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Re-evaluation of the age model for North Atlantic Ocean Site 982 – arguments for a return to the original chronology

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Abstract. Recently, the veracity of the published chronology for the Pliocene section of North Atlantic Ocean Drilling Program Site 982 was called into question. Here, we examine the robustness of the original age model as well as the proposed age model revision. The proposed revision is predicated on an apparent misidentification of the depth to the Gauss–Matuyama (G/M) polarity chronozone reversal boundary (2.581 Ma) based on preliminary shipboard paleomagnetic data, and offers a new chronology that includes a hiatus between ~ 3.2 and 3 Ma. However, an even more accurate shore-based, u-channel-derived polarity chronozone stratigraphy for the past ~ 2.7 Ma supports the shipboard composite stratigraphy and demonstrates that the original estimate of the depth of the G/M reversal in the Site 982 record is correct. Thus, the main justification forwarded to support the revised chronology no longer exists. We demonstrate that the proposed revision results in a pronounced anomaly in sedimentation rates proximal to the proposed hiatus, erroneous assignment of marine-isotope stages in the Site 982 Pliocene benthic stable oxygen isotope stratigraphy, and a markedly worse correlation of proxy records between this site and other regional paleoclimate data. We conclude that the original chronology for Site 982 is a far more accurate age model than that which arises from the published revision. We strongly recommend the use of the original chronology for all future work at Site 982.

1 Introduction

Ocean Drilling Program (ODP) Site 982 was drilled on the Rockall Plateau in the subpolar North Atlantic Ocean (58° N, 16° W, at 1134 m water depth) during Leg 162 (Fig. 1). Sediments recovered from Site 982 have been used to generate numerous paleoclimate data sets that have made important contributions to our understanding of past oceanic and climatic changes centered on the North Atlantic region (e.g., Bartoli et al., 2011; Bolton et al., 2011; Lawrence et al., 2009, 2010; Naafs et al., 2012; Pagani et al., 2009; Sosdian and Rosenthal, 2009; Venz and Hodell, 2002; Venz et al., 1999). Recently, Khelifi et al. (2012) have questioned the veracity of the age model for Site 982 that forms the cornerstone of these works. The original age model for Site 982 was published in the initial results volume for ODP Leg 162 (Shipboard Scientific Party, 1996). This age model was refined by Venz and Hodell (2002) and Venz et al. (1999) using oxygen isotope stratigraphy and later minimally adjusted, first by Channell and Guyodo (2004) based on new paleomagnetic data, and later when it was incorporated as one of the records in the global benthic LR04 $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005) (Fig. 2a). We subsequently collectively refer to these chronologies, which are negligibly different for the Plio-Pleistocene, as the “original age model”. Here, we explore the validity of both the original age model and the revisions to it proposed by Khelifi et al. (2012) in their Technical Comment to Climate of the Past (Fig. 2a). To this end, we consider the original shipboard Site 982 physical properties data used to develop the 982 composite splice, the Site 982

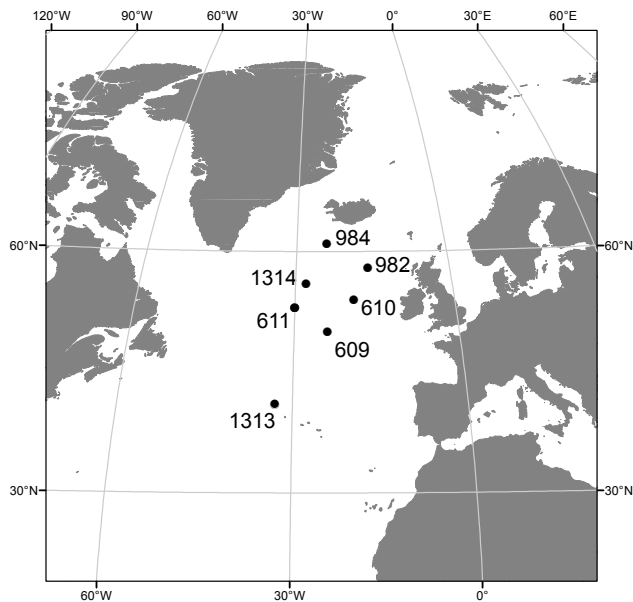


Fig. 1. Site map showing the location of ODP Site 982, as well as other relevant North Atlantic sites.

composite splice itself, subsequently generated shore-based u-channel paleomagnetic data (Channell and Guyodo, 2004), and all available Site 982 benthic oxygen isotope ($\delta^{18}\text{O}$) data. We also examine how the paleoclimate data generated from these sites compare to similar records developed from sediments at other localities in the North Atlantic Ocean. In this note, we focus on the disputed interval that falls between 50 and 85 m composite depth (mcd). As detailed below, this evaluation strongly supports the veracity of the original Pliocene Site 982 age model.

2 Splices and age models

2.1 Original splice and age model

A composite section for Site 982 was generated down to 597 mcd shipboard by splicing together spectral reflectance and GRAPE data that for the Pliocene portion of this record come from holes A and B (Fig. 3). Various age models have been assigned to this stratigraphy by correlation of its benthic $\delta^{18}\text{O}$ for the past ~ 2.7 Ma to ODP Sites 677 (Channell and Guyodo, 2004; Venz et al., 1999), 846 (Channell and Guyodo, 2004) and 849 (Flower et al., 2000), for the past 3.2 Ma to Deep Sea Drilling Project (DSDP) Site 607 (Venz and Hodell, 2002), and most recently for the past 5.3 Ma to the LR04 stack, following generation of additional $\delta^{18}\text{O}$ data between 68.09 and 160.62 mcd (Lisiecki and Raymo, 2005). The age model assigned to alkenone-derived sea surface temperature (SST) data from Site 982 presented in Lawrence et al. (2009) is the same one assigned to Site 982 during its incorporation into the LR04 stack (Lisiecki and Raymo, 2005).

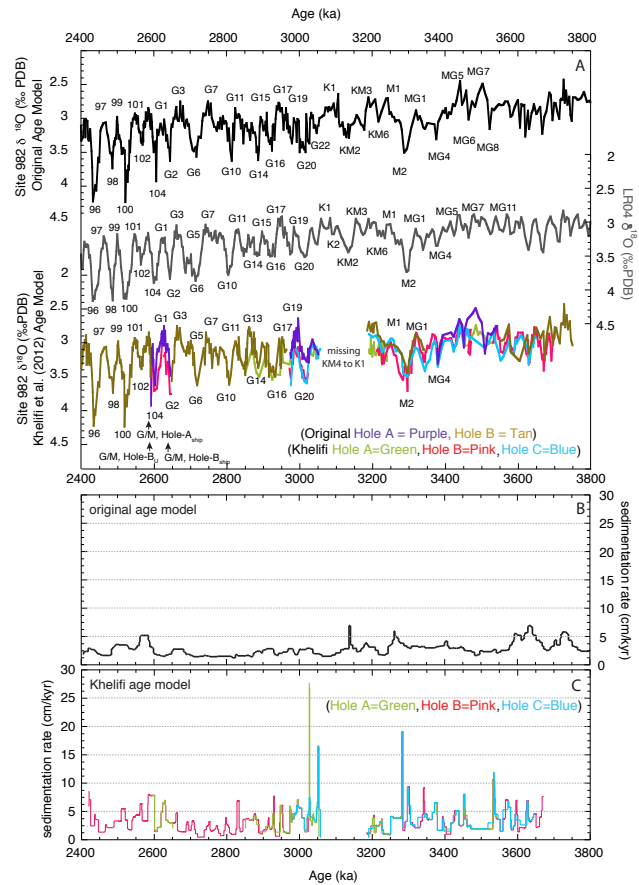


Fig. 2. ODP Site 982 isotopes and sedimentation rates: (A) oxygen isotopes from ODP 982 (Lisiecki and Raymo, 2005; Venz and Hodell, 2002) plotted on the original age model (black) and both the original and Khelifi et al. (2012) isotopes on rmcd_s of Khelifi et al. (2012) (colors) with associated correlations of both age models with the LR04 oxygen isotope benthic stack (gray) (Lisiecki and Raymo, 2005); (B) sedimentation rates at Site 982 estimated from the original age model (black); (C) sedimentation rates for holes A, B and C estimated from the age model proposed by Khelifi et al. (2012) (colors). Small black arrows and associated labels – lower left-hand corner of (A) – indicate the position of the Gauss–Matuyama chronozone reversal boundary from both shipboard and u-channel measurements.

2.2 Khelifi splice and age model

Guided by new benthic foraminiferal $\delta^{18}\text{O}$ data and $U^{K'}$ SSTs generated on holes A–C, Khelifi et al. (2012) revised the shipboard-derived composite depths between 59.1 and 84.44 mcd to 59.17 and 85 mcd (hereafter referred to as suggested revised mcd, rmcd_s), based on 194 new tie points (contrast with the four tie points used in the shipboard stratigraphy). Khelifi et al. (2012) justify the generation of the rmcd_s on the basis that, between 55 and 72 mcd, the shipboard-derived physical properties data are not characterized by oscillations from which reliable correlations can

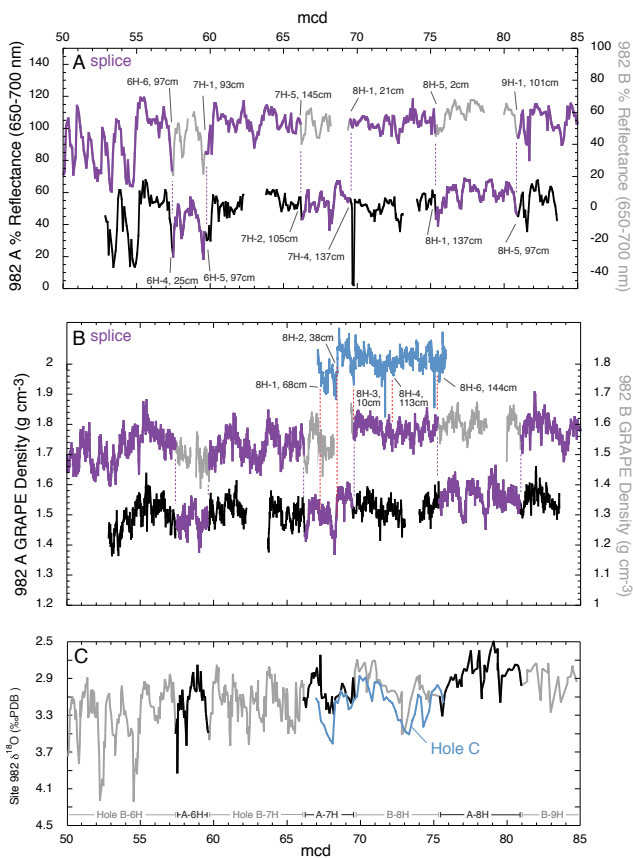


Fig. 3. Site 982 physical properties and benthic oxygen isotope data: (A) shipboard reflectance, (B) shipboard GRAPE density and (C) benthic $\delta^{18}\text{O}$ data for Site 982 holes A, B and C (black, gray and blue data, respectively) and the original shipboard splice (purple data) for the interval of the Site 982 age model in question (Shipboard Scientific Party, 1996). Black labels indicate the samples at core breaks. Dashed vertical purple lines (and labels) denote tie points used to generate the shipboard splice. Dashed vertical red lines (and labels) denote tie points used to tune Hole C GRAPE data to the GRAPE data used to generate the original splice (from Hole A/B). The splice point at Hole A-8H-1, 21 cm (69.55 mcd), is arguably the least secure tie between holes A and B in the original splice. The Hole C GRAPE data highlight, however, that no stratigraphy is missing from the original shipboard splice due to the inclusion of the tie point at 69.55 mcd. Note, no reflectance data was generated for cores 7H-9H in Hole C (Ortiz et al., 1999).

be made (i.e., data drops to background noise). Yet, inspection of the data used to generate the original mcd indicates that this is not the case (Fig. 3). Plots of the composite benthic $\delta^{18}\text{O}$ records on both splices are slightly different in the depth domain (Fig. 4). The expanded nature of rmcd_s relative to mcd reflects the very large number of tie points used by Khelifi et al. (2012), which is also responsible for the “better correlation” of $\delta^{18}\text{O}$ between holes in their Fig. 1. Specifically, they have effectively aligned all benthic $\delta^{18}\text{O}$ on the orbital scale between the original shipboard tie points.

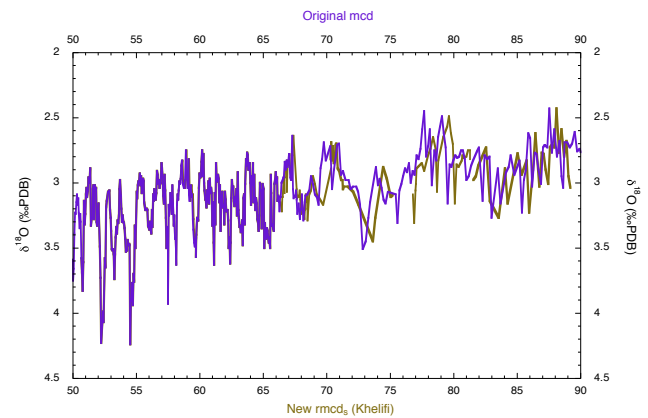


Fig. 4. Comparison of original oxygen isotope data (Venz and Hodell, 2002) on the original mcd (purple) and the rmcd_s (brown) of Khelifi et al. (2012). Note that there is not a large difference in mcd between the original and the interpretation of Khelifi et al. (2012), rather the significant difference comes in the approaches used to correlate to the LR04 stack (Lisiecki and Raymo, 2005).

All meter scale (glacial–interglacial) cycles in benthic $\delta^{18}\text{O}$ can be recognized in the composite $\delta^{18}\text{O}$ data sets in both records (Fig. 2a). Owing to the large number of tie points used by the Khelifi et al. (2012) composite depth sequence, and therefore the complicated nature of any future sampling plan that would ensue from its use, we recommend that future Pliocene research at Site 982 follow the original mcd. Regardless, given how comparable the original mcd is to rmcd_s (Fig. 4), it is not the veracity of the splice for the Pliocene that is critical to this work, but rather how it is tuned to the geological timescale (Fig. 2a).

To generate a new age model for Site 982, Khelifi et al. (2012) compressed three meter-scale benthic $\delta^{18}\text{O}$ cycles that in the stratigraphy of the original age model were attributed to MIS K2, G4 and G2 into a much shorter interval, which they now assign, respectively, to MIS G20, G2 and 104. They then proposed the existence of a hiatus, ~ 130 kyr in duration, that spans most of the mid-Pliocene warm period (MPWP, 3.19–3.06 Ma, MIS KM4–K1). Their justification for these changes hinges on their assertion that the composite depth to the Gauss–Matuyama (G/M) chronozone reversal identified in the original age model at 57.24 mcd (taken from Hole A) should be lower in the section, by 0.78 mcd (to match the mcd attributed to the G/M boundary identified shipboard for Hole B at 58.02 mcd; 982B 6H 7W, 0 cm, 52.55 m below sea floor, m.b.s.f.). This proposed alteration to the depth of the G/M boundary at Site 982 allowed Khelifi et al. (2012) to redefine isotope stages assigned to individual $\delta^{18}\text{O}$ cycles below 58.02 mcd. We believe that these changes are unwarranted.

The revision proposed by Khelifi et al. (2012) centers on the fact that the mid-point depths for G/M reversal in holes A and B, as determined on the ship, do not occur at the same

composite depth, and that the depth to the G/M boundary in the original mcd is assumed to correspond to the depth identified in Hole A (50.70 m b.s.f., 982A 6H 4W, 0 cm). In fact, neither ship-determined depth to the G/M boundary in holes A and B falls in the shipboard splice. Nevertheless, Khelifi et al. (2012) argue that the shipboard inclination data used to define the G/M boundary in Hole B (Channell and Lehman, 1999) are superior to those obtained for Hole A. Accordingly, they use the shipboard-derived depth to the G/M boundary in Hole B to identify MIS 104 (2.6 Ma, LR04 age), one $\delta^{18}\text{O}$ cycle lower in the mcd than attributed in the original age model.

In constructing age models for marine records, ODP shipboard polarity stratigraphies should always be considered preliminary, because stepwise alternating field demagnetization of natural remanent magnetization (NRM) is not feasible during cruises; most samples are only measured with a single demagnetization step. Shipboard-derived polarity records only represent guidelines for more comprehensive post-cruise age model generation, which can include shore-based u-channel research. Fortunately, and despite the reservations of Khelifi et al. (2012), a comprehensive shore-based polarity stratigraphy was generated for Site 982 following the shipboard composite depths between 7 and 66 mcd that also included the analysis of the section of core in Hole B that preserved the G/M chronozone reversal boundary (Channell and Guyodo, 2004). Following treatment of NRM on u-channel samples with alternating field demagnetization at peak fields of 80 and 70 mT and 60 to 20 mT (in 5 mT steps), the precise depth of the G/M chronozone boundary in Hole B has been identified at 57.29 mcd (51.77 m.b.s.f., 982B-6H-6 at 77 cm, Channell and Guyodo, 2004; J. Channell, personal communication, 2012) (Fig. 5), which compares favorably (within 5 cm) with the shipboard-derived depth of the G/M chronozone reversal boundary in Hole A (57.24 mcd). This depth in the original age model (= interglacial MIS 103; Channell and Guyodo, 2004) corresponds well to our understanding of the temporal relationships between the G/M chronozone reversal and records of benthic $\delta^{18}\text{O}$ (Ohno et al., 2012) (Figs. 2, 5).

2.3 Sedimentation rates

Through the generation of a u-channel polarity stratigraphy, Channell and Guyodo (2004) confirmed that the depth of the G/M chronozone boundary in the Site 982 shipboard splice is 57.29 mcd. Through the correct application of the finalized Site 982 polarity stratigraphy, we demonstrate that the major argument forwarded by Khelifi et al. (2012) to justify a revision of the Site 982 age model introduces erroneous changes to the Site 982 chronology. By using the correct depth for the G/M reversal in the Site 982 stratigraphy (at 57.29 mcd), we negate the proposed need to compress the $\delta^{18}\text{O}$ cycles assigned to MIS G4 and 104 in the original age model and the subsequent introduction of an ~ 130 kyr hiatus at 70.09 mcd. Such a hiatus would introduce unrealistic changes in sedimentation rates within the Pliocene portion of the Site 982

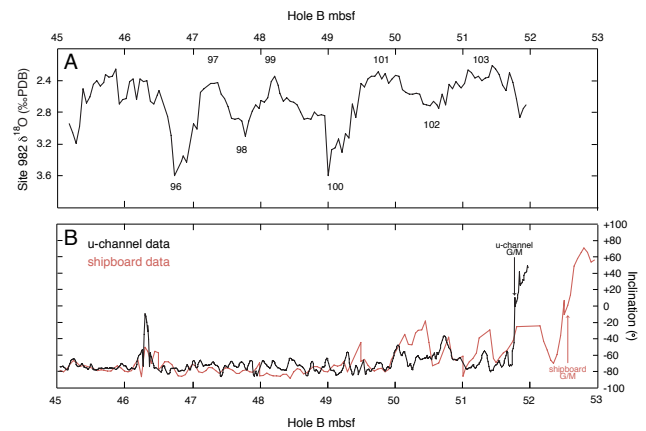


Fig. 5. ODP Site 982 benthic $\delta^{18}\text{O}$ and shipboard and u-channel-derived magnetization directions for Hole 982B, core 6H vs. meters below sea floor (m.b.s.f.), which preserves evidence of the Gauss–Matuyama (G/M) paleomagnetozone reversal. Shipboard inclination data are preliminary derived after only AF demagnetization at peak fields of 25 mT (Channell and Lehman, 1999). U-channel (inclination) data are component magnetizations based on regression from alternating field demagnetization at peak fields of 80 and 70 mT and 60 to 20 mT (in 5 mT steps), as described in Channell and Guyodo (2004). Note, u-channel data were only measured on Hole B cores included in the shipboard splice. Based on the preliminary shipboard data, the G/M boundary in Hole B was identified at 52.55 m b.s.f. (red label and arrow) (982B 6H 7H, 0 cm, 58.02 m composite depth, mcd; Channell and Lehman, 1999). Subsequent post-cruise u-channel analysis has identified the precise depth of the G/M chronozone boundary in Hole B at 51.77 m b.s.f. (black label and arrow) (982B-6H-6 at 77 cm, 57.29 mcd; Channell and Guyodo, 2004), which corresponds well to our understanding of the temporal relationships between the G/M chronozone reversal and records of benthic $\delta^{18}\text{O}$ (i.e., peak MIS 103; Ohno et al., 2012).

stratigraphy (Fig. 2b and c). In the original assignment of glacial stages to the Site 982 $\delta^{18}\text{O}$ stratigraphy, MIS G12 is not well resolved. While MIS G12 is not readily evident in the benthic $\delta^{18}\text{O}$ record in the original age model (Fig. 2a), it is clearly recorded in the alkenone-based SST data set for this site (Fig. 6).

Khelifi et al. (2012) argue that a hiatus proposed by Venz and Hodell (2002) to span MIS 88 to 86 demonstrates that sedimentation at Site 982 was “occasionally discontinuous”. They also suggest that Lisiecki and Raymo (2005) generated new benthic $\delta^{18}\text{O}$ data to span this gap before incorporating the benthic $\delta^{18}\text{O}$ stratigraphy of Site 982 into the LR04 (Khelifi et al., 2012). Channell and Guyodo (2004) took the possible existence of this hiatus into consideration when they assigned glacial stage numbers to the Site 982 benthic $\delta^{18}\text{O}$ record (see Channell and Guyodo, 2004; their Fig. 4). Despite the suggestion of Khelifi et al. (2012), no new benthic $\delta^{18}\text{O}$ data were generated by Lisiecki and Raymo (2005) to bridge this gap, and the proposed hiatus is not included in the record during the incorporation of the Site 982 benthic $\delta^{18}\text{O}$ data into the LR04. However, a sharp contact is evident

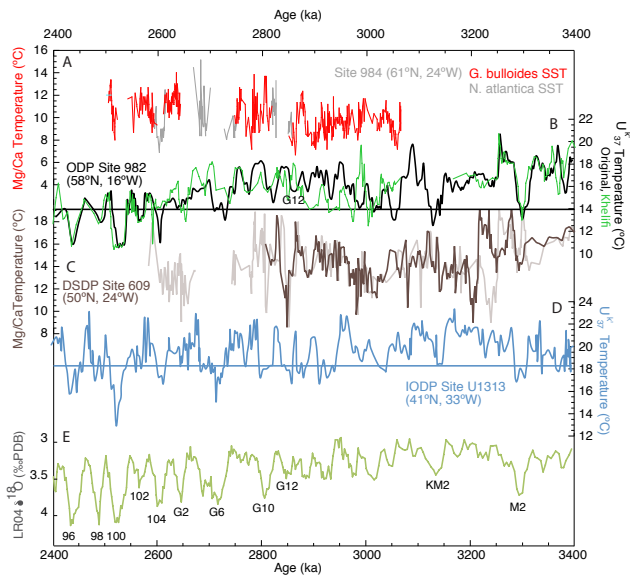


Fig. 6. Pliocene North Atlantic sea surface temperature data: (A) ODP Site 984 Mg/Ca SST (red = *G. bulloides*, light gray = *N. atlantica*) (Bartoli et al., 2005), (B) ODP Site 982 $U_{37}^{K'}$ SST (Lawrence et al., 2009) on the original age model (black) (Lisiecki and Raymo, 2005) and the revised age model (green) (Kheifli et al., 2012), (C) DSDP Site 609 Mg/Ca SST (light brown) (Bartoli et al., 2005) and revised age model (dark brown) (see Supplement), and (D) ODP Site U1313 $U_{37}^{K'}$ SST (dark blue) (Naafs et al., 2012). (E) LR04 global benthic stack (light green) (Lisiecki and Raymo, 2005) with significant glacial marine isotope stages labeled in black. Horizontal lines in (B) and (D) denote average Holocene SST for Site 982 and Site U1313.

in core photos at approximately the depth of the proposed hiatus (which falls between 49.45 and 49.50 mcd, 982C-6H-3W, 15–20 cm; Venz and Hodell, 2002). Regardless, no sedimentological evidence exists in core photographs for the proposed hiatus inserted by Kheifli et al. (2012) at 70.19–70.39 mcd (982C-8H-3W, 40–60 cm). Moreover, its introduction, which is not justified on the grounds outlined by Kheifli et al. (2012), induces unrealistic spikes in sedimentation rates in the Pliocene portion of the Site 982 record relative to those inferred from the original age model (Fig. 2b and c). In contrast, the original age model shows much smoother variations in sedimentation rates. We acknowledge that while on longer timescales more accurate age models do not tend to be characterized by sharp changes in sedimentation rates, sedimentation rates can be progressively more variable on shorter timescales (Sadler, 1999). An additional way to explore which age model is better is to employ dynamic programming, and indeed, because the Site 982 $\delta^{18}O$ record was one of the records incorporated into the LR04 stack, this approach was already used to optimize the “fit” of the Site 982 original age model to the global variations in benthic $\delta^{18}O$.

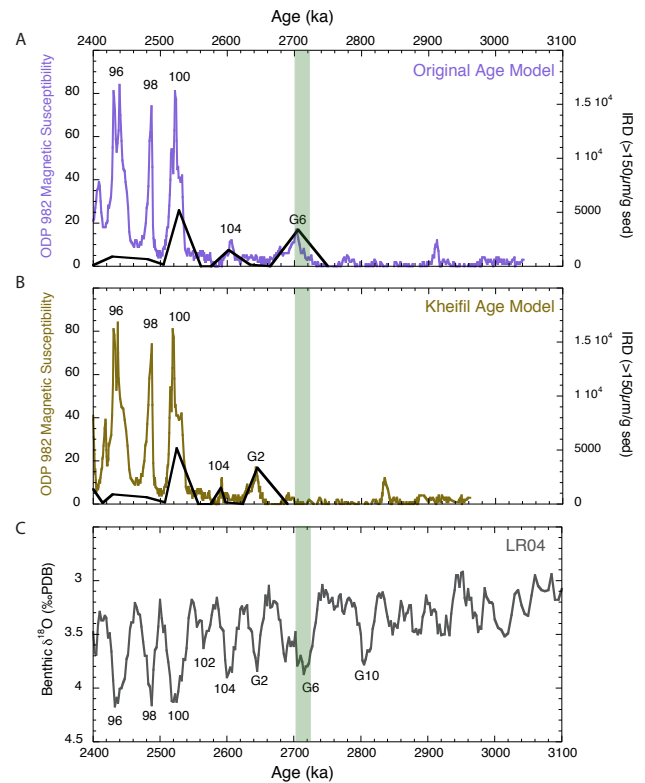


Fig. 7. Site 982 ice-rafted debris (Baumann and Huber, 1999) and magnetic susceptibility data (black) (Shipboard Scientific Party, 1996) plotted on (A) the original age model (purple) (Venz and Hodell, 2002) and (B) the age model proposed by Kheifli et al. (2012) (brown). (C) Benthic oxygen isotope data from the LR04 global benthic stack (Lisiecki and Raymo, 2005) (gray). The vertical green bar highlights the onset of major IRD deposition in the northeast North Atlantic Ocean. Significant glacial marine isotope states are labeled in black.

3 Regional data comparisons

One might expect that, in addition to more consistent sedimentation rates, an accurate age model would result in paleoclimate time series from Site 982 that are more consistent with analogous data sets regionally, compared to a less accurate age model. Site 982 SST data using the original Site 982 age model show a fairly strong correlation with SST estimates from other sites in the North Atlantic, in particular Integrated Ocean Drilling Program (IODP) Site U1313 (Fig. 6). In contrast, Site 982 SST data plotted on the Kheifli age model produce a much poorer correlation with other existing North Atlantic SST data (Fig. 6). The superior visual fit of Site 982 SST data on the original age model to other regional SST data sets is also supported by cross-spectral analysis of these data sets. Our analysis indicates that Site U1313 SSTs and Site 982 SSTs plotted on the original age model are highly coherent at the 100 kyr (0.98) and 41 kyr (0.96) orbital frequencies, with significance at the 95 % confidence level. In contrast, when the Kheifli age model is employed

for the Site 982 SST data set, these two time series are coherent only in the 41 kyr band (0.89) and only at the 80 % confidence level.

IRD deposition has been shown to increase significantly during MIS G6 at 2.72 Ma in the Northeast Atlantic Ocean at ODP Site 984 (Bartoli et al., 2005), DSDP Sites 610 (Kleiven et al., 2002) and 611 (Bailey et al., 2013), and IODP Site U1314 (Hayashi et al., 2010). In concert with other nearby records, the original age model for Site 982 indicates that IRD inputs to this region increase dramatically during MIS G6 (Baumann and Huber, 1999; Shipboard Scientific Party, 1996) (Fig. 7). In contrast, the age model proposed by Khelifi et al. (2012) for Site 982 indicates that the onset of abundant IRD deposition at this site occurred from MIS G2 (2.64 Ma or 80 kyr later) (Fig. 7).

4 Conclusions

Recently, Khelifi et al. (2012) proposed a revision to both the composite splice (55–72 mcd, Shipboard Scientific Party, 1996) and the widely accepted age model (Lisiecki and Raymo, 2005) for the Pliocene stratigraphy of ODP Site 982. Here, we demonstrate that neither of the main justifications put forward by Khelifi et al. (2012) for these changes – that shipboard physical property data cannot be used reliably to generate a composite splice below 55 mcd and that shipboard identification of the depth to the Gauss–Matuyama polarity chronozone reversal was in error – is correct. Instead, based on an inspection of the physical property data used to generate the Site 982 splice and the correct application of post-cruise, u-channel-derived inclination and declination data that follow the shipboard splice (following Channell and Guyodo, 2004), we have demonstrated the veracity of the Pliocene portion of the original Site 982 composite splice and age model. We further demonstrate that available Site 982 paleoceanographic data are most consistent with other regional data sets when plotted on this age model. We recommend that future use of these data and interpretation of new data sets generated for Site 982 continue to employ both the original shipboard splice (Shipboard Scientific Party, 1996) and age model for the Pliocene portion of this record published by Lisiecki and Raymo (2005).

Supplementary material related to this article is available online at <http://www.clim-past.net/9/1/2013/cp-9-1-2013-supplement.pdf>.

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