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Report on the doctoral thesis of Jaime Yesid Suarez-Ibarra
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PALAEOCEANOGRAPHIC EVOLUTION OF THE WESTERN SOUTH ATLANTIC DURING MARINE ISOTOPE STAGES 5 – 1: A FORAMINIFERAL PERSPECTIVE

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The thesis of Jaime Suarez-Ibarra presents a relevant multi-proxy foraminiferal micropaleontological and geochemical study tracing glacial-interglacial variability in primary productivity, export production and calcium carbonate dissolution/preservation over the last 110 kyr for the southern Brazilian continental margin. This is crucial for understanding the effectiveness of the biological carbon pump and its role in the carbon cycle during the last interglacial-glacial cycle in such a critical oceanographic area of the western South Atlantic, where data on this research topic are still scarce in the literature.
The main objectives are to understand the mechanisms that modulate the dynamics of primary productivity and calcium carbonate accumulation/dissolution, and to unravel the influence of environmental versus taphonomic conditions on the test size variation of planktonic foraminifera. To this end, three marine-cores from the continental slope of the southern Brazilian margin, covering different time intervals and seawater depths above the lysocline, were studied.
The results shed light on the important role of sea surface productivity and water mass properties in influencing the dynamics of carbonate dissolution/preservation during different climatic periods, with implications for the functioning of the carbonate biological pump.

The dissertation consists of two already published articles and one submitted article presented separately from an integrative manuscript, whose title is “"Palaeoceanographic evolution of the Western South Atlantic during marine isotope stages 5 - 1: a foraminiferal perspective".

The first article “Calcium Carbonate Dissolution Triggered by High Productivity During the Last Glacial–Interglacial Interval in the Deep Western South Atlantic”, published in 2022 in Frontiers in Earth Science, examines the relationship between surface productivity and benthic environmental conditions by analysing the **SAT-048A core** (1,542 mbsl), spanning 43 to 5 ka, from the continental slope of the southernmost Brazilian continental margin. 54 samples have been studied. Sea surface productivity, organic matter flux to the seafloor and foraminiferal calcite dissolution are reconstructed from micropaleontological, geochemical and sedimentological proxies. Statistical analyses support the hypothesis that at this site, well above the lysocline, increased productivity and hence organic matter export to the seafloor during glacial periods would have led to increased seafloor dissolution of planktic foraminiferal calcite.

The second article, “Surface fertilisation and organic matter delivery enhanced carbonate dissolution in the western South Atlantic”, published in Frontiers in Ecology and Evolution in 2023, reconstructs, over a wider time interval between 30 and 110 ka, the variability at the glacial-interglacial scale of sea surface productivity and of carbonate dissolution using planktic and benthic foraminiferal proxies and stable oxygen isotopes from the **SIS-249 core** (2.091 mbsl) recovered from the continental slope of the southernmost Brazilian continental margin. 45 samples were analysed. Principal component analysis was used to synthesise the variation of the proxies through time. Spectral analysis showed that the

synthesis of the productivity proxies is driven by orbital obliquity forcing. Under low obliquity conditions during glacial MIS 4, productivity increased as probably a result of the northward shift (from 40° S to 30° S) of the southwest wind band, which allowed fertilising windblown dust and fluvial inputs to reach the study area. The increase in productivity may also be associated with an increase in upwelling of the more nutrient-rich subsurface South Atlantic Central Water. Coupling of planktic and benthic data showed that such high productivity and the consequent export of labile organic matter to the seafloor during glacial MIS 4 triggered high dissolution, although the influence of corrosive Southern Component Water during glacial periods cannot be excluded.

The third article, "Planktonic foraminifera test size dictated by conditions in life and post-mortem" is reported as submitted to Journal of Foraminiferal Research. This paper aims to distinguish the effects of environmental conditions (eg. temperature, productivity and salinity) from those of taphonomic processes (calcium carbonate dissolution) in the variation of test size of planktonic foraminifera deposited above the lysocline. This was done by measuring the cross-sectional area of over 16,000 tests taken from **core SAT-048A** (the same core as in the first article), recovered at a depth of 1,542 metres from the continental slope of the southernmost Brazilian continental margin. Multiple linear correlation analyses revealed significant relationships between test sizes and the environmental parameters studied. In particular, smaller sizes increased during periods of increased upwelling. For symbiont-bearing species such as *Globigerinoides ruber*, this reduction in size may be associated with reduced light in the upwelling environment due to high levels of suspended particulate matter, as well as increased dissolution due to remineralisation of organic matter exported to the seafloor. Thus, a complex interplay between living and post-mortem conditions has been suggested, noting that they can be additive in the fossil record. In addition, this work warns against misidentifying the effects of dissolution, such as the loss of the last chamber, which is the most sensitive to dissolution, which could lead to an underestimation of the size of tests and the fragmentation of planktonic foraminifera, with potential implications for foraminiferal-based ecology and geochemical proxies.

The three papers mentioned above are well written and illustrated, two of which have already been peer-reviewed. For this raison, I will focus hereafter mainly on the thesis summary manuscript "Palaeoceanographic evolution of the Western South Atlantic during marine isotope stages 5 - 1: a foraminiferal perspective". This integrative text is divided into 7 chapters, consisting of 80 pages, 23 of which are devoted to the list of references.

Chapter 1, seven pages long, is the introduction and gives a clear and complete presentation of the context of the thesis, the problem, the field of study and the objectives. However, there is sometimes a lack of figures to support the text, especially on the study area and the complex interplay of different currents and different water masses, or to illustrate the CO_2 variations during the last interglacial cycle and the functioning of the biological pump. In addition, the part presenting the biological pump tends to focus mainly on the organic pump, while the concept and role of the "carbonate counter-pump" is not mentioned. The carbonate pump should indeed be presented in a temporal perspective, as it can act as a "counter-pump" and become a source of CO_2 or a CO_2 sink, depending on the time scale considered.

Chapter 2 briefly presents the structure of the thesis in three pages and, above all, provides a list of the articles already published (two) or presented (one) included in this thesis, as well as the articles published (two) or presented (two) outside the thesis. With regard to the three articles included in this thesis, Jaime Y. Suarez-Ibarra has well specified his contribution.

Chapter 3 is a brief two pages presentation of the material and methods used during the thesis. This chapter is perhaps a little too short. It would have been interesting to include a map showing the location of the three cores, as well as their photographs and logs with the lithological description, as well as a more detailed description of the foraminiferal proxies and methods, and finally a summary table of the new data obtained for the three cores during this thesis.

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Chapter 4 presents, in fourteen pages, the main results from the three cores studied (SAT-295 048A, SIS-203 and SIS-249), integrating and synthesising the data from the articles included in this thesis, especially those from articles 1 and 2, as well as from chapter 5. All these data obtained during the thesis are compared with other published records, particularly those from the western South Atlantic and the Southern Hemisphere. For example, Figures 3 and 4 summarise the intensity of upwelling variability, derived from the relative abundance of the *Globigerina bulloides* species and the ratio *G. bulloides/Globigerinoides ruber*, during the last glacial-interglacial cycle according to a latitudinal transect (between ~ 20°S and 30°S). Despite the fragmentary record, these figures would indicate that upwelling intensity does not seem to follow a clear glacial-interglacial scale variability and shows a significant latitudinal variation. In other words, high-intensity upwelling does not seem to be restricted to glacial periods. If high-intensity upwellings are associated to high primary productivity, these figures seem to contradict the assumption in lines 294 to 296 of this chapter that "the results of this thesis indicate that the southernmost Brazilian continental margin experienced higher glacial productivity (MIS 2 - 4) of the sea surface, as recorded by the SAT-295 048A, SIS-203 and SIS-249 cores". How can this contradiction be explained?
Figure 6 is also very interesting and shows that, when analysed together, the carbonate dissolution proxies from the deeper studied cores SIS-203 and SIS-249 (~ 2000 mbsl) and from other deep Atlantic cores show a similar variation following a glacial-interglacial dynamic driven by obliquity. The intensification of dissolution during the MIS2 and MIS4 glaciations observed in the cores SIS-203 and SIS-249 appears to be related to the expansion of corrosive SCW waters at the core sites rather than to an intensification of productivity, as also supported by new neodymium isotope analyses in core SIS-203, the latter discussed in detail in Chapter 5. Finally, this chapter questions the relationship between changes in surface productivity and carbonate dissolution for these deeper cores, since, as mentioned in the text, there is a lag of ~11 kyr between the two phenomena.
This chapter 4 is potentially very interesting because it is not just a long summary of the published articles, but a major effort of data integration and synthesis. However, it would need to be revised and restructured to better focus on the main findings of this thesis. First, the discussion should start with the main results on productivity and dissolution from the three cores studied and their correlation with other records published in the literature for the western South Atlantic (as well illustrated in Figures 3, 4, 6), the interpretations arising from these correlations, and finally whether they confirm what is already known in the literature or whether they suggest new interpretations about the connections of the western South Atlantic with the South Atlantic and Antarctic. Secondly, this text would benefit from being shortened. For example, it seems to me that the part from line 485 to line 501 is off-topic and not related to the data and results obtained in this thesis, and should be removed. In addition, I would suggest that the discussion of orbital control of productivity at the eccentricity scale (see lines 400 to 410) should also be removed, since a longer temporal record in the study region is currently lacking. The last part of this chapter from line 513 to line 558 is just a long summary of the above-mentioned third article on the role of environmental parameters versus dissolution on size changes of planktic foraminifera. It therefore does not seem useful here, also because it is not integrated with the other results described in the previous sections of this chapter. Finally, Figure 4 is not easy to understand, there are too many overlapping curves for planktonic foraminiferal fragmentation variations for the SIS-203 and SAT-048 cores to see any trends, and it is not explained what the different colours correspond to.

Chapter 5 presents a new article in preparation on a detailed study of calcium carbonate dissolution over the 7-31 ka interval of a new core (SIS-203), recovered from the southern Brazilian continental margin at 1,894 m below sea level. Supported by new neodymium isotope analyses in foraminiferal coatings, it suggests a strong relationship between dissolution and changes in the geometry of the bottom water mass. Indeed, these new data would show that much larger proportions of corrosive Southern Component Water (SCW) bathing the core site are correlated with increases in dissolution during the Last Glacial Maximum. On the other hand, productivity proxies in this core appear to be anti-correlated with dissolution proxies, suggesting less influence of organic matter remineralisation on

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carbonate dissolution at this site. This chapter is well written and clear and could quickly be submitted to a journal. It would only take a few more ^{14}C analyses to confirm the new age model, which is very different from the one published in the literature for the same.

Chapters 6 and 7 briefly present the conclusions drawn and the need for future research. The first point of the conclusions "differential fertilisation mechanism" requires more caution. For example, the sentence " the southeast region is more likely affected by eccentricity-paced mechanisms, while the southernmost margin might be influenced by Antarctic ice sheet dynamics" needs to be revised. This is because there are no long enough temporal records of the southern Brazilian continental margin to capture eccentricity cycles, so how can we exclude that this region is also affected by eccentricity-driven fertilisation mechanisms?

In general, the dissertation manuscript is well written, but if it is read without reading the articles first and as an independent manuscript, it is sometimes not always easy to follow, because figures supporting the text are sometimes missing. In addition, interpretations and hypotheses derived directly from the data of this thesis should be more clearly distinguished from those derived from the literature.
Regarding the general structure of this thesis, I am not used to this type of thesis where the published or submitted articles are separated from the thesis manuscript. It would have been easier for the reader if the published/submitted articles had been included in the manuscript as three separate chapters after Chapter 3 "Materials and Methods". In addition, Chapter 4, which is a synthesis chapter combining the main results from the three cores studied (SAT-295 048A, SIS-203 and SIS-249), should have been placed after Chapter 5, which presents new results from only one of the three cores studied (SIS-203).

I add here below some questions that might help in the final evaluation:

- How can paleoclimate archives tell us whether the oceanic biological carbonate pump acts more as a "counter-pump" or as an atmospheric CO_2 sink, and on what timescale?
- In addition to providing nutrients and controlling the fertilisation of the ocean, rivers can supply carbonate and calcium to the ocean, which in turn controls the production of calcium carbonate and promotes its preservation. Future work on the functioning of the carbonate pump in the western South Atlantic will have to take these processes into account, and with what proxies?
- One of the main assumptions of the thesis is that strong primary productivity and consequent organic matter fluxes and remineralisation cause carbonate dissolution on the seafloor, even above the lysocline. But wouldn't this assumption be highly dependent on seafloor oxygenation? Could intense organic matter fluxes reduce oxygenation and instead favour the preservation of both organic matter and calcium carbonates? Would it be appropriate to use proxies for the redox state of the seafloor to make the thesis assumption more robust?
- In the case of a greater influence of the SCW in the western South Atlantic, it can be said that the biological pump works better than during periods of greater influence of the NCW?
- According to the synthesis of the data from the three cores studied in Chapter 4, the relationship between intensification of primary productivity and dissolution should be more important for the shallower core SAT-048A than for the deeper cores (SIS-203 and SIS-249). How can this be explained?
- How to explain the latitudinal heterogeneity (between ~ 20°S and 30°S) and variability of the upwelling intensity along the Brazilian continental margin during the last glacial-interglacial cycle (see Figures 3 and 4 in Chapter 4)?
- In Chapter 5, the *G. bulloides*/*G. ruber* ratio record from core SIS-203 was synthesised with the relative abundance of *G. glutinata* using principal component analysis to track productivity. However, Figure 3 in this chapter shows that the patterns of the two proxies are not always correlated, especially during MIS 1. How can this different behaviour between the two proxies be explained?
- The benthic/planktonic ratio has sometimes been used as a proxy for dissolution and sometimes as a proxy for export production. How is it possible to distinguish between the two causes

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(dissolution versus export production) that drive this ratio in the deep ocean above the lysocline?

- If upwelling intensification as a mechanism for enhanced primary productivity can be detected by planktic foraminiferal assemblages, what proxies can detect enhanced Fe fertilisation?
- How is it possible to distinguish between dust aeolian, riverine terrigenous input and upwelling as the main mechanisms of high productivity in the study area? Which approach and which proxies allow to distinguish their respective influence?
- In the second article has been suggested that not only the increased organic matter export but also a change in its bioavailability (from refractory to labile) led to calcium carbonate dissolution. How was it possible to discern from the data presented in this article between labile and refractory material?

To conclude, I would like to congratulate Jaime Suarez-Ibarra on the high number of papers he has already published or submitted, which enhances his research activity during his thesis. It is worth noting that he has already published four papers, two of which are included in this thesis, and submitted three papers, one of which is included in this thesis.
Overall, this study provides new insights into productivity and carbonate dissolution/preservation in the western South Atlantic, with implications for the efficiency of the biological pump in this area during glacial and interglacial periods. It raises new questions and highlights some important gaps in our knowledge of biogeochemical processes in this key oceanographic area and their links to Antarctic dynamics.

For the above reasons, I strongly recommend the thesis of Jaime Suarez-Ibarra for the defence.

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