My Referee Overview

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A 500 kyr record of global sea level oscillations in the Gulf of Lion, Mediterranean Sea: new insights into MIS 3 sea level variability

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Handling Editor: Dr. Luc Beaufort, beaufort@cerege.fr

The Frigola et al. manuscript is very interesting in particular the different data sets included in it. I think the manuscript will have a much stronger impact if it was dramatically reorganized.

My proposal to improve the manuscript would be to focus first on the data set for the last Glacial cycle, let's say the last 150 ky, and with an emphasis on MIS-3. During the last 150ky, sea-level fluctuations are the best established. Also the chronology of the different data sets in borehole PRGL1-4 and core MD99-2348 are the best established. The conceptual model(s) could be then developed on these clear data sets at a long (full glacial cycle) and short (millennial) term time scale. Once developed, these models can be applied (tested) further back in time.

Past 150 ky, the chronology in borehole PRGL1-4 based on the the bulloides 18-O record is not as obvious. Because the entire scientific rationale is based on this rather complex 18-O planktic record, on would be skeptical about the overall time frame until additional biostratigraphic markers are used to solidly anchor its chronology. The lithologic record is very interesting, however its correlation with the 18-O record, and then sea level is not as clear as it is in the last 150 ky. To illustrate my point, I have marked discrepancies in Figure 3 in the linkages between fluctuations of silt/clay ratio, planktic 18-O, and seal level proxy (RSL).

In reading the manuscript, I believe that the connections between borehole lithology variability and the seismic line, crossing the borehole location, was done visually only (Figure 2). If it was not the case, the method used needs to be developed in the methodology section. If I understood well condensed sections are interpreted in the manuscript to correspond to sequence boundaries, which in a sequence stratigraphic framework should be interpreted as condensed sections related to maximum flooding time, which they are clearly interpreted as such in the manuscript. It is obviously confusing.

I have made many comments on the manuscript itself. Hopefully these will be helpful to improve the manuscript.

Andre Droxler, March 2012

A 500 kyr record of global sea level oscillations in the Gulf of Lion, Mediterranean Sea: new insights into MIS 3 sea level variability

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Abstract

Borehole PRGL1-4 drilled in the upper slope of the Gulf of Lion provides an exceptional record to investigate the impact of ~~Late~~ late Pleistocene orbitally-driven glacio-eustatic sea level oscillations on the sedimentary outbuilding of a river fed continental margin. High-resolution grain-size and geochemical records supported by oxygen isotope chronostratigraphy allow reinterpreting the last 500 ka upper slope seismostratigraphy of the Gulf of Lion. ~~which consists of F~~five main sequences, stacked during the sea level lowering phases of the last five glacial-interglacial 100-kyr cycles, make the upper part of the continental margin.. The high sensitivity ~~to sea level oscillations~~ of the grain-size record down the borehole to sea level oscillations ~~along the borehole~~, ~~favoured by~~can be explained by the ~~large~~ unusually great width of the Gulf of Lion continental shelf.~~, demonstrates that S~~sea level driven changes in accommodation space over the shelf ~~are able to~~ cyclically ~~modify~~ modified the depositional mode of the entire margin. PRGL1-4 data also illustrate the imprint of sea level oscillations at millennial time scale, as shown for Marine Isotopic Stage 3, and provide unambiguous evidence of relative high sea levels at the onset of each Dansgaard-Oeschger Greenland warm interstadial. The PRGL1-4 grain-size record represents the first evidence ~~ever~~ for a one-to-one coupling of millennial time~~-~~scale sea level oscillations associated with each Dansgaard-Oeschger cycle.

1 Introduction

120 m amplitude ~~Sea~~ sea level oscillations ~~of about 120m of amplitude~~ paralleled the orbitally-driven 100-kyr climate cycles of the ~~Late~~ late Pleistocene in response to global ice volume changes (Imbrie et al., 1992??, Siddall et al., 2006). Jointly with sediment input and subsidence, these sea level oscillations controlled the stratal geometry of passive continental margins where migration of fluvial-influenced deposits generated regressive/transgressive depositional sequences. The seismostratigraphic study of those~~e~~ stackied~~ng of those~~ sequences ~~allowed to generate~~

the first approximationscan help to develop the linkage between to sea level evolution fluctuations and sedimentary unit depostion after application ofonce the seismic interpretation is placed in a sequential sequence stratigraphy framework principles (Posamentier and Vail, 1988; Vail et al., 1977). More refined sea level

More refined sea level -curves based upon benthic and planktic oxygen isotopes in marine sediment cores, in some cases corrected for temperature variations, and dated uplifted coral terraces have been achieved published during the last decades through the measurement of oxygen isotopes on marine sediment cores and dating of coral terraces (Chappell, 2002; Rohling et al., 1998, 2009; Shackleton et al., 2000; Siddall et al., 2003; Thompson and Goldstein, 2005, 2006; Waelbroeck et al., 2002; Yokoyama et al., 2001; Miller et al., 2005). However, intrinsic limitations of sea level reconstruction methods and the diffficulty of obtaining better and more precise age control of marine records disabled the possibilitymake difficult the task to accurately constrain orbital and millennial-time scale sea level fluctuations. Thus, continental margin sedimentary records ffrom rom river fed continental margins consisting of depostional units characterized with very high sedimentation rates and precise chronology of depositional units could provide a better time control and resolution high enough to improve the reconstruction of past sea level oscillations.

In the Gulf of Lion (GoL) margin, western Mediterranean Sea, deltaic forced Regressive Progradational Units (RPUs) stacked on the outer-shelf and upper slope during relative sea-level falls (Fig. 1), leading some authors to describe this margin as a forced regressive system (Posamentier et al., 1992; Tesson et al., 1990, 2000). The noticeable significant subsidence rate of the margin, 250m Myr^{-1} at the shelf edge (Rabineau, 2001), eased the preservation of RPUs in the upper slope as it was continuously submerged even during pronounced lowstands. Note most importantly this significant subsidence rate also preserve the majority of the outer-shelf units (former coastal deposits). These conditions allowed the preservation of regressive/transgressive depositional sequences across the outer shelf (old lowstand coast lines) and the upper slope accumulation where dating is easier, thus resulting in an ideal area for the study of the late Quaternary sedimentary succession. The huge amount of seismic reflection profiles obtained in the GoL margin eased identifying major unconformities defining sequence boundaries in the outer-shelf that become correlative conformities in the upper slope from where five major RPUs were initially described and interpreted to correspond to the last five 100-kyr cycle sea level falls (Fig. 1b) (Bassetti et al., 2008; Rabineau et al., 2005, 1998). (note in Figure 1 the fifth and sixth upper slope sequences seem to be easily correlated with corresponding outershelf units. Upper slope sequences 3 and 4 do not have any equivalent outershelf units in Figure 1. Sequences 1 and 2 do not clearly correspond to the younger two out shelf units, also it can be assumed they do. Obviously the correlation between the slope sequences recovered in the borehole and the outer shelf units is the foundation of this manuscript). However, precise dating of RPUs sequence boundaries was still needed to better constrain the imprint of sea level oscillations on the GoL margin and to determine the leading cyclicity of the deposition of those units, i.e., if they originated during sea level lowerings of 20 or 100 kyr cycles (Lobo et al., 2004). (Note I agree, the question is can this be done?)

In addition, millennial-scale sea level oscillations at times of rapid climate change during Marine Isotope Stage (MIS) 3 result of special interest since determining their amplitude and phasing (? You mean between the ice core and sea level records?) is crucial to understand the role (but also the overall behavior of the ice sheets, in particular ice sheet growth rates to explain millennial sea level fluctuations of 10 m amplitude or so) of ice sheets on millennial climate variability (Siddall et al., 2008). In fact, MIS 3 relative sea level rises have been tentatively related to both Antarctic and Greenland (? You mean Laurentide?) climate variability (Arz et al., 2007; Rohling et al., 2008; Siddall et al., 2003, 2008; Sierro et al., 2009), which evidences the lack of consensus (I am not sure what do you refer to in terms of lack of consensus. Are you saying that we do not know the contribution of the Laurentide and the Antarctic ice sheets? If so write it down clearly. I thought rates of ice sheet growth to explain millennial scale sea level fluctuations of the order of 10 m in amplitude is the main unknown; the phasing seems to be an impossible to question to ask because of the accuracy of the available chronologies) on the sea level response to rapid climate variability.

Here we present grain-size and geochemical records from a borehole ~~-~~in the GoL upper slope together with a robust oxygen isotope chronostratigraphy, which allow identifying and precisely (you might want to be a little less enthusiastic!) dating the main RPUs of the last 500 ka, and yield the timing of millennial-scale sea level changes in response to abrupt climate variability during MIS 3.

2 Setting and present day conditions

The GoL forms a crescent-shaped passive margin that is characterized by a wide continental shelf, 70 km of maximum length (you mean width I guess?), covering an area of about 11 000 km^2 (Fig. 1a).

The overall morphology of the GoL continental shelf ~~is mainly derived~~ was mainly built ~~from~~ by ~~the last~~late Quaternary glacio-eustatic oscillations and post late glacial sedimentation. ~~It~~ The shelf can be subdivided ~~includes~~ in three distinct parts~~main domains~~(? : (i) the inner shelf, extending from 0 to 90m, ~~with~~ is characterized by ~~soft~~ gradual and regular morphological gradients, illustrated by ~~and~~ parallel and regularly spaced isobaths~~, ; also comprising a~~the inner shelf corresponds to the modern deltaic prism; (ii) the middle shelf, ranging in depths from 90 to 110–120m, is mostly flat ~~with very low gradient and~~ with an irregular~~a~~ ~~rugged~~ morphology, mainly capped by relict offshore sand shoals~~s~~; and (iii) the outer shelf, a narrow band with depths ~~from~~ ranging from 110–120m, extends to the shelf break and ~~to the shelf break that~~ is characterized ~~again~~ by a general smooth morphology (Bern´e et al., 2004a) (Fig. 1a). The shelf break, ~~locates~~ located between 120–150m in the upper slope where numerous submarine canyons and gulies ~~cut~~ indent the ~~margin~~ shelf edge thus connecting the continental shelf ~~with~~ to the deep basin. ~~This~~ (Note these point sources for sediment accumulating on the upper slope could limit the easy correlations between upper slope sequences and the continental shelf units) The overall GoL continental shelf morphology offers ~~confers~~ ~~to the GoL shelf~~ a huge accumulation space for water and sediment storage during periods of relative rising and high sea level during late Quaternary deglacial and interglacial intervals~~l~~, while ~~it~~ the GoL continental shelf remained totally or partly subaerially exposed during ~~past~~ late Quaternary sea level lowerings and lo~~n~~wstand glacial ~~periods~~interglacials.

The Rhone River is ~~The~~ the main source of sediment to the GoL shelf is ~~the Rhone River~~ while other minor fluvial inputs ~~are distributed~~ also occur along the coastline (Pont et al., 2002). ~~Nowadays, all~~Modern ~~these~~fluvial sediments are mainly trapped ~~in~~ on the inner shelf ~~domain~~, although they can also be reworked and transported further offshore to the middle/outer shelf and beyond to the upper slope by shelf erosive and re-suspension processes, mainly driven by the southwestward general circulation pattern of the Northern Current (NC) (Figure 1A), easterly storms and dense shelf water formation and cascading events (DSWC) (Bassetti et al., 2006; Canals et al., 2006; Dufois et al., 2008; Ulses et al., 2005). In addition to northerly wind-induced DSWC, offshore deep-water formation also takes place during windy winters (Millot, 1999) though with a very low sediment load if compared to major storms and DSWC, both constituting the most effective processes of sediment export from the shelf to the basin mainly through submarine canyons (Canals et al., 2006; Palanques et al., 2006; Pasqual et al., 2010; Sanchez-Vidal et al., 2008).

3 Material and methods

This ~~work~~ study is based on the detailed analyses of the 300 m-~~-~~long continuous sediment ~~core~~ accumulation recovered in borehole PRGL1-4 (42◦41.39_ N and 03◦50.26_ E), drilled at 298m of water depth in the interfluve separating Aude and H´-erault submarine canyons ~~in the GoL~~ during *MV Bavenit* PROMESS1 cruise, and on the 22.77m long IMAGES core MD99-2348 retrieved at the same location as PRGL1-4, ~~whose upper 20m overlap PRGL1-4~~ (Fig. 1a). The top 20 meters of MD99-2348 and PRGL1-4 nicely overlap (Note you need to show this overlap or mention a reference in which the overlap is illustrated and/or proven)

Grain-size analyses on the bulk and the de-carbonated ~~fractions~~ sediment were carried out at 20 cm sampling interval with a Coulter LS 100 Laser Particle Size ~~Analyser~~Analyzer after removing organic matter by treatment with excess H_2O_2 and carbonates by treatment with HCl. Grain-size results are discussed here as the silt/clay ratio of the carbonatefree fraction, an established proxy for ~~which relates to~~ energy levels at the time of particle deposition (Frigola et al., 2007). Matching of silt/clay ratio records from both ~~fractions~~ bulk and de-carbonated sediments allows discarding the in-situ paleoproductivity signal ~~to~~ that could affect the grain-size record (Fig. 2b). Semi-quantitative analysis of major elements (Ca, Fe, Ti and K) was carried out at 4 cm resolution using the first generation Avaatech non-destructive X-ray fluorescence

(XRF) core scanner of the University of Bremen. Here, we present the Ca record as the main indicative of fluvial inputs to the GoL since variability ~~from~~ in all of the XRF-elements is related to ~~oscillations in~~ Ca supply fluctuations, mainly derived from the fluvial discharge of fine sediment~~s~~.

The age model was obtained by synchronizing the records of planktik *Globigerina bulloides* δ^{18}O and abundance of temperate to warm planktic foraminifers to the North GRIP ice core isotope record for the last 120 ka (I thought we have not yet recovered MIS 5e in any Greenland ice cores, and the NGRIP only extend to 100 ka http://www.ncdc.noaa.gov/paleo/pubs/ngrip2004/ngrip2004.html) (Andersen et al., 2006; NGRIP, 2004; Svensson et al., 2008). From ~~120~~ 100 to 530 ka the age model was built by aligning the PRGL1-4 *G. bulloides* δ^{18}O record to the SPECMAP isotope stack (Martinson et al., 1987) (no one anymore uses the SPECMAP stack as a reference, you will need to use the Lisiecki Raymo, 2005 known as LR04, benthic stacked record http://www.lorraine-lisiecki.com/LR04stack.txt). For more details on the age model, tie points and ^{14}C-AMS dates see Sierro et al. (2009) and Table 1. Temporal variability of sedimentation rates (SR) resulted in a mean temporal resolution of 160 and 1550 yr during glacial and interglacial periods, respectively. (note obviously a variation with a factor 10, which can create some issues when one look at the G. bulloides 18-O record in depth as shown in figure 2. To convince the reader that the long term correlation between the 18-O record and the LR04, you really need to show in a figure the G. bulloides 18-O record on time beside the LR 04. In Figure 3, the G. bulloides record is compared with the RSL curve of Rohling et al, this cuve is basically a benthic 18-O curve and show what the pitfalls might be in the general establishment of the chronology in PRGL1-4. The interpretation of the G. bulloides 18-O is not straightforward because of the large range of O-18 values for the different interglacial stages. In the Interpreted MIS-9 interval, the 18-O values seem unusually heavy, whereas the 18-O values at the end of MIS 7 and MIS 6 are unexpectedly light. One needs to see more comparisons with well established more pelagic records from the western Mediterranean to convince a reader that the chronology in PRGL1-4 is solid.

Did you use any other time markers to anchor the chronology based on G. bulloides 18-O, I am thinking that nannofossil markers, like Pseudo emiliania lacunose (disappearance on MIS 12) or the first appearance of E. huxleyi (in MIS 8), or any other potential biostratigraphic markers available in the Mediterranean Sea, such as the Menardii complex, …)

On the other hand and in contrast with the long record, in Figure 5 correlations between the G. bulloides 18-O and the NGRIP oxygen record in MIS 3 are quite amazing. It would be nice to learned more how the depth-time model was developed in PRGL1-4/MD core. I just did in reading the Sierro et al article!)

Also regarding the methods, how was the borehole data sets plotted downcore in depth (m) is correlated to the seismic line in depth in figure 2? Is it purely a visual correlation, if yes you need to say it.

4 Results and discussion

4.1 The orbital 100-kyr sea level imprint

The silt/clay ratio and Ca records from PRGL1-4 show a seesaw (not really clear seesaw in the silt/clay!) pattern defining five main units characterized by an upwards fining and Ca content increasing trend, which Nicely (??) correlate with the main seismostratigraphic units (Fig. 2). The sedimentary units end with an abrupt increase in the silt/clay ratio and a rapid decrease in the Ca content coinciding with the main reflectors corresponding to sequence boundaries in the seismic reflection profile (how was the ties between seismic and the lithology determined, need to explain more in method sections). The excellent correlation of these analytical sequences with the seismostratigraphy, together with chronostratigraphy from the *G. bulloides* δ^{18}O record (the reader needs to open the article to convince himself about the chronostratigraphy!) (Sierro et al., 2009), confirms the 100-kyr-cycle origin of these units. The data derived from PRGL1-4 borehole allowed reinterpreting the seismostratigraphy of the GoL upper slope, where seven units (S1, S2a, S2b, S3a, S3b, S4 and S5) are now documented (Jouet, 2007) instead of the five (S1 to S5) previously identified from seismic reflection profiles only (Rabineau, 2001). The seven units result from ~~decomposition~~subdividing

The~~of~~ former sequences S2 and S3 into S2a and S2b, and S3a and S3b, respectively (Fig. 2a). The lowermost seismostratigraphic units S1 and S2a were not penetrated at PRGL1-4, (Note can you prove this?) and our results suggest that the base of the drill likely correspond to MIS 13 (also here if you can find P.lacunosa in this interpreted MIS 13 you should be able to identify it, unless the disappearance of P. lacunose is not a marker in the Mediterranean Sea) while Termination VI (TVI) was not reached (Fig. 2d note no mentioned of Terminations in this figure 2! Yes in figure 3). Accordingly, the top five major depositional sequences stacked on the upper slope of the GoL, corresponding (how do you know this for sure!) to RPUs driven by global sea level oscillations of the last five glacial cycles, are ~~perfectly~~ (avoid to say perfect I am not sure you have proven this correlation!) ~~i~~identified in the continuous (is it continous? Why one might have doubt about it, playing the devil's advocate!) sedimentary record of PRGL1-4 borehole. Abrupt increases in the silt/clay ratio and decreases in the Ca content respond to rapid sea level rise, continental shelf flooding and subsequent landward migration of deltaic systems during glacial-interglacial transitions giving birth to sequence boundaries (sequence boundaries are related to lowering sea level in the Vail et al. scheme, here during the deglacition in the sequence stratigraphy framework it is more a condensed section) in the upper slope (Fig. 2).

RPU stacking in the upper slope resulted from seaward migration of deltaic systems and the subsequent enhancement of riverine supply because of the sea level lowering during each 100-kyr cycle. That is why maximum sedimentation rates (1.5–2.5mkyr^{-1}) in the upper slope were recorded during periods when the distance to river mouths was minimal (i.e. during glacial lowstands) (Figs. 3f and 4a). The presence of relict offshore sands at 110–115m depth along the outermost shelf further supports the location of lowstand glacial paleo-shorelines in the vicinity of the Aude Canyon head (Alo¨ısi, 1986; Bassetti et al., 2006; Bern~~´~~e et al., 2004a; Jouet et al., 2006). The increasing trend of SRs paralleling???? (linked to) sea level lowering across a glacial period is particularly well resolved for the last glacial period (MIS 2, 3 and 4) ~~thanks to the~~ during which intervals ~~robustness of~~ the chronostratigraphic control is particular robust (Fig. 3f). Sedimentation rates also peaked during previous 100-kyr cycles glacial sea level ~~minima~~maxima , although the weaker ~~reduction in~~ chronostratigraphic control with depth does not allow distinguishing SR trends during previous full forced regressions, but only low or high SR during interglacial and glacial ~~periods~~ (periods should not be used here rather stages?), respectively. Co-occurrence of lowest silt/clay ratios and highest Ca contents during glacial sea level minima confirms the reinforced influence of nearby glacial river mouths on the sedimentation of fines over the upper slope ~~interfluve~~interfluves (you mean inter gullies?) (Fig. 3c,e). Accordingly, while during glacial lowstands the coarsest fractions were mostly trapped and funnelled by glacial

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adjacent submarine canyons/gullies, as demonstrated (indirect lines of evidence; note one would know this only if coarse sediment would be systematically observed at the canyon/gully head in the lower slope) by pronounced axial incisions within their upper courses (Baztan et al., 2005), large amounts of fine particles supplied by the nearby river mouths remained in suspension (probably transported by along shore current) un-trapped by the canyons and leading to substantial accumulation in inter-canyon areas (i.e. the interfluves why interfluves here again).

In contrast, SRs were lowest (0.10–0.25 m kyr^{-1}) ~~at~~ during interglacial stages / sea level highstands associated with the landward migration of deltaic systems far away from the shelf-break and upper slope (Figs. 3f and 4b), as illustrated by the modern Holocene epicontinental prism extending down to 90m water depth over the inner shelf (Aloïsi, 1986; Berné et al., 2007, 2004b). Obviously, these glacial/interglacial contrasting sedimentation rates resulted in expanded glacial intervals (~~i.e.~~ therefor resulting ~~with~~ in higher temporal resolution) and condensed interglacial intervals ~~along~~ down ~~our~~ the 500 kyr-long record in PRGL1-4 borehole (Fig. 3). ~~That means that with~~ With each sea level rise, sedimentation rates reduce significantly in the upper slope and PRGL1-4 records lose (??? You mean low) time resolution (e.g. just few points represent a full interglacial period) (Note it would be interesting to know when, during the main deglaciations, the sed rates decrease . Because the time resolution is much higher during the last deglaciation, it would make sense to observe the timing of the sed rate decrease during that particular interval, and then compare the results with the older transgression. We need to remember that the sed rates are totally depending on selection of time points in the depth to time conversion) .

In addition, the very low SRs during the main interglacial highstands led to the formation of condensed layers (CLs), i.e. sandy layers rich in pelagic skeletal material, along the GoL upper slope (Fig. 3d), as shown by the total fine sand record of Sierro et al. (2009). (good point the dilution factor from the input of fine sediments is minimum when the fine sediments are trapped in esturaries and along the coastal system)

However, the landward excursion of deltaic systems ~~pushed by~~ linked to the updip migration of the coastline when sea level rise is rising cannot explain the continuous supply of coarse particles to the upper slope during highstand intervals. ~~and the~~ The associated reduction in sediment flux to the upper slope during glacial/interglacial transitions do not explain by themselves the sustained supply of coarse particles to the upper-slope during ~~all~~ every interglacial ~~periods~~ stages as evidenced by the elevated silt/clay ratio (Fig. 3c) nor the observed increase in sand particles into the carbonate-free fraction (mainly quartz grains) [Note the maxima values of the silt/clay ratio do not systematically correspond to the same parts of the interglacial stages, sometime at the very beginning of the interglacials (for instance MIS 5e), sometime in the middle or during the late part of the interglacial stages]. The silt/clay ration maxima do not always correspond with the high sand particle values in Figure 3. The pattern is not very clear to say the least]Then, it is probable that the interglacial flooding of the 70 km wide GoL shelf (Fig. 4b) reactivated oceanographic processes able to erode, ~~Re~~re-suspend and transport coarse particles, li~~l~~kely contributing to the formation of CLs. While the southwards flowing Northern Current (NC) sweeping the shelf edge and upper slope (Fig. 1a) could contribute to winnow the finest particles during long lasting periods of reduced sediment input to the upper slope, it could not explain the arrival of new lithic coarse material found in CLs and, more generally, in deposits formed during interglacial periods. The inundation of the shelf during interglacial periods generated a relatively thin layer of water that was highly sensitive to atmospheric forcings, which may trigger the remobilisation of sedimentary particles temporarily stored on the shelf, as it happens during the present day highstand (Bassetti et al., 2006; Canals et al., 2006; Dufois et al., 2008). Recent studies have demonstrated that nowadays northern cold, strong and persistent winds lead to DSWC down-slope at high speed (up to $1 ms^{-1}$ or more) during late winter and early spring months in the GoL (Canals et al., 2006). Cascading waters carry large amounts of organic matter and sedimentary particles whose coarser fraction efficiently scours and erodes the shelf edge and canyon heads and upper courses (Gaudin et al., 2006; Lastras et al., 2007; Pasqual et al., 2010; Puig et al., 2008; Sanchez-Vidal et al., 2008). Activation in the past of continental shelf erosive processes like DSWC probably did not lead to significant sediment accumulation in upper slope interfluves but favoured the winnowing of fines and the supply of coarse lithic particles that, in combination with low sedimentation rates, contributed to generate CLs. When the "cooling platform" disappeared, i.e. during subaerial exposure of the continental shelf (lowstand conditions, Fig. 4a), there was no room left for dense shelf waters to form and, therefore, this type of continental shelf erosive processes ceased. During transitional periods, when the shelf was partly flooded, the volume of water involved in cascading and other continental shelf erosive processes was smaller, subsequently lessening downslope transport by dense shelf waters (one could argue during time intervals when the water depths were lower than the depths we observed today and other max sea level intervals, the DSWC could be even more frequent). Therefore, changes in the silt/clay ratio also respond to the flooded shelf area and, consequently, to sea level oscillations. This explains the relatively good match~~ing~~ between the silt/clay ratio and sea level for the last 500 ka (Fig. 3a,c), which is especially evident for the last glacial cycle where the chronostratigraphic control is more precise (honestly the match is only good during MIS 5! In the previous interglacials, one observes that the maxima in the silt/clay ratio values did not occur during the maximum sea level intervals but instead during the late part of the interglacial stages, it is well illustrated for MIS 11, 9, and 7!) . Obviously, the silt/clay ratio did not respond linearly to sea level oscillations and reactivation of continental shelf erosive processes could be also related to some environmental threshold, e.g. the volume of water stored on the shelf. This, together with significant reductions of SRs during each sea level rise, and subsequent reductions in time resolution, prevent us to use the silt/clay ratio as an exact indicator of the beginning of sea level rises. However, the persistent (?????) pattern observed in the silt/clay ratio through the last five glacial/interglacial cycles (It would be difficult to convince the reader for the interglacials other than MIS 5!) and also at millennial time scales, as described below, confirms this ratio is a good indicator of relative high sea level conditions (highstands) in the GoL margin (again this conclusion is not strengthened by the interglacials 7, 9, and 11, only for interglacial 5; this conclusion is not supported by figure 3).

These results support a shelf and upper slope depositional model for inter-canyon RPU stacking over the last 500 ka that considers two main processes: (i) oscillations in sediment supply due to the migration of river mouths and deltaic systems and, (ii) activation-deactivation of continental shelf erosive processes like DSWC, both of them ultimately driven by the 100-kyr glacio-eustatic cycle (Fig. 4). (this conceptual model looks too simplistic in particular when only two end members lowstand and higstand scenarios are considered, and transition intervals of time, deglaciation – sea level fall, are not included)

4.2 The millennial MIS 3 sea level imprint

Since this combined (? Why combined) depositional model has been ~~working~~ tested at glacial/interglacial scales, it is reasonable to expect that minor scale sea level oscillations would also result ~~in some sort of~~ in similar sedimentary signature in the GoL margin outbuilding ~~too~~. Taking into account the passive character of the margin, the flatness and width of the GoL shelf, and the robust chronostratigrafic frame for the last glacial cycle (i.e. excellent synchronization between the PRGL1-4 *G. bulloides* δ^{18}O record and the NGRIP ice core record (yes this is quite surprising!) , Fig. 5a and B) due to elevated SRs (ranging from 0.2 to 2 m kyr^{-1}), the PRGL1-4 record could be highly valuable to disentangle the millennial scale sea level variability during MIS 3. Independently of chronologies, the exhaustive compilation of MIS 3 sea level reconstructions by Siddall et al. (2008) shows two common patterns of variability: (1) the mean sea level during the first half of MIS 3 was approximately 20 m higher than in the second half, and (2) four 20–30 m- ~~in~~ amplitude millennial-scale sea level fluctuations occurred during this period (Fig. 5e). These features are also observed in the PRGL1-4 silt/clay record (Fig. 5c)(It is quite impressive, one would agree), thereby demonstrating that the GoL system responded to both long and short-term sea level fluctuations during MIS 3. (One would make the point first with the short term sea level fluctuations when those are really well established, and then extend the model to longer term sea level fluctuations when sea level is most likely not well established in particular in the glacial/interglacial cycle older than MIS5-4-3-2-1)

The general decreasing trend observed in the PRGL1-4 silt/clay ratio during the progressive sea level lowering of the last glacial cycle (Fig. 3), is punctuated by a series of grain-size increases (are you referring to the total fine sand % in Fig. 5?), which suggest that millennial-scale relative sea level rises

occurred during MIS 3 (Fig. 5c). By temporally extending the flooded area of the GoL shelf, MIS 3 relative sea level rises reduced the clay supply to the upper slope and contributed to expose a larger volume of water to atmospheric forcing, eventually leading to DSWC and hence indirectly reinforcing the transport of coarse particles to the upper slope. Both mechanisms contributed to increases in the silt/clay ratio (Fig. 5c). Those grain-size increases are unrelated to periods of intensification of deep-water formation in the GoL since most of them occurred during relatively warm Greenland interstadials (GIS) (Fig. 5c, b), in contrast with observations of enhanced Western Mediterranean Deep Water (WMDW) formation during MIS 3 cold Greenland Stadials (GS) (Cacho et al., 2000, 2006; Frigola et al., 2008; Sierro et al., 2005).

Confirming or discarding the occurrence of sea level oscillations at Dansgaard-Oeschger (D/O) scale has been prevented so far because none of the existing sea level records was able to resolve variations lower than 12m in amplitude during time intervals as short as 1 kyr (Siddall et al., 2008). Nevertheless, prominent increases in iceberg calving during cold Greenland stadials (GS) (non Heinrich events, HE) suggest that sea level should have oscillated within each D-O cycle (Bond and Lotti, 1995; Chappell, 2002; Siddall et al., 2008; van Kreveld et al., 2000). Disentangling MIS 3 sea level variability also faces the difficulty to establish the absolute timing of the observed oscillations, which is necessary to understand the role of sea level in millennial-scale climate variability during MIS 3 and to determine the relative contribution of "northern" versus "southern" sources (Clark et al., 2007).

Early evidence of millennial-scale sea level variability were obtained from the benthic δ^{18}O record of Portuguese margin core MD95-2042 (Shackleton et al., 2000), that although may be influenced by oscillations in deep ocean temperature and local hydrographic variability an important part of the record is linked to global sea level change (Skinner et al., 2007), and sea level reconstruction from the Red Sea (Siddall et al., 2003) (Fig. 5e). Since both records display a variability pattern remarkably similar to the one found in Antarctic ice cores (Fig. 5g), it has been suggested that MIS 3 sea level oscillations followed Antarctic climate variability (Rohling et al., 2008; Siddall et al., 2003). Contrary to these interpretations, recent results from the Red Sea and the GoL have shown millennial-scale sea level rises to occur during major warm Greenland interstadials (GIS) (Fig. 5f and d) (Arz et al., 2007; Jouet et al., 2011; Sierro et al., 2009), further highlighting the still high uncertainty about the timing of MIS 3 sea level variability.

The co-occurrence of silt/clay increases and planktic δ^{18}O depletions in the PRGL1-4 record (Fig. 5c,b) imply, independently of the age model applied, that relative high sea levels occurred during warm GIS events (It is interesting that these excellent correlation between silt/clay increases and planktic δ^{18}O depletions are observed when sea level was systematicly below 60 m, resulting in a shelf width at least 2/3 of the modern one. This should have modified the hydrodynamic conditions on MIS continental shelf/) . Concurrently, Shackleton et al. (2000) and Siddall et al. (2003) records also show maximum sea levels to occur during the onset phase of major GIS interstadials (i.e. GIS14, 12 and 8) (Fig. 5e). However, discrepancies on the precise time of the sea level rises exist with our PRGL1-4 record. The excellent time constrain provided by the *G. bulloides* δ^{18}O record of the PRGL1-4 borehole demonstrates a perfect peak to peak coupling between sea level variability (as indicated by increases in the silt/clay ratio) and all D-O cycles, including the shortest ones. Nevertheless, not every relative high sea level resulted in the formation of CLs since these were only observed during major GIS (16, 14, 12, 8 and 7) (Sierro et al., 2009), all of which coincide with higher values of the silt/clay ratio (Fig. 5d,c). The differences between the total fine sand record of Sierro et al. (2009) and our silt/clay ratio indicate that sea level increases during minor GIS (15, 13, 11, 10, 9, 6, 5, 4 and 3) were likely not high and/or long enough to generate CLs, therefore demonstrating once more the strong sensitivity of the silt/clay ratio to sea level oscillations.

A limitation of the PRGL1-4 silt/clay record is that the amplitude of sea level variations cannot be directly derived as nowhere is proven that grain-size oscillations respond linearly to sea level fluctuations. This very same limitation, and reduction of PRGL1-4 time resolution due to decreasing SRs with sea level increases, also prevents setting up the precise timing of sea level rises whether they occurred at the beginning of each warm GIS or during the previous cold stadial. This relates to the exact time of deltaic migration and their relative position following sea level rise. In addition, the enhanced supply of coarse particles by reactivation of continental shelf erosive processes, such as DSWC, should normally occur some time after the start of each sea level rise, i.e. when the volume of water over the shelf is again large enough.

Our results imply that sea level was relatively high during all warm GIS within MIS 3 (Fig. 5c,a), although intrinsic limitations of the methodology applied in this study do not allow establishing the precise time nor the mechanism of such millennial scale sea level rises, which could initiate by instabilities and melting of continental ice-sheets during cold GS, whether or not they correspond to HEs.

5 Conclusions

The last 500 ka continuous sediment record of the 300m long PRGL1-4 borehole drilled in the upper slope of the river fed GoL holds the imprint of sea level oscillations at orbital (only clear in the last full glacial cycle or last 150ky) and millennial time (yes) scales during MIS-3. The sedimentary succession of PRGL1-4 consists of five regressive progradational (it is more aggradational on the upper slope) units that relate to the glacio-eustatic 100-kyr cyclicity. The consistent chronostratigraphy of the investigated section (the bulloides 18-O record appear easy to interpret down to MIS-7, further back in time one would have some doubts that the record is representing a continuous record. Even MIS stages 7/6 the bulloides record has some issues in particular how to explain the lightest 18-O during the beginning of MIS-6? Other time markers would need to be used to anchor the correlation between the bulloides 18-O record and the Lisiecki and Raymo, 2005, record –the Specmac stack should not be used anymore) and the ~~perfect~~ matching between seismic reflection profiles and the grain-size record (in no place in the manuscript one sees how the depth in the borehole has been converted in time in the seismic lines, in Figure 2 the correlations appears only as visual correlations, is it true?) provide clues to understand the nature of seismic reflections in mud-dominated slope sequences like the ones found at the investigated site and also provides a tool to identify and precisely (again avoid such adverb) locate the boundaries of seismostratigraphic units while helping to tie them with global sea level oscillations. This resulted in a reinterpretation of the stratigraphy of the upper slope in the GoL following an approach that can be extended to similar continental margin settings. (one would like to argue that only the last glacial-interglacial cycle – 150 ky is convincing)

In addition of pushing the shoreline and associated sedimentary environments landwards, thus disconnecting the upper slope from direct riverine sediment sources, we have demonstrated (it was discussed but never demonstrated!)that sea level rise can reactivate transient energetic hydrosedimentary processes, such as DSWC, which are able of eroding, resuspending and transporting large (? It is a time of condense sections) volumes of sediment from the continental shelf and upper slope to the deep basin. The sedimentary starvation of the upper slope during highstands, jointly with both episodic and persistent hydrodynamic processes winnowing the fine fraction,

determined the formation of CLs that mark the periods of continental shelf flooding during interglacial epochs, as evidenced by our grain-size records.

Finally, the excellent match of the PRGL1-4 silt/clay record with previous records of sea level variability at millennial-scale during MIS 3, together with the good time constrain provided by the *G. bulloides* $\delta^{18}O$ record, strongly support the occurrence of relatively high sea levels during each single warm GIS, even the smallest ones. This (MIS-3) very concincing part of the record is perhaps triggered by the fact that sea level was oscillated between minus 60 and 80 m, when the continental shelf was not fully exposed as during MIS-2, and its width decreased by at least one third and its water depth by 50 % relative to MIS-5, Unfortunately, the precise starting time of sea level rises cannot be established solely from the sediment record of the upper slope GoL, which points to the need of further devoted research to resolve the origin and magnitude of MIS 3 sea level variability.

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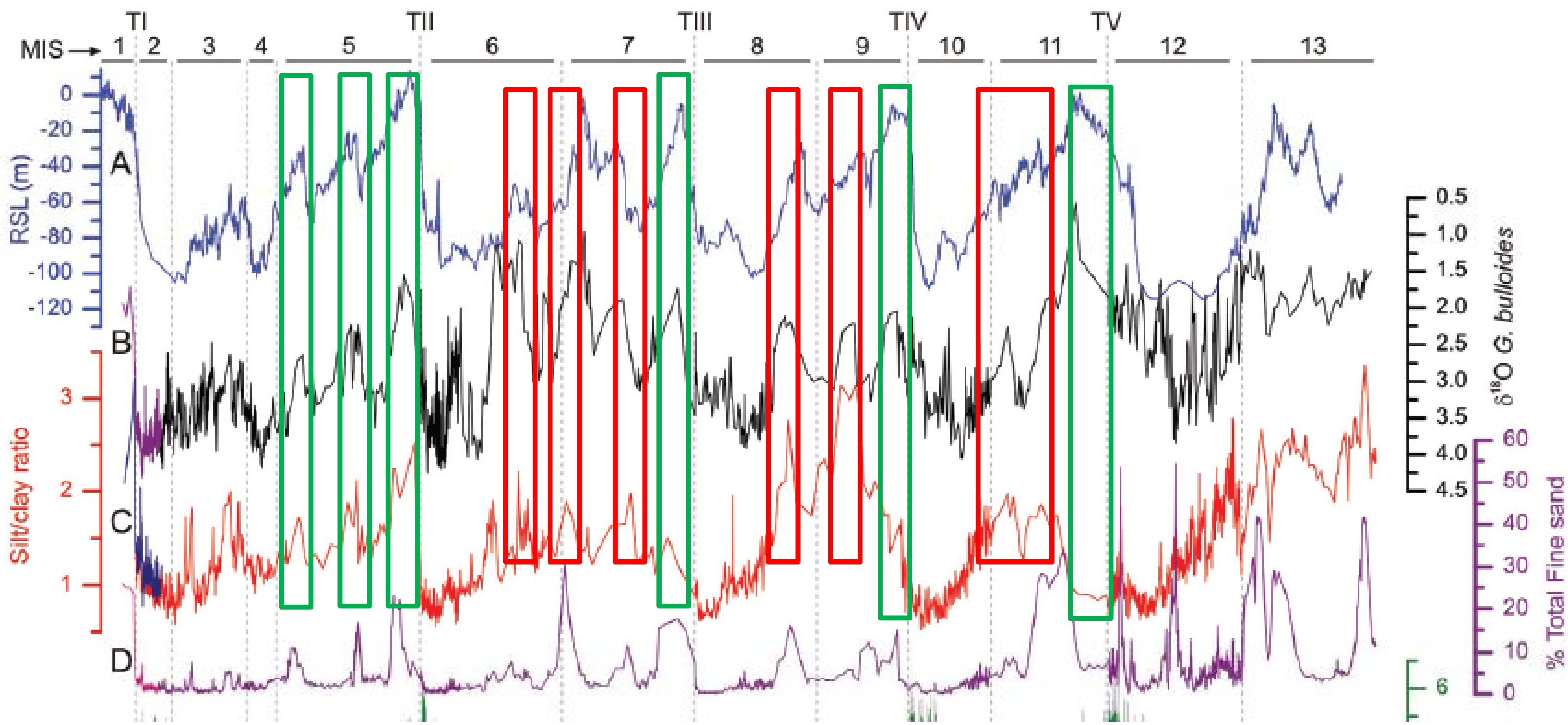
TI
TII
TIII
TIV
TV
MIS →
1
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3
4
5
6
7
8
9
10
11
12
13
A
B
C
D
RSL (m)
0
-20
-40
-60
-80
-100
-120
Silt/clay ratio
3
2
1
δ18O G. bulloides
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
% Total Fine sand
60
50
40
30
20
10
0
6