tropical Water (TW) at the surface layer. The BC flows along the South American margin slope until it converges with the Malvinas Current (MC), a northward surface current carrying cold (\( T < 15^\circ C \)) and fresher (\( S < 34.2 \) psu) Subantarctic Water, forming the Brazil/Malvinas Confluence (BMC) close to 38\(^\circ\)S (Gordon & Greengrove, 1986). The BMC forms a large meander which separates southward from the continental margin (Peterson & Stramma, 1991; Piola & Matano, 2017), and varies seasonally and interannually, moving to the north in austral autumn and winter, and to the south in spring and summer, influencing the nutrient distribution along the continental shelf of the Argentinian, Uruguayan and southern Brazilian coasts (Gonzalez-Silveira et al., 2006). Presently, two main continental sources of nutrients and freshwater for the area are the Río de la Plata Estuary (RdPE) and the Patos-Mirim Lagoon System (PMLS). Although the configuration of continental drainage certainly changed under the varying sea-level conditions of the late Quaternary, they both represent sources of continental drainage, and thus, nutrients to the study area.

The water masses that circulate in the subsurface (Figure 1c) immediately below the TW are: South Atlantic Central Water (SACW), Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) (Reid et al., 1976; Campos et al., 1995; Hogg et al., 1996; Stramma & England, 1999). The NADW represents slightly warmer and saltier water bodies when compared to AAIW, UCDW and AABW. In addition, the NADW also promotes the preservation of carbonate, due to the oversaturation of the carbonate ion (\( CO_3^{2-} \)), in relation to the overlying UCDW and the underlying AABW, both undersaturated in \( CO_3^{2-} \) which, therefore, may lead to the dissolution of carbonate (Frenz et al., 2003). Indeed, the interface between the NADW and the AABW defines the depth of the lysocline (Frenz & Henrich, 2007), through which occurs a great change in the dissolution indexes.

3 Material and methods

The piston core SAT-048A was collected by FUGRO Brasil – Serviços Submarinos e Levantamentos Ltda for the Agência Nacional do Petróleo (ANP, Brazilian National Agency of Petroleum, Natural Gas and Biofuels) at 29\(^{\circ}\)11’S, 47\(^{\circ}\)15’W, 1542 m water depth (Figure 1). The core, with a total recovering of 315 cm, was sampled at intervals of about six cm, totaling 54 samples. The core lacks the top 20 cm and the 196-217 cm interval (Figure 2). Each sample was washed over a 0.063 mm sieve and oven dried under temperatures below 60°C. The taxonomical identification of the planktonic Foraminifera species, from subsamples of at least 300 specimens larger than 0.15 mm, followed Bé (1967), Bé et al. (1977), Bolli & Saunders (1989), Hemleben et al. (1989), Kemle von Mücke & Hemleben (1999), Schiebel & Hemleben (2017) and Morard et al. (2019).

It was used a revised version of the Frozza et al. (2020) age model, carried out by Savian et al. (submitted), based on rbacon package (Blaauw & Christen, 2011; version
2.4.2) for the R software (R Core Team, 2019), considering the Laschamp geomagnetic excursion as a control point besides ten AMS radiocarbon dates.

Past Sea Surface Temperatures (SST) were estimated using the Modern Analogue Technique (MAT, Hutson, 1980) tool from the software PAST (version 3.2; Hammer et al., 2001), considering 100 meters below sea level (SST\text{100m}). The paleo SST\text{100m} were calibrated with a dataset composed as follows: i) relative abundances of planktonic Foraminifera of surface sediments from the South Atlantic Ocean extracted from the ForCenS database (Siccha & Kučera, 2017) coupled to ii) modern mean annual temperature estimates for 100 meters below sea level, obtained from the World Ocean Atlas 2013 (Locarnini et al., 2013), extracted with the software Ocean Data View (Schlitzer, 2020). For the Weighting parameter it was used the inverse dissimilarity, for the dissimilarity it was used the squared chord, a Threshold of 0.28 and five analogues.

Surface paleoproductivity was assessed from the relative abundances of the species *Globigerinita glutinata* (Conan et al., 2000; Souto et al., 2011) and the ratio between *Globigerina bulloides* and *Globigerinoides ruber (albus & ruber)* (*G.bull*:*G.ruber*, Conan et al., 2002; Toledo et al., 2008). The OM flux to the seafloor was estimated based on the benthic-planktonic Foraminifera ratio (Berger & Diester-Haass, 1988; Loubere, 1991; Gooday, 2002), called B:P hereafter, the ostracods valves abundances (number of valves in the >150 µm fraction per gram of sediment), and the $\delta^{13}C$ record of *Uvigerina* spp. ($\delta^{13}C_{Uv}$, Mackensen, 2008). Part of these data (*G. bulloides %, G. ruber % and $\delta^{13}C_{Uv}$) were previously published by Frozza et al. (2020). As a sea surface fertilization index, the $\delta^{13}C$ record of *G. ruber ruber* ($\delta^{13}C_{G.rub}$) was analyzed (Wefer et al., 1999). Approximately seven specimens of the benthic genus *Uvigerina* spp. and 12–15 specimens of the planktonic species *G. ruber ruber* were selected from the >250 µm fraction for each sample. The geochemical analyses were performed with a Thermo Scientific MAT-253 mass spectrometer, coupled to a Kiel IV carbonate device, by the Laboratory of Stable Isotopes of the University of California, Santa Cruz (SIL-UCSC). All results are expressed relative to the Vienna Pee-Dee Belemnite (VPDB) standard.

The dissolution effect was estimated based on the planktonic Foraminifera Fragmentation Intensity (Suárez-Ibarra et al., accepted manuscript), which follows Berger (1970)'s fragments and broken shells counting. Other dissolution effect indicators and proxies used were bulk sand fraction (%; Berger et al., 1982; Gonzales et al., 2017), the number of planktonic Foraminifera tests per gram (PF/g; Le & Shackleton, 1992) and CaCO$_3$ content (%). Bulk sand contents were determined using a laser diffraction particle size analyzer Horiba Partica-LA-950 at the Climate Studies Center (CECO, Centro de Estudos Climáticos) of the Universidade Federal do Rio Grande do Sul (UFRGS). The calcium carbonate content for the samples was determined by weight loss after reaction with 10% hydrochloric acid (HCl) at the Calcareous Microfossils Laboratory of the UFRGS. All dissolution data were previously published by Suárez-Ibarra et al. (accepted manuscript).

4 Results

The core SAT-048A sediments correspond to hemipelagic muds rich in carbonate. The average grain size of the samples is slightly sandy mud, ranging from slightly clayey mud to muddy sand in some cases. The recovered sediments correspond to the latest Pleistocene and early/middle Holocene muds of the Imbé Formation. The age model (Supplementary material) revealed a sediment recovery ranging from 43 to 5 ka BP, with sedimentation rates varying between 3 to 10 cm/kyr (Figure 2).
Figure 2. The sedimentation rate (cm/kyr) through the timespan recorded by core SAT-048A shows a progressive increase from 43 to 15 ka BP, when it decreases to a minimum between 14 and 11 ka BP and remains low until 5 ka BP. Data gap interval corresponds to unavailable samples.

4.1 Planktonic Foraminifera

Planktonic Foraminifera species display two contrasting temporal distribution patterns: i) species with higher abundance values during the Late Pleistocene that decreased towards the Holocene (Globigerinita glutinata, Globigerina bulloides, Globoconella inflata and Neogloboquadrina incompta; Figure 3a-d) and ii) species with lower abundance values during the Late Pleistocene and higher abundances in the Holocene (such as Globigerinoides ruber albus and ruber, Trilobatus trilobus, Globorotalia menardii, Globigerinella calida, Orbulina universa, Globorotalia tumida and Globigerinoides conglobatus; Figure 3e-l).

4.2 SST and Paleoproductivity estimates

Figure 4 presents the performance of the Modern Analogue Technique for the SST\textsubscript{100m} reconstructions (Figure 4a), with an $R^2$ of 0.9932, and the annual mean past SST\textsubscript{100m} estimates (Figure 4b) for core SAT-048A through time, while residuals are shown in the supplementary material. The annual mean SST\textsubscript{100m} reconstructions showed lower values from the base until 37 ka BP (on average 16°C), although the lowest value occurred at 25 ka BP (15.2°C). More variable temperatures were obtained for the 37 – 15 ka BP period, ranging from 16 to 18°C. A warming trend was established from the Last Glacial Maximum (LGM) onwards, with values between 19 – 23°C and the warmest value (22.5°C) observed at 7 ka BP.

The paleoproductivity estimates are presented in Figure 5. For the 43 – 35 ka BP interval, the highest values were obtained for G. glutinata (Figure 5a), G.bull:G.rub ratio (Figure 5b) and B:P ratio (Figure 5c), followed by an interval (35 – 25 ka BP) characterized by lower values. Subsequently, from 25 to 13 ka BP, the G. glutinata and the B:P ratio exhibited relatively higher values at the end of this period, although generally smaller than those from the 43 – 35 ka BP interval. Meanwhile the G.bull:G.rub ratio showed higher values at the beginning of this period. From 13 ka BP onwards, a decreasing trend for the three tracers reaches the top (5 ka BP), registering the lowest values of the record. The geochemical tracers $\delta^{13}C_{G.rub}$ (Figure 5d) and $\delta^{13}C_{Uvi}$ (Figure 5e) showed similar fluctuations. The $\delta^{13}C_{G.rub}$ displayed low values for the 43 – 35 ka BP interval, followed by variable values until 19 ka BP. Finally, the lowest value (0.6‰) occurred at 16.8 ka BP, while an increasing trend was established. The $\delta^{13}C_{Uvi}$ showed the minimum values at the base of the core framed in an increasing trend during the 43 – 23 ka BP. Lower values were obtained during the 23 – 12 ka BP interval, followed by...
Figure 3. Relative abundances (%) of cool (blue, a-d) and warm (red, e-l) water species (Kučera, 2007) along the core SAT-048A from the recovered period. (a) *G. glutinata*, (b) *G. bulloides*, (c) *G. inflata*, (d) *N. incompta*, (e) *G. ruber albus*, (f) *G. ruber ruber*, (g) *T. trilobus*, (h) *G. menardii*, (i) *G. calida*, (j) *O. universa*, (k) *G. tumida* and (l) *G. conglobatus*. LGM: Last Glacial Maximum.
Figure 4. Modern Analogue Technique (MAT) performance and results of the annual mean paleotemperature estimates at 100 m waters below sea level (SST\textsubscript{100m}) at the study site. (a) Regression (R\textsuperscript{2} = 0.9932) curve between reconstructed annual mean SST\textsubscript{100m} (°C) and the annual mean modern SST WOA13\textsubscript{100m} (°C) (Locarnini et al., 2013). (b) Reconstructed SST\textsubscript{100m} (°C) along SAT-048A. LGM: Last Glacial Maximum.

increased values until the top. The ostracods’ abundance (Figure 5f) showed low values during the 43 – 27 ka BP interval, when an increasing trend was established until 18 ka BP, followed by a decreasing trend until 5 ka BP.

4.3 Dissolution indicators

The Fragmentation Intensity (Figure 6a) showed a decreasing trend since 40 ka BP until 25 ka BP, with a plateau of relatively low values during the 36 – 32 ka BP interval. From 25 ka BP values increased until 17 ka BP, to then decrease until 11.8 ka BP, where the lowest value (0.31) was obtained. For the 11.8 – 5 ka BP interval, values increased again. In general terms, the CaCO\textsubscript{3} content (Figure 6b), the PF/g (Figure 6c) and Bulk sand content (Figure 6d) showed an increasing trend from 43 to 24 ka BP, although more variable for the Bulk sand content values. From 24 to 16 ka BP the trend was inverted, and values decreased. For the 16 – 12 ka BP period, a fast increase was registered, followed by decreasing values during the Holocene portion of the record.
Figure 5. Paleoproductivity and paleofertility estimates for the core SAT-048A based on relative abundances (%) of (a) *G. glutinata*, (b) *G. bull:*G. *rub* ratio, (c) B:P (benthic:planktonic) Foraminifera ratio, (d) $\delta^{13}C_{G. rub}$, (e) $\delta^{13}C_{Uvi}$ and (f) ostracod abundance (number of valves/g). Inverted axes for (d) and (e) to aid visualization. LGM: Last Glacial Maximum.

Figure 6. Dissolution indicators applied to the core SAT-048A: (a) Fragmentation Intensity, (b) CaCO$_3$ content (%), (c) PF/g (number of planktonic Foraminifera tests per gram of dry sediment) and (d) Bulk sand content (%). Inverted axes for (a) to aid visualization. LGM: Last Glacial Maximum.
5 Discussion

5.1 Long term fluctuations

Portilho-Ramos et al. (2019) explained the high productivity during the last glacial near the study area by two mechanisms: i) prolonged winter conditions and ii) short austral summer upwellings. The first implies prevalent southwesterly (SW) winds year-round carrying outflows from the Río de La Plata (RdLP) (Pimenta et al., 2005; Piola et al., 2000) and other continental sources (Camaquá, Jaguarão and Jacuí rivers) which presently converge in the PMLS, closer to the study area (Piola et al., 2000; Nagai et al., 2014). Strengthened SW winds would also displace the BMC closer to the area (Gonzalez-Silveira et al., 2006). The high relative abundance of *G. inflata* and *N. incompta* (Figure 3c, d) can be interpreted as a closer BMC (Boltovskoy et al., 1996), due to the enhanced SW winds during the late last glacial. The second mechanism involves the NE winds blowing along the shore, pushing surface waters offshore due to the Ekman transport, allowing summer upwelling (Chen et al., 2019).

Additionally, Mahiques et al. (2007) proposed that during low relative sea levels (glacial times) periods of higher nutrients and terrigenous sediments input were favored due to the more offshore position of the BC and the exposure of the continental shelf. Moreover, the Río de la Plata (Lantzsch et al., 2014) and Jacuí and Camaquá river palaeodrainages (Weschenfelder et al., 2014) were closer to the study area during this interval (higher influence of the PMLS). Higher Fe/Ca values (Heil, 2006), higher proportion of eutrophic dinocysts (Gu et al., 2017) and high terrestrial palynomorphs proportions (Bottezini et al., 2019), are all evidence of the greater influence of continental outflow in the study area under lower relative sea levels of the late last glacial. In contrast, for the Holocene, the higher relative sea level and onshore displacement of the BC, as well as the absence of the SACW, inhibited the photic zone fertilization, leading to oligotrophic conditions (Mahiques et al., 2007).

The *G.bull:* *G.rub* ratio records from the western South Atlantic (Figure 7a-e) display a clear tendency to reduction since the LGM, except by a small increase in the Pleistocene/Holocene transition, also recorded in the cores SAN-76 (Toledo et al., 2007; Figure 7a) and JPC-17 (Portilho-Ramos et al., 2019; Figure 7c). A clear warming tendency starting at about 35 ka BP was registered by Lessa et al. (2019) (Figure 7g), with scarce data for the Pleistocene/Holocene transition. Warming trends during the LGM were also recorded by Portilho-Ramos et al. (2019) (Figure 7h) and more clearly by Pereira et al. (2018) (Figure 7i), although in the latter, cooler temperatures were reestablished prior to the LGM end. In the SAT-048A record (this study), SST$_{100m}$ reconstructions showed variable cooler temperatures until 25 ka BP, and a warming and relatively stable trend afterwards, with the coolest temperatures being registered prior to the LGM (Figure 7j). Temperatures cooler than 20°C at 100 m water depth (Campos et al., 2000; Silveira et al., 2000; Castelão et al., 2004), along with *G.bull:* *G.rub* ratio values higher than 0.25 (Lessa et al., 2014), can be interpreted as a constant presence of the SACW in the subsurface during the short austral upwelling of the late glacial. The *G.bull:* *G.rub* ratios from the mentioned cores show no relation with the summer insolation (Figure 7), supporting Pereira et al. (2018) who stated no orbital cycle forcing.

The reported fluctuations took place in a context of gradual Atlantic Meridional Overturning Circulation (AMOC) weakening, leading to uninterrupted heat accumulation in the subtropical South Atlantic gyre and, therefore, a high glacial maxima out-of-phase (Santos et al., 2017). Luz et al. (2020) showed that this cool or warm water presence during the LGM is associated to the water masses that interplay at the surface near the continent: the offshore warm TW carried by the BC and the onshore cooler CW transported by the Brazil Coastal Current (BCC) (Luz et al., 2020, and references therein). The authors found that the alkenone-derived SST estimates varied according to the BC/BCC (TW/CW) influence: a shallower and closer to the coast core (RJ-1501) registered a late
Figure 7. Higher *G. bull:* *G. rub* ratios and temperatures cooler than 20°C are interpreted as intrusions of the SACW in the subsurface, as a result of late glacial enhanced upwelling. *G. bull:* *G. rub* ratios of cores (a-e): (a) SAN-76 (Toledo et al., 2007), (b) GL-852 (Lessa et al., 2019), (c) JPC-17 (Portilho-Ramos et al., 2019), (d) SAT-048A (this study), (e) SIS-188 (Duque-Castaño et al., 2019), (f) austral summer (February) insolation at 31°S (Laskar et al., 2004); annual mean subsurface (100 m) temperatures for cores (g-j): (g) GL-852 (Lessa et al., 2019), (h) JPC-17 (Portilho-Ramos et al., 2019), (i) GeoB21073 (Pereira et al., 2018) and, (j) SAT-048A (this study).
deglacial warming, while in a deeper and more offshore core (RJ-1502), the early deglacial warming trend (Santos et al., 2017) was recognized.

5.2 Short term fluctuations

5.2.1 Surface paleoproductivity

Four intervals for the last 43 kyr can be defined according to the fluctuations in productivity indicators: IV (43 – 35 ka BP), III (35 – 24 ka BP), II (24 – 13 ka BP) and I (13 – 5 ka BP) (Figure 8). Intervals IV, III and II were characterized by higher productivity than interval I. But more interesting are the fluctuations during the late glacial, with intervals IV and II, characterized by a higher summer insolation (Figure 8a), which leads to stronger NE winds, strengthened BC, intensified meanderings and therefore, the enhancement of shelf break upwelling-fertilization (Portilho-Ramos et al., 2015; Pereira et al., 2018). This is inferred from: i) the increased relative abundance of *G. glutinata* (Conan et al., 2000; Souto et al., 2011) from cores GeoB2107-3 (Pereira et al., 2018; Figure 8b) and SAT-048A (this study; Figure 8c); ii) the higher relative abundance of *Globigerina falconensis* (Figure 8d) during intervals IV and II, associated with eutrophic conditions (Sousa et al., 2014), and iii) the relatively increased values of Turborotalita quinqueloba (Figure 8e), associated with intrusions of cooler SACW into the photic zone (Souto, et al., 2011; Lessa et al., 2014, 2016). Although quite variable from 35 – 18 ka BP, the $\delta^{13}C_{G.rub}$ (Figure 8g) increased values also corroborate the SACW intrusions (Venancio et al., 2014, 2016) and, therefore, higher fertilization in the area (Prell & Curry, 1981; Curry et al., 1992).

Additionally, the “silicic acid leakage hypothesis”, brought by Portilho-Ramos et al. (2019) to explain high glacial productivity complements the “enhanced NE winds-enhanced SACW intrusions-enhanced subsurface productivity” dynamics. According to this hypothesis, glacial SACW enriched in dissolved Si(OH)$_4$ intruded the subsurface water during the short austral summer conditions, enhancing diatom blooms. Higher diatom record of Bottezini et al. (2019) and *G. glutinata* from SAT-048A and GeoB2107-3 (Pereira et al., 2018) for the late glacial support this hypothesis, since the species *G. glutinata*, that feeds on diatoms (Schiebel and Hemleben, 2017), can be favored under these conditions.

After high *G.bull:*$G.rub$ ratio values and low SST$_{100m}$ suggesting an enhanced upwelling of cool and nutrient-rich SACW intrusions for interval IV (Figure 9d), and a relatively not so productive interval III due to low summer insolation values and weaker NE winds (Figure 9c), it was expected an increase of *G.bull:*$G.rub$ ratio and decrease of SST$_{100m}$ during interval II, where higher upwelling would be expected because of the higher summer insolation and stronger NE winds (Figure 9b). The absence of an increasing trend can be associated to the record of heat accumulation in the South Atlantic subtropical Gyre (Santos et al., 2017; Luz et al., 2020), which was observed at about 25 ka BP for the SAT-048A core, coinciding with the beginning of interval II, and hampering upwelling. Another factor proposed as a fertilization control in the south Brazilian continental margin (SBCM) is the relative sea level variation (Gu et al., 2017; Pereira et al., 2018, Portilho-Ramos et al., 2019). Since during interval II (Figure 9b), the eustatic level was lower (Waelbroeck et al., 2002) than during interval IV (Figure 8o), a higher (terrigenous-related) fertilization was expected. However, paleoproductivity estimates for interval II are lower when compared to interval IV (Figure 8), suggesting a small role for the continental terrigenous fertilization for cores from mid-depths of the continental slope. Finally, during interval I (Figure 9a), NE winds were not strong enough to effectively pump SACW (which would also be depleted in silicic acid) to the photic zone (as shown by warmer SST$_{100m}$, low *G.bull:*$G.rub$ ratio, and low relative abundance of *G. glutinata*). Furthermore, the onshore displacement of the BC, along with higher relative sea level, and rivers outflowing farther away, inhibited the terrigenous input, leading to oligotrophic conditions. Thus,
Figure 8. Caption on next page
Figure 8. Fluctuations in surface productivity, organic matter (OM) flux to the seafloor and planktonic foraminifers carbonate dissolution as a response to austral summer insolation variations at the study area. Intervals IV and II are characterized by very high productivity, III by high productivity and I by low productivity. (a) austral summer (February) insolation at 31°S (Laskar et al., 2004); relative abundances (%) of (b-e): (b) G. glutinata (GeoB2107-3, Pereira et al., 2018), (c) G. glutinata (SAT-048A), (d) G. falconensis, (e) T. quinqueloba; (f) $\delta^{13}C_{G.rub}$ (‰), (g) $\delta^{13}C_{Uvi}$ (‰), (h) B:P, benthic:planktonic Foraminifera ratio, (i) CaCO$_3$ content (%), (j) PF/g (number of planktonic Foraminifera tests per gram), (k) Bulk sand content (%), (l) Fragmentation Intensity, (m) $^{231}$Pa/$^{230}$Th values from McManus et al. (2004, squares), Lippold et al. (2009, circles) and Böhm et al. (2014, triangles), (n) Ostracods per gram (valves/g), and (o) RSL (m, Relative Sea Level, Waelbroeck et al., 2002). Inverted axes in (f), (g) and (i-k) to aid visualization. Proxies in black belong to core SAT-048A.

Based on the aforementioned data, it is possible to infer that the orbital forcing was able to modulate the productivity fluctuations in the study area, for the last glacial-interglacial transition, supporting previous studies from the western South Atlantic (G. bulloides – Lessa et al., 2017, 2019; eutrophic environmental dinocysts – Gu et al., 2017; Portilho-Ramos et al., 2019) and the North Atlantic (e.g., Villanueva et al., 1998).

### 5.2.2 Organic matter flux to the seafloor

Orbital to suborbital climate cycles can influence the abundance shifts of deep-sea benthic communities (Cronin et al., 1999). Since abundance fluctuations of benthic Foraminifera and ostracods are related to variations in particulate organic carbon fluxes to the seafloor (Smith et al., 1997; Rex et al., 2006; Rex & Etter, 2010), their use as surface paleoproductivity indicators is widespread (Nees et al., 1999; Herguera, 2000; Rasmussen et al., 2002; Gooday, 2003; Yasuhara et al., 2012). The surface productivity fluctuations, indicated by G. glutinata (Figure 8c), are similar to those of the OM flux recorded by the B:P ratio (Figure 8h). This effective OM exportation (from the surface to the seafloor) revealed a high benthic-pelagic coupling (Toledo et al., 2007). Intervals II and IV show higher OM flux than I and III, with lower contributions registered during the Holocene, when oligotrophic conditions prevail. The B:P changes are inversely accompanied by similar $\delta^{13}C_{Uvi}$ trends (Figure 8g), which are expected to decrease when higher OM fluxes, rich in $^{12}$C due to the preferential incorporation of the light isotope during photosynthesis (Wefer et al., 1999), reach the seabed (Ravello & Hillaire-Marcel, 2007). The B:P ratio showed a positive linear relationship with productivity, whereas ostracods valves abundance showed a hump-shaped relation with productivity (Yasuhara et al., 2012), increasing under enhanced – but still moderate – supply of OM and declining under very high productive conditions, where oxygen levels tend to decrease, and deep-sea ostracods, mostly epifaunal (Jöst et al., 2017), would not respond well to this environment.

Additionally, abundance oscillations of deep-sea benthic organisms can also be related to paleobathymetric variations, decreasing exponentially with depth increase (Rex et al., 2006; Rex & Etter, 2010). However, a 120 m range in relative sea level changes during the late Quaternary is not sufficient to explain the observed abundance changes at mid-depths of the continental slope. While the ostracods record showed a negative relation (Figure 8n), the B:P ratio did not follow the same fluctuations than the relative sea level (Figure 8o).

Dissolution indicators showed higher calcium carbonate dissolution during intervals IV and II (Figure 8i-l), and their fluctuations are related to the OM flux. Enhanced dissolution could be triggered by two different processes: i) fluctuations in CO$_2$ concen-
Figure 9. Schematic sea surface reconstruction for the study area next to the cores SAT-048A (this study) and GeoB2107-3 (Pereira et al., 2018). In light gray, (paleo)relative sea levels according to Waelbroeck et al. (2002) for the time interval, which in turn represent the exposed continental shelf. During interval I (a), the terrigenous nutrients input into the coastal surface waters by RdlPE (Río de la Plata Estuary, green arrows, Lantzsch et al., 2014), Jacuí and Camaquã paleo-rivers (nowadays Patos-Mirim Lagoon System, PMLS; black arrows, Weschenfelder et al., 2014) discharges is further away than during intervals II (b), III (c) and IV (d). In intervals IV and II, enhanced northeast (NE) winds triggered subsurface water pumping (blue honeycomb), as a mechanism of subsurface water fertilization. Pink dots represent intrusions in subsurface water rich in dissolved Si(OH)$_4$ (Portilho-Ramos et al., 2019), which were enhanced during the strengthened NE winds (intervals IV and II). Intervals: I (13 – 5 ka BP), II (24 – 13 ka BP), III (35 – 24 ka BP) and IV (43 – 35 ka BP).
trations (decreasing pH) due to the remineralization of OM at the seafloor (Jahnke et al., 1997; Schiebel, 2002) (Figure 10) or ii) the reorganization of bottom water masses related to AMOC dynamics. Although the B:P ratios are also used as a dissolution indicator (Berger & Diester-Haass, 1988; Conan, 2002), Kučera (2007) states it is only applied for abyssal depths.

Figure 10. Schematic representation of the two possible settings affecting dissolution on deep-water assemblages of core SAT-048A. The paleoceanographic changes could be triggered by: (a) low OM inputs at the sea floor which results in lower benthic abundances and better preservation of CaCO$_3$, and (b) high OM inputs that increase benthic abundances, rise CO$_2$ concentrations, decrease the pH of the water and dissolve the planktonic Foraminifera tests (fragmentation on benthic Foraminifera was not assessed).

In the SBCM basins, the $\delta^{13}$C$_{Uvi}$ values have been used to infer oscillations of OM inputs (Toledo et al., 2007; Rodrigues et al., 2018; Dias et al., 2018; Frozza et al., 2020). Nevertheless, $\delta^{13}$C$_{Uvi}$ values involve several controlling factors, such as accumulation rates of organic carbon, regional changes of water masses, global carbon cycle, photosynthesis-respiration processes, temperature, and pH (Zahn, 1986; Ravelo & Hillaire-Marcel, 2007; Hesse et al., 2014). Lund et al. (2015) suggested that lower values of benthic $\delta^{13}$C during glacial times are associated to a weak AMOC, which lead to: i) a pre-deglacial BC warming trend and the accumulation of heat in the South Atlantic subtropical gyre (Santos et al., 2017), due to a reduced exportation of heat and salt to the North Atlantic through the North Brazil Current, ii) the shallowing of the NADW due to lower density values, being restricted to the upper 2.5 km during the LGM and iii) the reconfiguration of the water masses (Curry & Oppo, 2005; Lynch-Stieglitz et al., 2006). However, according to Lund et al. (2015)’s logic, the $\delta^{13}$C$_{Uvi}$ more negative values during interval II would suggest the higher presence of the UCDW, (Figure 11) what contrasts with the shallowing of NADW during the LGM, and therefore, changes in $\delta^{13}$C$_{Uvi}$ probably do not mainly reflect the water $\delta^{13}$C variations but other factors.
The carbonate preservation and the fluctuations of $\delta^{13}C_{Uvi}$ could be the result of the interplay between the OM flux and water masses changes. However, the fluctuation range of $\delta^{13}C_{Uvi}$ values (Figure 11b) is up to 1‰, i.e. two times higher than the difference between the present-day $\delta^{13}C$ of dissolved inorganic carbon values for the UCDW and the NADW which is up to 0.4‰ (Fig 11a). Therefore, the observed pattern is more likely linked to changing OM fluxes to the seafloor. Additionally, after $\delta^{13}C$ “corrections” (e.g., Schmiedl et al., 2004; -2‰) from benthic foraminifers tests and ambient bottom water, SAT-048A $\delta^{13}C_{Uvi}$ still remains more negative from the supposed original values, which also points to the input of OM fluxes, richer in $^{12}C$ than $^{13}C$.

Based on eNd in benthic Foraminifera at mid-depths at the western South Atlantic, Howe et al. (2016b, 2018) showed variations of water masses inter-phase depths at 1000-1200 m (GeoB2107-3 and KNR159-3-36GGC) and 2200 m (GL-1090). After the Heinrich Stadial 1, core GL-1090 eNd values decreased, becoming more related to modern upper NADW values, while cores GeoB2107-3 and KNR159-3-36GGC eNd values increased after about 10 ka BP, showing more affinity with modern AAIW. But between the aforementioned cores is located core GeoB2104-3 (1500 m) – at the same depth of the here studied core SAT-048A –, which eNd values remained stable during 25 - 4 ka BP (Howe et al., 2016b). This i) suggests that if recent water masses distribution has kept stable since 4 ka BP, based on eNd in benthic Foraminifera of core GeoB2104-3, the SAT-048A $\delta^{13}C_{Uvi}$ points to the presence of the NADW, contradicting direct measures which would indicate the presence of the UCDW (Figure 1C, Figure 11A); and ii) indicates that SAT-048A $\delta^{13}C_{Uvi}$ fluctuations were actually produced by the OM bottom flux rather than water masses reconfiguration, since there were no changes through the register. This idea is supported by Howe et al. (2016a), where the authors stated that depleted glacial $\delta^{13}C$
values in the deep Atlantic are not solely explained by water masses changes but also by high respired carbon accumulated on a sluggish deep overturning cell.

In addition, the $^{231}$Pa/$^{230}$Th ratio, used to track the intensity of the AMOC (Mc-Manus et al., 2004; Lippold et al., 2009; Böhm et al., 2014) – where lower values mean a strengthened AMOC – can also shed a light on the discussion. In periods of high $^{231}$Pa/$^{230}$Th values and AMOC slowdown (like Heinrich Stadials), a higher concentration of respired CO$_2$ is accumulated at seafloor water masses, as proposed by Howe et al. (2016a), being a possible explanation for the higher calcium carbonate dissolution intervals. But when compared, the $^{231}$Pa/$^{230}$Th values (Figure 8m) and the dissolution proxies (Figure 8i-l), no relation is found during interval IV, where high dissolution contrasts with the intermediate $^{231}$Pa/$^{230}$Th ratios. Also, during interval III and the transition to interval II, high $^{231}$Pa/$^{230}$Th values did not cause high dissolution. Only a good match can be observed at the Heinrich Stadial 1, where both, high productivity and high dissolution, coincide with an interval of sluggish AMOC, as suggested by the high $^{231}$Pa/$^{230}$Th ratios.

Finally, since the AMOC’s intensity do not to explain the whole changes in the calcium carbonate dissolution in core SAT-048A, the surface productivity and OM flux to the seafloor is shown as the principal agent of the calcium carbonate dissolution, related to orbital forcings. Furthermore, special attention must be taken when interpreting Fe/Ca ratios, since higher values can be the response of i) higher Fe input but also to ii) high productivity and high OM fluxes to the sea floor that lead to calcium carbonate dissolution – as here explained –, contrary to the stated by Pereira et al., (2018), where the authors, when interpreting the ln(Fe/Ca) ratios from Heil (2006), affirmed that higher ln(Fe/Ca) values can not be result of high productivity due to the expected higher input of carbonate tests to the sea floor, disregarding the effects of high OM fluxes. Further studies must explore the impact of the biological pump in the benthic $\delta^{13}$C values of the deep South Atlantic to quantify their relation, as well as the Total Organic Carbon burial to better understand the glacial inorganic carbon sequestration hypothesis.

6 Conclusions

Planktonic Foraminifera assemblages from core SAT-048A, along with geochemical analyses and sedimentological data, enabled us to reconstruct the surface and bottom paleoceanographic fluctuations that occurred – in phase – during the last 43 kyr at the western South Atlantic, and to contextualize the related processes in the area. In long term changes, the Pleistocene-Holocene transition witnessed a shift from glacial eutrophic environment to more oligotrophic post-glacial conditions, as suggested by the G. bull:G. rub ratio and the SST$_{10m}$, where intrusions of the nutrient-rich SACW were inhibited and the Río de la Plata Estuary (RdPE) and local river discharges (nowadays PMLS) were placed further away from the core site. In short term changes, the orbital-scale fluctuations of the upwelling dynamics (indicated by G. glutinata, T. quinqueloba and $\delta^{13}$C$_{G.rub}$), modulated by insolation and NE wind changes, influenced directly the surface productivity and the OM fluxes to the seafloor (as shown by the B:P ratio and $\delta^{13}$C$_{Uvi}$). Imposed to the already well-known mechanisms behind the high glacial productivity, the stronger NE winds, strengthened BC and increasing meanders – generated by precessionally-controlled higher insolation – enhanced the intrusion of cooler and nutrient-richer waters in subsurface for 43 – 35 and 24 – 13 ka BP, fertilizing the photic zone. The enhanced upwelling conditions were also registered at the sea floor, where the bacterial decomposition of OM and the respiration of higher abundances of benthic communities increased the CO$_2$ concentration, creating more acidic conditions that caused different levels of carbonate dissolution. Nevertheless, the reorganization of deep waters could cause the alternation of two water masses in contact with the core location seabed: i) the NADW, linked to preservation of CaCO$_3$ and, ii) the UCDW, related to CaCO$_3$ dissolution, due to its CO$_3^{2-}$ undersaturated condition. Even though the registrated fluctuations of $\delta^{13}$C$_{Uvi}$
values are two times bigger than the difference between modern UCDW and NADW $\delta^{13}$C values of the dissolved inorganic carbon (1‰ vs. 0.4‰), along with its more negative values and the geometric ($\epsilon$Nd in benthic Foraminifera) and intensity ($^{231}$Pa/$^{230}$Th) proxies of water masses, point to the control of the OM fluxes. Additionally, the continental influence (i.e., terrigenous input) must be better assessed, since no increased productivity was registered during the lowest relative sea level (LGM). Finally, the dissolution of planktonic Foraminifera tests, induced by an enhanced biological pump (evidenced in the high glacial surface productivity and the high OM fluxes to the sea floor), must call the attention to future research since our study area is not effective for removing, sinking and stocking glacial biogenic carbonates.

Acknowledgments
This work was supported by the Brazilian Coordination of Higher Education Staff Improvement (CAPES) (grant number 88887.091729/2014-01) and the Brazilian National Council for Scientific and Technological Development (CNPq) (grant number 407922/2016-4). The authors are grateful to Prof. Gilberto Griep (in memoriam) for his commitment to making sediment cores retrieved for the industry available to the scientific community. We are also grateful to Maria Helena Saraiva and Tiago Menezes Freire for sample processing and to Igor Venâncio, João Coimbra and Geise dos Anjos Zerfass for comments and suggestions. J.Y.S.I. thanks the CNPq for his master’s scholarship. C.F.F. thanks CAPES for her PhD scholarship. The data presented in this paper is under submission process on the virtual repository Pangaea.

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Supporting Information for

Calcium carbonate dissolution triggered by high productivity during the last glacial-interglacial interval at the deep western South Atlantic

J.Y. SUAREZ-IBARRA\textsuperscript{1,2}, C.F. FROZZA\textsuperscript{1}, S.M. PETRÓ\textsuperscript{3}, P.L. PALHANO\textsuperscript{1}, M.A.G. PIVEL\textsuperscript{4}

\textsuperscript{1}Programa de Pós-Graduação em Geociências, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, Cx. P. 15001, 91501-970, Porto Alegre, RS, Brazil.
\textsuperscript{2}Ústav Geologie a Paleontologie, Přírodovědecká fakulta, Univerzita Karlova, Albertov 6, Praha 2, 12843, Czech Republic, present address.
\textsuperscript{3}ITT FOSSIL - Instituto Tecnológico de Micropaleontologia, Universidade do Vale do Rio dos Sinos, Av. UNISINOS, 950, 93022-750, São Leopoldo, RS, Brazil.
\textsuperscript{4}Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, Cx. P. 15001, 91501-970, Porto Alegre, RS, Brazil.

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Introduction

The present Supporting Information file presents data for: i) other analyzed cores (Table S1), ii) the Sea Surface Temperature (SST) residuals (Figure S1), iii) the age model construction (Figure S1, Table S2 and Table S3), as well as iv) the appendix of planktonic Foraminifera species (Appendix S1).

Table S1

In the manuscript Figure 1 are shown the core SAT-048A location, as well as the location of the other analyzed cores. Names, coordinates, and depths below sea level of the mentioned cores are shown in Table S1.
Table S1. Location of the other analyzed cores, all recovered from the western South Atlantic.

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<td>1514</td>
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</table>

**Figure S1**

The SST estimates at 100 m waters below sea level, performed on the present study, are show in manuscript Figure 4. Residual of this reconstruction is showed in Figure S1. The 95% of the residuals are located between 2.5 and -2.5°C, while the 90% are between 1.8 and -1.8°C.

![Residuals vs. Annual mean SST estimates at 100 m waters below sea level for core SAT048A. Red lines encompass 95% of the residuals (between 2.5 and -2.5°C) and blue lines encompass 90% (between 1.8 and -1.8°C).](image-url)
Text S1.

From the 54 samples, a total of 21,962 specimens of planktonic Foraminifera were classified into 28 morphospecies (supplemental material). A total of 4878 specimens of benthic Foraminifera were counted. Table S1 lists the morphospecies, total relative abundance and total absolute abundance in descending order. The dominant species in the associations were *Globigerinoides ruber albus*, with a maximum relative abundance of 25.32%, followed by *Globigerinita glutinata* (15.56%) and *Globigerina bulloides* (15.56%). Other representative but less abundant species are *Neogloboquadrina incompta* (8.57%), *Globigerinoides ruber ruber* (8.22%) and *Globoconella inflata* (7.69%).

Other species, with total relative abundances between 5 and 1% are (in decreasing order): *Trilobatus trilobus*, *Globoturborotalita tenellus*, *Neogloboquadrina dutertrei*, *Globorotalia scitula*, *Globoturborotalita rubescens*, *Globigerinella calida*, *Globorotalia truncatulinoides* (R), *Globorotalia crassaformis* and *Globorotalia truncatulinoides* (L).

Finally, species with extremely low total absolute abundance (> 1%) are *Candeina nitida*, *Globigerina falconensis*, *Globigerinella siphonifera*, *Globigerinoides conglobatus*, *Globorotalia hirsuta*, *Globorotalia menardii*, *Globorotalia tumida*, *Neogloboquadrina pachyderma*, *Orbulina universa*, *Pulleniatina obliquiloculata*, *Trilobatus sacculifer*, *Turborotalita humilis* and *Turborotalita quinqueloba*. 
Age Model

The performing results of the rBacon package for core SAT-048A are shown in Figure S2. It is possible to see the $^{14}$C correlation points, as well as the identified Laschamp geomagnetic excursion (Savian et al., submitted).

Figure S2. Age-depth plot for core SAT048A (bottom panel). The red stippled line indicates the mean age-depth model, 95% confidence ranges indicated by dark-grey stippled curves and calibrated dates in blue. Upper panels from left to right display (1) the Markov chain Monte Carlo (MCMC) iterations, the prior (green curves) and posterior (grey histograms) distributions for (2) the sedimentation rate and (3) memory.

The AMS $^{14}$C results of core SAT-048A (Frozza et al., 2020) are shown in Table S2. The Marine Reservoir Correction Database (Delta R= -85 +/-40) is based on ages from Nadal de Masi (1999), Angulo et al. (2005), and Alves et al. (2015). Rbacon package (Blaauw & Christen, 2011; version 2.4.2), for open source R software (R Core Team, 2020), used the calibration curve Marine20 (Heaton et al., 2020).
Table S2. SAT-048A (Frozza et al., 2020) AMS $^{14}$C ages.

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Table S2 shows data the radiocarbon data published by Frozza et al., 2020 used for the former age model.

Table S3. SAT-048A data points for age model building on rbacon package.

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<td>260</td>
<td>295</td>
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</tr>
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</table>

Table S3 shows data used for the age model (Figure S2) building. Laschamp (Table S3) correlation point is from Savian et al. (submitted).
Appendix S1. List of the species/morphospecies/subspecies identified and their total relative and absolute abundances.

<table>
<thead>
<tr>
<th>Species/Morphospecies/subspecies</th>
<th>Total relative abundance (%)</th>
<th>Total absolute abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Globigerinoides ruber albus</em></td>
<td>25.32</td>
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<tr>
<td><em>Globigerinita glutinata</em></td>
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<td><em>Globigerina bulloides</em></td>
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<td><em>Neogloboquadrina incompta</em></td>
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<td><em>Globoconella inflata</em></td>
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<td><em>Trilobatus trilobus</em></td>
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<td><em>Globoturborotalita tenellus</em></td>
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<td><em>Globorotalia scitula</em></td>
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<td><em>Globoturborotalita rubescens</em></td>
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<td><em>Globorotalia crassaformis</em></td>
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<td><em>Globorotalia truncatulinoides</em> (L)</td>
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<td><em>Globorotalia hirsuta</em></td>
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<td><em>Globigerinella siphonifera</em></td>
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<td><em>Globorotalia menardii</em></td>
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<td><em>Orbulina universa</em></td>
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<td><em>Globigerinoides conglobatus</em></td>
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References


