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Revisiting the absolute calibration of the Greenland ice-core age-scales

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Abstract

Recently, an absolute "calibration" was proposed for the GRIP and GISP2 Greenland ice-core time scales (Shackleton et al., 2004). This calibration attempted to reconcile the stratigraphic integration of ice-core, marine and speleothem archives with the absolute age constraints that marine and speleothem records incorporate. Here we revisit this calibration in light of the new layer-counted chronology of the NGRIP ice-core (GICC05). The GICC05 age-scale differs from the proposed absolute calibration by up to 1200 years late in the last glaciation, with implications both for radiocarbon cycling and the inferred timing of North Atlantic climate events relative to absolutely dated archives (e.g. relative sea-level). By precisely aligning the stratigraphy of Iberian Margin marine cores with that of the Greenland ice-cores, it appears that either: 1) the radiocarbon content of mid-latitude Atlantic surface-waters was extremely depleted (resulting in average surface reservoir ages up to 1700 years prior to ~22 ka BP); or 2) the GICC05 age-scale includes too few years (is up to 1200 years too young). It is shown here that both of these possibilities are in fact correct to some degree. Northeast Atlantic surface reservoir ages should be revised upward by ~350 years, while the NGRIP age-scale appears to be "missing" time. These findings illustrate the importance of integrated stratigraphy as a test for our chronologies, which are rarely truly "absolute". This is an important point, since probably the worst error that we can make is to entrench and generalise a precise stratigraphical relationship on the basis of erroneous absolute age assignations.

1 Introduction

All palaeoenvironmental inference hinges on chronostratigraphy. Without a way to accurately link and order our observations spatially and temporally, they remain at best of ambiguous, and at worst of dubious, significance. Nevertheless, a given chronostratigraphy is best viewed as an hypothesis. Much like any proxy, a chronostratigraphy must be employed in a manner that explicitly allows it to be tested. The Greenland and Antarctic ice-core stratigraphies, together with North Atlantic marine archives, low-latitude speleothem and coral records, and the radiometric dates that these latter archives contain, comprise an integrated chronostratigraphic system that is eminently amenable to consistency testing. The integration of these "chronostratigraphic elements" results in a system that remains underdetermined, in that it's chronology cannot be resolved unequivocally. However, this is only true to the extent that proposed stratigraphic links and absolute ages can be questioned, and that radiometric ages are subject to uncertain "calibrations" (i.e. we may not be able to account for the movement of all radio-isotopes in the system). Nevertheless, this integrated chronostratigraphic system remains explicit, in the sense that any proposed uncertainties or difficulties in the correlations or chronologies carry clear implications that can be explicitly evaluated. Thus if the Greenland, Cariaco, Iberian Margin, Hulu, Dongge and Boutavera records all contain the same "event stratigraphy", then their chronologies must be consistent; both with each other, and with existing radiometric calibrations (such as paired radiocarbon-uranium-series dated corals). Should this not be the case, one can (and must) draw clear conclusions: either regarding absolute age-determinations, radiometric calibrations and/or reservoir effects, or regarding the initial stratigraphic correlations.

It is worth noting that much hinges on the fine-scale accuracy of the Greenland ice-core chronology. Importantly, this includes a determination of the precise timing of sea-level change relative to abrupt North Atlantic and Antarctic climate change (Chappell, 2002). On its own, this phase relationship sets important constraints on the mechanisms responsible for past abrupt climate change (Knutti et al., 2004). At present, the precise phasing of sea-level and abrupt climate change remains highly uncertain (Siddall et al., 2003; Skinner et al., 2007), partly because of a current paucity of sub-millennial resolution sea-level reconstructions, and partly because of the difficulty of obtaining a perfectly accurate ice-core chronology and "Δ-age" (ice-age versus gas-age) estimation technique.

With the aim of helping to set firm constraints on the timing of millennial events

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recorded in the Greenland ice-core, we revisit the "absolute calibration" of the GRIP age-scale recently proposed by Shackleton et al. (2004). This is carried out in the light of the new layer-counted GICC05 age-scale for the NGRIP ice-core (Svensson et al., 2008), and based on new radiometric dating of marine and speleothem archives (Hughen et al., 2006; Wang et al., 2006). The aim of this exercise is not to propose a "final" age-scale for the Greenland ice-cores (which would best be derived from glaciological constraints), but rather to illustrate the first order importance and utility of stratigraphy in assessing the accuracy of a given North Atlantic event chronology. After investigating the consistency of Greenland, North Atlantic, low-latitude speleothem and coral archives, it is concluded that a definitive "absolute" glaciological age-scale for Greenland might still elude us. This is despite the very great merits of the most recent developments of the Greenland ice-core chronology.

2 Methods

In a seminal paper, Shackleton et al. (2000) demonstrated a remarkably close coupling between surface-water temperature changes recorded on the Iberian Margin and stadial-interstadial temperature changes recorded in the Greenland ice-cores (Fig. 1). More recent studies have successfully replicated and confirmed this close stratigraphical link, which has allowed a variety of marine archives from the Iberian Margin to be securely tied to the Greenland chronostratigraphy (Vautravers and Shackleton, 2006). For the most part, the correlation illustrated in Fig. 1 relies on near identical surface temperature signals; however Heinrich layers (ice-rafted debris) deposited on the Iberian Margin also provide robust markers for major Greenland stadial-interstadial transitions. This is particularly important during Marine Isotope Stage (MIS) 2, where the similarity between Iberian Margin and Greenland temperature signals degrades (Skinner et al., 2003). Hence if the correlation shown in Fig. 1 is altered significantly, this will affect the inferred timing of Heinrich events with respect to Greenland stadial-interstadial variability. An alternative correlation that would, for example, place Heinrich 2 after GIS 2, rather than before GIS 2 as is widely assumed, would represent a significant departure from the pattern indicated by other Heinrich events, which generally occur just before major Greenland stadial-interstadial transitions. Robust support for this canonical view is provided by independent assessments of the relative timing of the most pronounced Antarctic millennial warm (AIM) events (EPICA community members, 2006), as well as the phasing of major precipitation anomalies recorded in low-latitude speleothem deposits (Wang et al., 2001, 2004, 2006).

One opportunity that arises from the close alignment of Iberian Margin and Greenland records, which has long been recognised and exploited by Edouard Bard and colleagues, is that of being able to place marine radiocarbon dates from Iberian Margin sediment cores onto an independent glaciological age-scale. Seen from one angle, this may provide a useful radiocarbon calibration tool (Bard et al., 2004a). Seen from another angle, it may simply provide a crosscheck for a given Greenland/Iberian Margin stratigraphical alignment (Skinner and Shackleton, 2004). Going further still, it may be used to transfer radiometric dates from marine cores (or indeed speleothems) to the Greenland stratigraphy, thus effectively "calibrating" the Greenland age-scale. This approach was used by Shackleton et al. (2004) to propose the "absolutely calibrated" SFCP04-GRIP age-scale for Greenland (hereafter referred to as SFCP04). Perhaps most significantly, this calibration attempt has served as a reminder that glaciological age-scales may not necessarily represent absolute calendar age-scales.

More recently, a new age-scale has been devised for the NGRIP Greenland ice-core based on careful layer counting and associated uncertainty estimates (Andersen et al., 2006; Svensson et al., 2008). This new age-scale (hereafter referred to as GICC05) has in effect superseded previous Greenland age-scales, and one of its great advantages is that it possesses clearly defined uncertainty estimates. However, the GICC05 age-scale differs from the apparently well-conceived SFCP04 age-scale by up to 1200 years. We are therefore in the possession of no fewer than 5 independent Greenland age-scales, none of which are in clear agreement. If the GICC05 age-scale can be said to represent the current best estimate for the timing of the North Atlantic event stratigraphy, a clear explanation of its differences with regard to the "absolutely calibrated" SFCP04 age-scale seems necessary.

Figure 2 shows a compilation of planktonic radiocarbon dates performed in four Iberian Margin cores (Bard et al., 2004b; Shackleton et al., 2004; Skinner and Shackleton, 2004), expressed as deviations from modern atmospheric $\Delta^{14}C$. This way of presenting the radiocarbon dates accentuates the dynamic range of their deviations from stratigraphically assigned (ice-core) calendar ages. Two ice-core age-scales are adopted in Fig. 2: SFCP04 and GICC05. What this figure shows is that, when placed on the SFCP04 age-scale, Iberian Margin radiocarbon dates are in very good agreement with available radiocarbon calibration datasets, including both the coral datasets of Bard et al. (1998) and Fairbanks et al. (2005), and the Cariaco Basin dataset of Hughen et al. (2006). The Cariaco dataset shown in Fig. 2 adopts the Hulu speleothem uranium-series age-scale, and is hereafter referred to as "Huliaco". It is noteworthy that the Huliaco chronostratigraphy reproduces the same history of atmospheric $\Delta^{14}C$ change as predicted independently by paired U-Th/^{14}C dates performed on tropical corals. It is also noteworthy that the Iberian Margin reproduces a very similar history of atmospheric $\Delta^{14}C$ change when placed on the SFCP04 Greenland age-scale. If ascribed younger calendar ages, the Iberian Margin and Cariaco $\Delta^{14}C$ records would fall below the coral data (which are assumed here to be correct and representative of atmospheric $\Delta^{14}C$), unless the reservoir ages in both settings were increased by a commensurate amount. Hence a ^{14}C date that is assigned a revised calendar age 1200 years younger will maintain its $\Delta^{14}C$ at appropriate levels if it is also assigned a revised reservoir age 1200 higher. Under the proviso that reservoir ages have remained close to ~420 years in the Cariaco Basin (Hughen et al., 2006), and ~500 years on the Iberian Margin (Shackleton et al., 2004), Fig. 2 would therefore suggest close agreement between the SFCP04 Greenland age-scale and radiometric dating of tropical corals, Hulu, Cariaco Basin and the Iberian Margin.

The same is not true of the GICC05 age-scale. As shown in Fig. 2, Iberian Margin radiocarbon dates placed on the GICC05 Greenland age-scale (and corrected for a

500 year reservoir age) do not agree with Huliaco or tropical coral dates. The immediate implication that arises from Fig. 2 is that either the GICC05 age-scale is right and Iberian Margin reservoir ages should be more than doubled (to as much as 1700 years); or the GICC05 age-scale is "missing time", in particular between Greenland interstadials (GIS) 2 and 8. Below we discuss each of these possibilities in turn.

3 Discussion

One way to assess Iberian Margin reservoir ages, relative to Cariaco basin reservoir ages, is to compare radiocarbon dates performed on correlative stratigraphical events from each region. This is illustrated in Fig. 3, where Cariaco Basin grey-scale is shown correlated to Iberian Margin planktonic δ^{18}O; and offsets between the GICC05 and SFCP04 age-scales are compared with differences between correlative Iberian Margin and Cariaco radiocarbon dates. For this comparison, radiocarbon dates have been interpolated from the much higher resolution radiocarbon dataset. The reason for interpolating Cariaco dates in this way is to permit, as far as possible, a comparison of radiocarbon dates from precisely the same stratigraphic interval. A comparison of dates from a given "event", yet from different times within that event would not be sufficient. What emerges from Fig. 3 is that Iberian Margin reservoir ages are indeed likely to explain part of the discrepancy between the GICC05 and SFCP04 age-scales, as surmised by Svensson et al. (2008). Furthermore, Iberian Margin reservoir ages are likely to be larger than Cariaco Basin reservoir ages by ∼430 years on average, prior to ∼22 ka BP. Revising the Iberian Margin reservoir ages upward to ∼850 years (420+430 years) prior to 22 ka BP goes some way in reconciling the GICC05 chronology with Huliaco, coral and speleothem dates. However, it does not go quite far enough: between ∼24 and 38 ka BP the discrepancy between GICC05 and SFCP04 is significantly larger than the difference between Iberian Margin and Cariaco radicarbon dates. This statement must be true unless the grey line in the bottom panel of Fig. 3 can be said to be representative of the distribution of black crosses in the same figure. Reservoir ages alone cannot therefore resolve the SFCP04/GICC05 age-scale discrepancy.

It is worth noting that if Cariaco and Iberian Margin reservoir ages are both increased further, for example to ∼1300 and 1730 years respectively (in order to completely reconcile Iberian Margin radiocarbon dates with both the GICC05 age-scale and tropical coral dates), then agreement between the Huliaco and coral datasets is destroyed. Therefore, if we accept the Hulu age-scale for Cariaco and the coral dates, then we cannot increase Cariaco and Iberian Margin reservoir ages much higher than ∼420 and 850 years respectively. This would also suggest that GICC05 ages tend to be "too young", at least between GIS 2 and 8.

In order to assess the "absolute" accuracy of GICC05 further, a comparison can be made with ages drawn from absolutely dated speleothem records. The comparison of speleothem records shown in Fig. 4 is used as an illustration of the reproducibility (and hence uncertainty) of the event stratigraphy and chronology in these archives. It is noteworthy that despite the necessarily greater accuracy of absolute dating in the speleothem records, they do not all exhibit the exact same stratigraphic signal, nor are they in complete agreement on the precise timing of individual event boundaries. Differences between speleothem event ages (i.e. their true uncertainty) can be as large as ∼1100 years, at least for now. This serves as a reminder that stratigraphic reproducibility ultimately constrains the true uncertainty limits of our records.

The correlations shown in Fig. 4 also allow the Iberian Margin radiocarbon compilation to be placed on an age-scale that is consistent with average Hulu and Boutavera uranium-series ages inferred for Greenland event boundaries. Because Huliaco is broadly consistent with this age-scale no attempt has been made to alter it, with the exception of one small modification that has been made to bring it into better agreement with the high resolution Boutavera Cave record at ∼28 ka BP. This results in slightly younger calendar ages than provided by Hughen et al. (2006) near 28 ka BP.

Figure 5 now shows the Iberian Margin radiocarbon compilation placed on: 1) the GICC05 age-scale; and 2) the "speleothem age-scale" illustrated in Fig. 4. If our marine reservoir age estimates are accurate, and the GICC05 age-scale is consistent with speleothem ages, all of the $\Delta^{14}C$ time-series should overlap. While there is good agreement in Fig. 5 between the coral data, Huliaco and the Iberian Margin on a "speleothem age-scale" (thus confirming the reservoir age corrections proposed above), there remain significant discrepancies when the Iberian Margin is placed on the GICC05 age-scale. The GICC05 age-scale thus still appears to be slightly too young relative to speleothem ages (as observed relative to SFCP04 ages) between GIS 2 and GIS 6 in particular, even when higher reservoir ages are applied. The age offsets are not extremely large (~800 years at most), but they are consistently positive rather than randomly distributed about zero. The apparently non-random bias in age-offsets between GICC05 and speleothem records (with speleothem ages tending to be older) is also apparent in Figs. 4 and 6 of Svensson et al. (2008). We might therefore conclude that while approximately half of the original discrepancy between GICC05 and SFCP04 can indeed be attributed to larger than expected glacial reservoir ages on the Iberian Margin, the other half may still be attributed to missing years in the GICC05 age-scale. Arguably, this type of bias might be expected, given the "smoking gun" problem of layer counting. When no indication of an annual layer is found in an ice-core, it is nigh impossible to assess the likelihood that it disappeared over the likelihood that it never existed at all. Of course, as the speleothem chronostratigraphy improves in future, it may be possible (and necessary) to revise this proposed explanation of the discrepancy between the GICC05 and SFCP04 age-scales. The method outlined here indicates one way that this can be done.

4 Conclusions

The primary purpose of this investigation has been to illustrate a viable method of testing for chronostratigraphic convergence on an accurate "absolute" Greenland age-scale. In doing so, it has been shown that a distinction can still be made between even the best glaciological ages and absolute ages. The importance of making this distinction is more practical than principled, in that it has implications for climatic phase relationships, and for the history of cosmogenic nuclide production and radiocarbon cycling. It is hoped that this analysis will contribute to the further improvement of the GICC05 age-scale (or indeed other glaciological age-scales) so as to provide an even more definitive and consistent picture of the timing of millennial climate events, in particular with respect to "absolutely-dated" sea level, palaeoceanographic or archaeological archives. The determination of the phasing of millennial sea-level fluctuations relative to North Atlantic climate events and Atlantic overturning circulation perturbations represents a case in point. The methodology presented here would suggest that paired radiocarbon and uranium-series dating performed on corals amenable to sea-level reconstructions could eventually allow coral archives, ice-cores and ocean circulation proxies to be successfully integrated chronostratigraphically.

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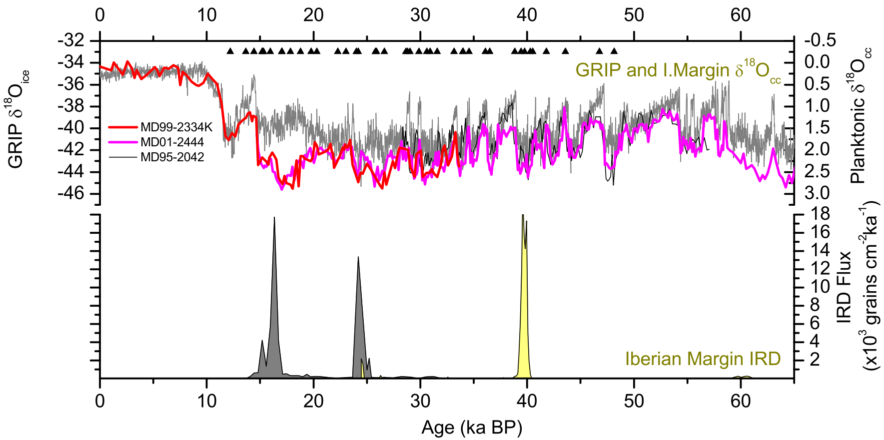

Fig. 1. Example of the correlation between Greenland and planktonic δ^{18}O from three Iberian Margin sediment cores. Black filled triangles indicate a selection of published radiocarbon dates performed on Iberian Margin planktonic foraminifera (Bard et al., 2004b; Shackleton et al., 2004; Skinner and Shackleton, 2004). Lower plot shows spikes in ice-rafted debris abundance recorded in MD99-2334K (dark shading) and MD01-2444 (light shading; reduced vertical scale) indicative of Heinrich-layer deposition (Skinner et al., 2003; Vautravers and Shackleton, 2006).

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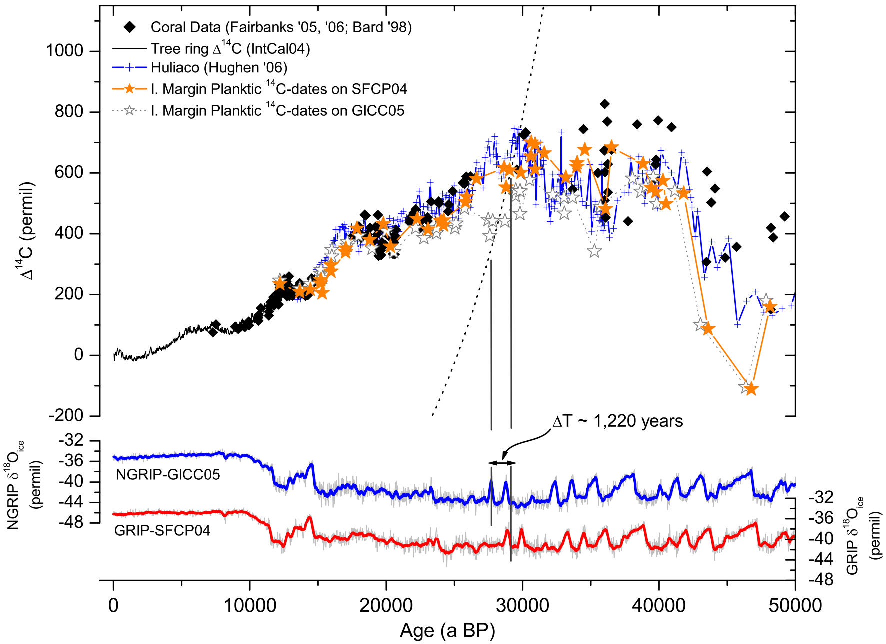

Fig. 2. Past atmospheric $\Delta^{14}C$ variability as inferred from: the INTCAL tree-ring dataset (solid black line); paired radiocarbon and uranium-series dating of tropical corals (Bard et al., 1998; Fairbanks et al., 2005) (filled diamonds); Cariaco planktonic radiocarbon dates placed on the Hulu chronology Hughen et al., 2006) (crosses); Iberian Margin planktonic radiocarbon dates placed on the SFCP04 age-scale (filled stars); and Iberian Margin planktonic radiocarbon dates placed on the GICC05 age-scale (open stars). Lower panels show NGRIP on the GICC05 age-scale compared with GRIP on the SFCP04 age-scale (Svensson et al., 2008); vertical lines indicate the difference between SFCP04 and GICC05 for Greenland Interstadial (GIS) 3. The dotted curve is a decay line showing how altering the calendar age of GIS 3 affects $\Delta^{14}C$ inferred from Iberian Margin radiocarbon dates.

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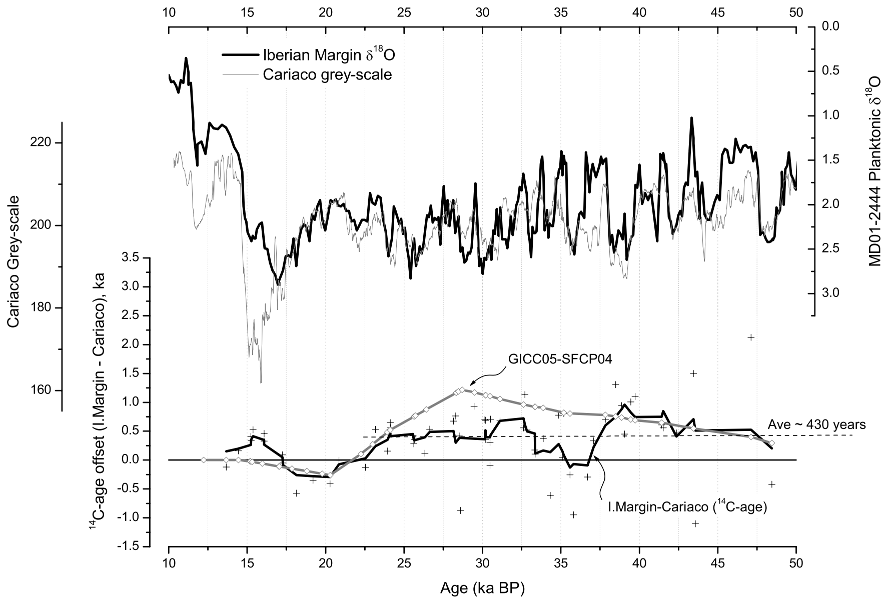

Fig. 3. Assessment of radiocarbon surface-water reservoir ages on the Iberian Margin, relative to the Cariaco Basin. Upper plot shows Cariaco grey-scale correlated with Iberian Margin planktonic δ^{18}O from core MD01-2444 (Vautravers and Shackleton, 2006). Lower plot shows the offset between Iberian Margin radiocarbon dates and their Cariaco correlates (black crosses and 5-point running mean), and the offset between the GICC05 and SFCP04 ages-scales (grey line and open diamonds). Dashed horizontal line indicates the overall average radiocarbon age-offset prior to GIS 2 (~430 years). For Cariaco Basin reservoir ages ~420 years (Hughen et al., 2006), Iberian Margin reservoir ages should therefore approach ~850 years on average prior to GIS 2.

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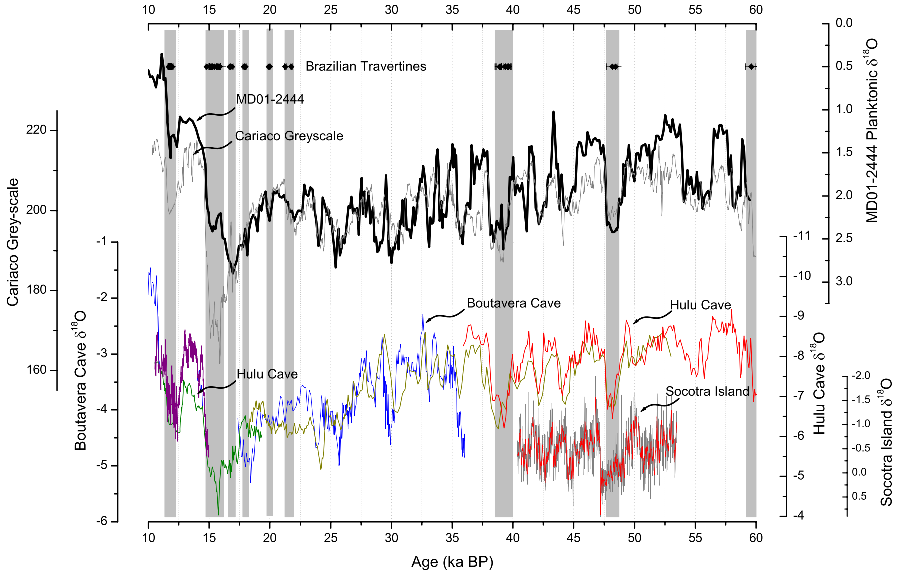

Fig. 4. Correlation of Iberian Margin planktonic δ^{18}O from core MD01-2444 (Vautravers and Shackleton, 2006) with both the Hulu Cave and Boutavera Cave speleothem records (Wang et al., 2001; Wang et al., 2006). These records are shown compared with absolutely dated Brazilian travertine deposits (indicative of wet-periods coincident with North Atlantic stadials) (Wang et al., 2004), the Socotra Island speleothem record (Burns et al., 2003; Burns et al., 2004), and Cariaco grey-scale on the Hulu chronology (Hughen et al., 2006). The Cariaco age-scale has been slightly modified from (Hughen et al., 2006) near ∼28 ka BP to bring it into closer agreement with Boutavera, but is otherwise unchanged.

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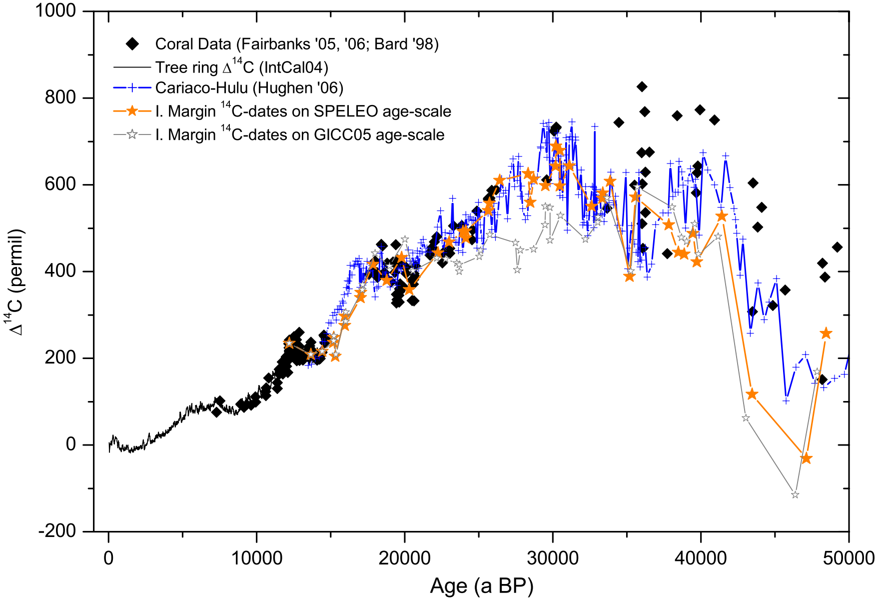

Fig. 5. Past atmospheric $\Delta^{14}C$ variability as inferred from: the INTCAL tree-ring dataset (solid black line); paired radiocarbon and uranium-series dating of tropical corals (Bard et al., 1998; Fairbanks et al., 2005) (filled diamonds); Cariaco planktonic radiocarbon dates placed on the slightly modified Hulu chronology shown in Fig. 4 (crosses); Iberian Margin planktonic radiocarbon dates placed on a speleothem age-scale (filled stars); and Iberian Margin planktonic radiocarbon dates placed on the GICC05 age-scale (open stars). Iberian Margin radiocarbon dates are corrected for a 500-year reservoir age after GIS 2, and for an 850-year reservoir age before GIS 2, as per Fig. 3.