Response to "Comment to "*The transition on North America from the warm humid Pliocene to the glaciated Quaternary traced by eolian dust deposition at a benchmark North Atlantic Ocean drill site*, by David Lang et al. Quaternary Science Reviews 93: 125-141""

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1. Introduction

In volume 93 of Quaternary Science Reviews we published a new record of terrigenous inputs to Integrated Ocean Drilling Program (IODP) Site U1313 that tracks the history of aeolian dust deposition in the North Atlantic Ocean and aridity on North America during the late Pliocene-earliest Pleistocene intensification of northern hemisphere glaciation (iNHG, 3.3 to 2.4 Ma). Naafs et al. (2014) are generally supportive but question one of our conclusions, specifically our argument that "*glacial grinding and transport of fine grained sediments to mid latitude outwash plains is not the fundamental mechanism controlling the magnitude of the flux of higher plant leaf waxes from North America to Site U1313 during iNHG."* They suggest that our argument "is predominantly based on our observation that the relationship between sediment lightness (L*)-based terrigenous inputs and dust-derived biomarkers, which is observed to be linear elsewhere (Martínez-Garcia et al., 2011), is non-linear at Site U1313."

We welcome their interest and the opportunity to clarify one or two misunderstandings. Contrary to their impression, our argument that the role of glacial grinding is not the principle driver of increased North American aeolian dust flux to the mid latitude North Atlantic during iNHG is based mainly on our radiogenic isotope provenance data (not on the non-linear relationship between biomarker and terrigenous dust inputs). Our provenance data indicate a North American source for this dust (~3.3 to 2.4 Ma) in keeping with the interpretation of the biomarker data. Crucially, however, all of our data point to a mid-latitude provenance regardless of (inter)glacial state. This finding is inconsistent with the Naafs et al. (2012; 2014) interpretation of the importance of glacial grinding and transport to mid latitude outwash plains for deflation because of the radically changing latitudinal extent of continental ice on North America throughout this this 900 kyr-long interval. Nevertheless, below we critically reassess this 'non-linearity' issue in light of Naafs et al. (2014) making available some of the XRF data from Site U1313 and then explain why the evidence presented in Lang et al. (2014) supports our original conclusions.

2. Non-linearity between dust biomarkers and terrigenous inputs at Site U1313.

As highlighted in Lang et al. (2014), our desire to generate an orbital-resolution record of terrigenous inputs to Site U1313 by calibrating a high resolution record of L* with discrete measurements of percent calcium carbonate (%$CaCO_3$) was driven by: 1) the pioneering work on Deep Sea Drilling Project Site 607 on the observed relationship between variations in %$CaCO_3$ and Neogene climate (Ruddiman et al.,

1987) and 2) observations of the IODP Expedition 306 Scientists (2006), specifically those of Jens Grützner who correlated variations in L* at Site U1313 to the LR04 global benthic $\delta^{18}O$ stack for the past 3.3 Ma on board the JOIDES *Resolution*, during IODP Exp. 306 (an expedition in which one of us (IB) participated and contributed to the team effort to generate this remarkable sediment colour record).

Having demonstrated that variations in %$CaCO_3$ at Site U1313 are not driven by dissolution (as originally hypothesized by Ruddiman et al., 1989), Lang et al. (2014) used the relationship found between discrete measurements of %$CaCO_3$ and the higher resolution shipboard L* record (Fig. 3 of Lang et al. (2014)) to generate a proxy record of terrigenous inputs in the interval for which a high quality independent age model exists (3.3 to 2.4 Ma, Bolton et al. (2010)). Naafs et al. (2014) suggest that this L*-derived record of terrigenous inputs is “biased” for two reasons: (i) because our choice of a linear calibration equation results in an overestimation of %$CaCO_3$ from the L* record and therefore an underestimation of terrigenous content for key glacials such as marine isotope stage (MIS) 100 (2.52 Ma) and, (ii) because the non-carbonate fraction at Site U1313 does not only reflect variations in aeolian dust inputs. Instead, they use a scanning XRF-derived record of elemental Fe intensity data to re-assess the relationship between dust biomarker and terrigenous inputs asserting that the XRF record represents “a pure terrigenous signal in the absence of a large input of ice-rafted debris (IRD).”

Both the L*-to-$CaCO_3$ and XRF-Fe count datasets, used as proxies for aeolian dust, are subject to the same potential sources of ‘contamination’ (e.g., from diagenetically derived iron sulphides, volcanic ash or IRD in the clay through sand-sized sediment fractions). As originally noted in Lang et al. (2014), factors in addition to variations in $CaCO_3$ content can lead to changes in L* (Balsam et al. 1999) and similar issues arise with the use of XRF records. Specifically we caution against use of XRF elemental intensity data that are either not converted to dimensionless units or to percent Fe data. The absolute values of XRF-derived elemental intensity data can be strongly influenced by sediment inhomogeneity (e.g., variations in sediment water content, grain-size distribution and irregularities in the split core surface) (Weltje and Tjallingii, 2008). We would welcome publication of data series of the natural logarithms of Fe/Ca and Ti/Ca derived from the XRF data that were obtained when the Site U1313 cores were scanned because a log-ratio calibration model provides a more reliable prediction of sediment element concentrations from XRF core-scanner output than that derived from elemental intensities alone (Weltje and Tjallingii, 2008).

Regardless, it is perhaps useful to re-emphasize an observation that we stressed in Lang et al. (2014): Non-linearity in the relation between the biomarker record and our terrigenous record cannot be explained by 'contamination' of the terrigenous fraction at Site U1313 by contributions invoked from sources other than dust (e.g. from IRD and volcanism as documented for MIS 100 by Bolton et al., 2010). This is because additional terrigenous inputs would act to amplify the terrigenous rather than the biomarker record during glaciations and IRD and volcanic accumulation rates are always higher in glacials than in interglacials. Thus, there is no way to explain amplification of the glacial values in the biomarker record (relative to the terrigenous fraction) by invoking decreases in IRD and/or volcanic inputs while a linear relation is maintained between biomarker and lithogenic dust. In other words, some mechanism (increased export/burial efficiency of biomarkers or vegetation biome shifts) must act to amplify the glacial jumps in the biomarker record relative to those in the terrigenous record.

Naafs et al. (2014) raise concern over the fact that the linear equation used by Lang et al. (2014) to produce a high resolution record of %$CaCO_3$ from the Site U1313 L* record underestimates the abundance of the terrigenous sedimentary component (%terrigenous) deposited at this site during MIS 100 by up to 6.8%. MIS 100 is a key glacial in this context because Lang et al. (2014) suggest that it is characterised by one of the most pronounced amplifications of biomarker content relative to terrigenous content during iNHG. We agree that it is not possible to determine via regression analysis whether a cross plot of %terrigenous (derived from our discrete $CaCO_3$ data) and biomarker abundance for our iNHG study interval exhibits non-linearity. But the question is whether or not we see non-linearity or amplification in the contribution of biomarkers to terrigenous content at Site U1313 *during certain glacials* (rather than for the full population of discrete %terrigenous data, n = 119 over ~5.3-2.4 Ma) and that question is not best addressed by simple cross plots. This is why we sought to assess the evolution of non-linearity between these two parameters in the time series presented in Fig. 10 of Lang et al. (2014). Ratios of *n*-alkane abundance to the fractional percentage of the terrigenous component from Site U1313 (i.e. nannograms of biomarkers per gram of terrigenous sediment), with full error propagation, derived from our original discrete %terrigenous dataset and from a new higher resolution record of $CaCO_3$ for MIS G7-99 (n = 102, every 10 cm) from the secondary splice (118.65-130.8 mcd) show that amplification of biomarker inputs relative to terrigenous deposition (i.e., a non-linear relationship) is real for MIS 100 and other big glacials from 2.7 Ma onwards (Fig. 1). In fact, a similar result is also obtained for iNHG in the time domain when the biomarker data are compared to the XRF-derived Fe (albeit elemental intensity) data of Naafs et al. (2014).

3. The importance of non-glaciogenic versus glacial grinding mechanisms of dust generation for terrigenous deposition at Site U1313 during iNHG

Naafs et al. (2012; 2014) argue that the sharp increase in the deposition of aeolian dust biomarkers at Site U1313 from 2.72 Ma is related to an increase in the availability of dust for deflation on North America due to expansion of glacial outwash plains south of a North American Ice Sheet during MIS G6. This mechanism was plausible based on the evidence available to Naafs et al. (2012) but, as explained in Lang et al. (2014), it is inconsistent with the uniformly mid latitude provenance of the terrigenous material at Site U1313 throughout iNHG (regardless of glacial-interglacial state) and the failure of North American ice sheets to advance into the mid-latitudes by G6 (and probably not until MIS 100, Fig. 2).

In Lang et al. (2014) we noted that, in the absence of significant NHG prior to MIS G6 (Kleiven et al., 2002), the large fluxes that we observe for terrigenous deposition at Site U1313 prior to 2.7 Ma indicate that non-glaciogenic mechanisms of aeolian dust generation represent important sources of terrigenous sediment for our study site. We also demonstrated that the terrigenous component deposited at Site U1313 throughout iNHG has a definitive (non-volcanic) mid-latitude origin independent of (inter)glacial state and, critically, that the provenance of this sediment does not change across the onset of significant NHG, ~2.7 Ma. These observations suggest that the dominant sources of dust deposited at our study site, and the mechanisms responsible for its generation on North America, remained unchanged across 2.7 Ma despite the big glacial increases in both the L*- and biomarker-derived records of dust accumulation at Site U1313 across this interval.

Our provenance data show that if glacial outwash plains on North America were the dominant source of aeolian dust deposited at Site U1313 from ~2.7 Ma, a large proportion of the subglacial erosion responsible for generating this material would have been required to take place in the mid latitudes of North America[1]. Yet, this requirement is at odds with important lines of evidence (including one of those used by Naafs et al. (2014)). Comparison of the history of biomarker accumulation at Site U1313 with the reconstructions of glacial extent on North America from observation-constrained inverse ice-ocean modelling (de Boer et al., 2014) (Fig. 2) and diverse geological lines of evidence (Brigham-Grette et al., 2013; Balco and Rovey, 2010; Bailey et al., 2013; Hennissen et al., 2014) indicates that, although late Pleistocene-magnitude glacial fluxes in biomarkers are established at Site U1313 during MIS G6, glacial expansion on North America around 2.7 Ma was modest (Fig. 2). Results from the inverse ice-ocean modeling reconstruct small (~12 of sea-level equivalent ice volume) ice caps restricted to Alaska and the high latitudes of Canada (mainly centred on Hudson Bay; http://www.staff.science.uu.nl/~boer0160/data_anice_5myr/) where they would have been emplaced on predominantly Archaean bedrock having a much more extreme unradiogenic isotope composition than the terrestrial material accumulating at Site U1313 (Lang et al., 2014). These observations raise a serious question mark over the plausibility of glacial grinding as the mechanism responsible for the order of magnitude increase in biomarker deposition ~2.7 Ma.

4. Conclusions

[1]As was the case for the Last Glacial, which is why North American terrestrial loess deposits are isotopically similar to the signature of mid-latitude North American geologic terranes (Aleinikoff et al., 1999; Lang et al., 2014).

In keeping with the previous work of three of us (IB, GLF, PAW, e.g., Bailey et al. (2013)), we did not suggest in Lang et al. (2014) that North America remained unglaciated during MIS G6, 2.7 Ma. We maintain, however, that the indirect impact of ice-sheet growth on aridity, vegetation and westerly wind strength south of the North American ice sheet (the “non-glaciogenic” mechanisms) played a far greater role in controlling the magnitude of North America dust delivery to the mid latitude North Atlantic Ocean during iNHG than the direct contribution of glacial grinding.

5. Acknowledgements

We thank David Naafs for making available the secondary splice XRF Fe data for Site U1313 and David Hodell for access, at short notice, to his LECO carbon analyser at the Godwin Laboratory, Cambridge University to permit generation of additional $CaCO_3$ data from the secondary splice at Site U1313 (data available on the on-line Pangaea database).

6. References

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7. Figure captions

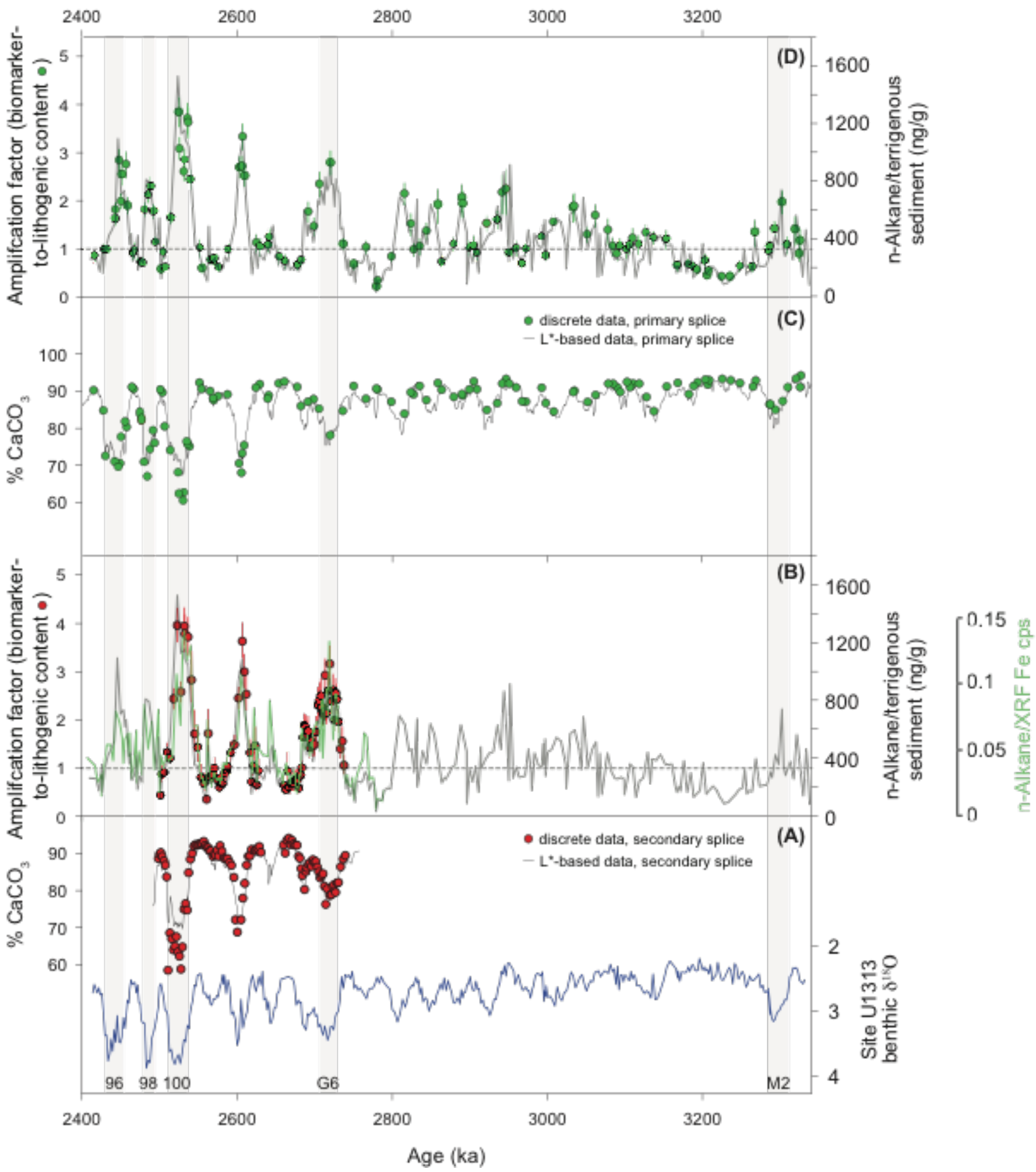

Fig. 1. New (this study) and published data sets (Lang et al., 2014 and Naafs et al., 2012) from IODP Site U1313. Estimates of %$CaCO_3$ (**A** & **C**) and the ratio of the abundance of the long-chain odd *n*-alkane (Naafs et al., 2012) and the terrigenous sediment component in Site U1313 sediments (**B** & **D**). Also shown is time series of ratio of the abundance of n-alkanes (from primary splice) and XRF Fe counts per second, cps, (from secondary splice; Naafs et al. (2014)) after converting secondary splice composite depths assigned to the XRF Fe data to primary splice composite depths. Grey time series of %$CaCO_3$ in A & C derived from sediment lightness (L*) data from the Site U1313 primary splice estimated using a linear equation from Lang et al. (2014). Red %$CaCO_3$ data in A is new (this study).

Green %$CaCO_3$ data in C is from Lang et al. (2014). Terrigenous abundance data used to generate ratio time series in B & D estimated using inverse fractional percentage (i.e. grams of terrigenous sediment per gram of bulk sediment) of the L*-based proxy record of %$CaCO_3$ shown in A and C and of discrete measurements of %$CaCO_3$ from both the secondary and primary splices also shown in A and C. Vertical bars centred on red and green data in B & D represent propagated error (95% confidence interval) based on individual external uncertainties reported for the discrete %$CaCO_3$ (based on replicate measurements of a pure carbonate standard (±1.4 wt.% (Lang et al., 2014), and ±1.9 wt.%, this study) and *n*-alkane measurements (7%, Martinez-Garcia et al., 2011). Amplification factors shown in B & D represent normalisation of n-alkane/discrete %terrigenous ratio data by average ratio for the Piacenzian PRISM time-slab (defined as 3.025–3.264 Ma) in our primary splice discrete %terrigenous-derived ratio dataset. For consistency with Naafs et al. (2014) we linearly interpolate data for the higher resolution records of the two datasets used to calculate the ratios shown in B & D so that they match the resolution and specific ages of the data from the lower resolution records used. In B the lower resolution record used to calculate all three ratio time series shown is the n-alkane abundance data. Prior to assigning ages to our new %terrigenous data from the secondary splice (red data points in A) the composite depths assigned to this record were converted to primary splice depths by manual graphical correlation of Site U1313 primary and secondary splice L* records (tie points available on Pangaea online database). For reference, also shown in A is Site U1313 benthic foraminiferal calcite $\delta^{18}O$ data (Bolton et al., 2010). Vertical grey bars and labels denote key marine isotope stages. All data plotted on the age model of Bolton et al. (2010).

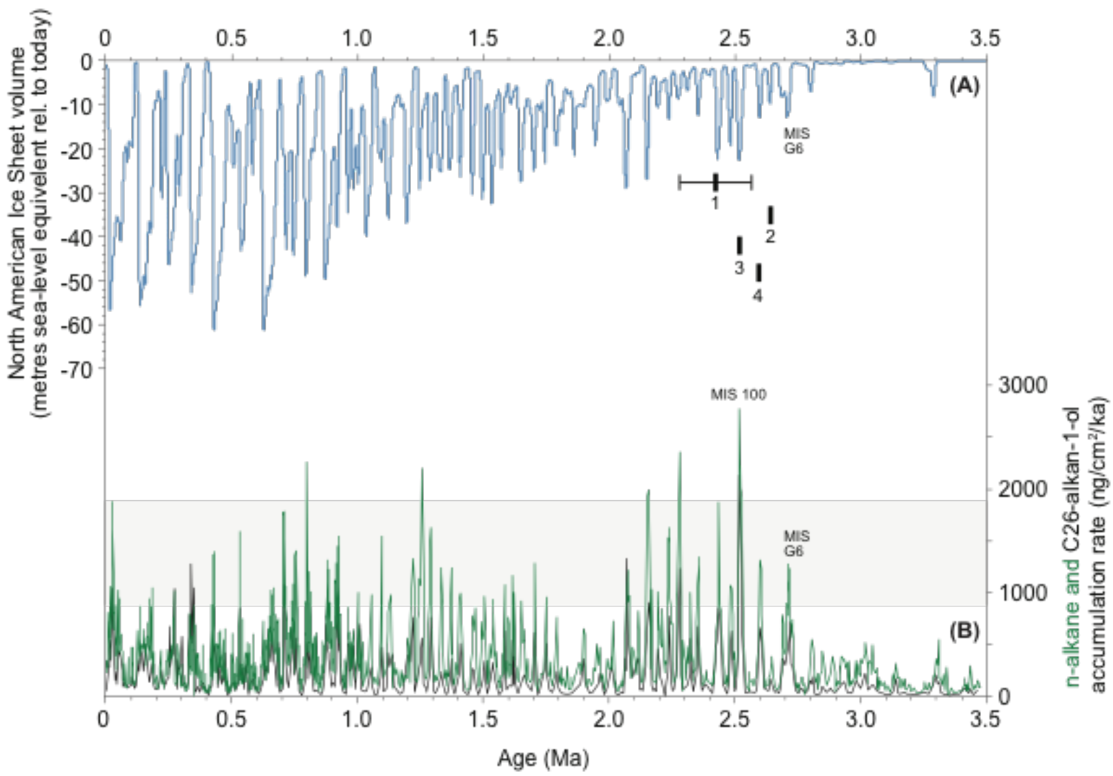

Fig. 2. Relationship between simulated North American Ice Sheet extent (de Boer et al., 2014) (**A**) and dust biomarker deposition at Site U1313 **(B)** (Naafs et al., 2012) for the past 3.5 Myr shows that, although late Pleistocene-magnitude glacial fluxes in dust biomarkers are established at Site U1313 during MIS G6, glacial expansion on North America around 2.7 Ma was modest and did not extend into the mid latitudes at this time. Horizontal grey bar in B denotes range of n-alkane accumulation rates associated with large-magnitude North American glacial episodes of the past ~700 kyr. 1 = timing of oldest evidence for mid-latitude glaciation of North America in the form of cosmogenic-nuclide dated glacial tills at 39˚N in Missouri, USA at 2.41 ± 0.14 Ma (Balco and Rovey, 2010). 2 = Onset of North American-sourced IRD deposition in the open North Atlantic Ocean (Bailey et al., 2013). 3 = First time that Arctic air temperatures tend towards Last Glacial Maximum values (Brigham-Grette et al., 2013). 4 = First excursion of the polar front in the glacial North Atlantic Ocean south of ~53˚N (Hennissen et al., 2014). MIS = marine isotope stages. All data plotted on published age models derived from the LR04 global benthic stack.