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Title Relative paleointensity (RPI) in the latest Pleistocene (10-45 ka) and implications for deglacial atmospheric radiocarbon

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Abstract

We report magnetic properties and relative paleointensity (RPI) proxies from a suite of 10 conventional piston cores and Kasten cores from the SW Iberian Margin collected during cruise JC089 of the RSS James Cook in August 2013. Mean sedimentation rates are in the 10-20 cm/kyr range. Age models were acquired by correlation of Ca/Ti and Zr/Sr XRF core-scanning data to L* reflectance from the Cariaco Basin that is, in turn, tied to the Greenland ice-core chronology. The natural remanent magnetization (NRM) is represented by a single magnetization component carried by a low-coercivity mineral (magnetite), although reflectance and bulk magnetic properties indicate the presence of a high-coercivity (hematitic) magnetic phase, possibly from eolian dust. The presence of fine-grained hematite means that the sediments are not ideal for RPI studies, however the detrital hematite does not appear to contribute to the NRM or anhysteretic remanent magnetization (ARM). In order to test the usefulness of the RPI data, we construct a stack of 12 RPI records from the SW Iberian Margin for the 0-45 ka interval and compare it with a stack of 12 globally distributed marine and lake records, chosen on the basis of mean sedimentation rates (>15 cm/kyr) and superior age models. The two stacks are similar, but different from published RPI stacks, particularly for the 10-30 ka interval, and imply a virtual axial dipole moment (VADM) high at ~15-18 ka followed by a drop in field strength from ~15 to 13 ka. A revised VADM estimate calculated from Greenland 10Be ice-core flux using a contemporary age model is remarkably consistent with the new overall RPI stack, based on Iberian Margin and global RPI records. The elevated atmospheric 14C levels of the last ice age cannot, however, be fully explained by this RPI stack although relative changes such as the long-term drop in atmospheric 14C from 30 to 15 ka are reproduced, supporting the hypothesis of a combined influence of production rate and ocean ventilation on 14C during the last ice age.

Keywords Relative geomagnetic paleointensity; latest Quaternary; SW Iberian Margin; carbon cycle; ice-core 10Be; “Mystery Interval”.

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Submission Files Included in this PDF

File Name [File Type]

Channell Lett final rev.doc [Cover Letter]

Response to reviewers May 2018.docx [Response to Reviewers]

Highlights rev.docx [Highlights]

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Supplemental Table 1.docx [Table]

Supplemental Table 2.docx [Table]

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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data are included in Supplementary Tables 1 and 2, other data can be obtained on request.

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Prof. Claude Hillaire-Marcel,
Editor
Quaternary Science Reviews

Re: JQSR-2018-235
Relative paleointensity (RPI) in the latest Pleistocene (10-45 ka) and implications for deglacial atmospheric radiocarbon.
By: J. E. T. Channell, D. A. Hodell, S. J. Crowhurst, L. C. Skinner and R. Muscheler

Dear Claude,

Thank you for the reviews of the above manuscript.
We are hereby submitting a revised version for publication in *Quaternary Science Reviews.*

Our response to the reviewers' comments have been submitted on-line. Please note that the title of the paper has been changed, as both you and one of the reviewers suggested.

Thank you for your help and editorial guidance.

Sincerely,

Jim Channell

JQSR-2018-235

Editor's comments:
We have completed the review of the new version of the above manuscript. Both reviewers are in favor of its publication with some minor revision suggested by the second reviewer. Their comments are appended below. I do not think a point-by-point response to the second reviewer's comments will be needed as he mostly invites your to work a little bit more on the introduction and perhaps, the title of the paper. I do not have any specific opinion about adding or not a figure as he also suggests.

We have eliminated the term "mystery interval" from the title of the paper (we agree that this term is unnecessary jargon). We have added a sentence to the first paragraph of the Introduction (Lines 51-55): "Because the strength of the AD field is an important control on atmospheric cosmogenic isotope production, RPI records have implications for the calibration of radiocarbon dates and for the carbon cycle including the apparent drop in atmospheric $\Delta^{14}C$ in the "mystery interval" at 17.5-14.5 kyr (Broecker and Barker, 2007)."

Reviewer 1:
- I already agreed for the acceptance of the former version (rejected for an incomprehensible reason)
I maintain my advice to publish this thorough , precise and accurate study .

Reviewer 2:
This manuscript presents data that should be of interest to the readership of QSR, but is currently very much oriented as a paleomagnetism paper. It presents a new relative paleointensity (RPI) stack derived from several cores from the Iberian Margin. Most of the paper is written to demonstrate how the RPI proxies were constructed and tested for validity, with several interesting points along the way regarding the influence of different coring techniques on sedimentation rates or the influence of hematite on the RPI proxies, but a clear objective is currently lacking. I think this can easily be corrected in a revised version. To do that, the authors need to refocus their introduction. Currently, it is a mixture of introduction, methodology, and core/site selection. I would refocus the introduction by clearly stating the objectives of the paper and by highlighting the key points that will be discussed later: the mystery interval (it is actually in the title and not very much discussed afterwards), ocean ventilation and cosmogenic isotopes, etc. and move some of the other elements in the Methods section. For QSR, I think the main point should be to illustrate the implication of the new stack in terms production rate and ocean ventilation.

We believe that the additional sentence in the Introduction and the change of Title (see above) will satisfy these concerns.

Finally, it its present form, it is difficult to assess the quality of the proposed chronology for each individual JC089 cores and figure 3 is not helping. The authors could add a figure illustrating that the JC089 cores can actually be correlated together.

In additions to Figure 3, Supplementary Figures S1-S4 illustrate how the cores are correlated.

Specific comments below:

Latest Quaternary and Latest Pleistocene vs. Late Quaternary or Late Pleistocene. Why Latest?

The term Late Pleistocene refers to the interval from ~126,000 ka (base of MIS 5) to the base of the Holocene, equivalent to the Tarantian stage. Our interval (0-45 ka) is best described as latest Pleistocene, an informal term hence no upper case letters in "latest".

P. 6. Lines 176-178. "there is a good agreement between our correlation". Could you provide statistics to support this point?

We have changed the wording here. It now reads:

"There are only very minor differences between our age models constructed via Cariaco and those of Freeman et al. (2016) in which the same JC089 cores were correlated directly to Greenland (Figs. S5 and S6)." Lines 181-183.

P. 8. Lines 240-241. Why are the Laschamp, nor the Mono Lake excursions seen in any of the JC089 cores? This is puzzling and need a little more discussion!

We have added a sentence (Lines 248-253):

"Recordings of directional aberrations associated with Laschamp and Mono Lake excursions are rare in sediments with similar (~15 cm/kyr) sedimentation rates, presumably due to filtering of the directional signal by non-instantaneous remanence-acquisition, the stochastic nature of sediment accumulation on short timescales, and the centennial-scale duration of these two directional excursions (see Laj and Channell, 2015)."

P.9 Line 270. I am missing characters in my copy, but this is likely due to the pdf conversion

The core labels (now Line 280) have been re-written, so this should be OK now.

P. 10. Laguna Potrok Aike record used in the stack. The authors mention that the uncorrected record is influenced by lithological variability. Would it be more appropriate to use the corrected RPI record? Differences between the Iberian Margin records and the Laguna Potrok Aike corrected record could be real differences in the geomagnetic field associated with the location of two sets of records (Northern and Southern Hemispheres, South America vs. Europe), with significant differences both in terms of latitude and longitude.

Yes, this deserves further explanation. We have added a few sentences (Lines 361-367):

"Lisé-Pronovost et al. (2013) offered a "corrected" NRM/ARM RPI proxy record, designed to compensate for the influence on RPI of magnetic grain-size changes. The correction method was originally applied to NRM/IRM data from Lake Pepin (Brachfeld and Banerjee, 2000), and has rarely been used since. We utilize the Potrok Aike RPI record before "correction" because we have concerns about the veracity of the correction, particularly for NRM/ARM data. Age models for lacustrine RPI data incorporated in the stack are as published, and are based on radiocarbon, tephrochronology, and for Lake Van, correlation of XRF core-scanning records to ice-core chronologies."

JQSR-2018-235
Highlights:

Revised view of relative paleointensity for the latest Quaternary (0-45 ka).

Stack of SW Iberian and global relative paleointensity records for 0-45 ka.

RPI stack consistent with recalculated ^{10}Be-based estimate of field intensity.

Implications for the carbon cycle, ocean ventilation, and the “mystery interval”.

Relative paleointensity (RPI) in the latest Pleistocene (10-45 ka) and implications for deglacial atmospheric radiocarbon

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Abstract

We report magnetic properties and relative paleointensity (RPI) proxies from a suite of 10 conventional piston cores and Kasten cores from the SW Iberian Margin collected during cruise JC089 of the RSS *James Cook* in August 2013. Mean sedimentation rates are in the 10-20 cm/kyr range. Age models were acquired by correlation of Ca/Ti and Zr/Sr XRF core-scanning data to L* reflectance from the Cariaco Basin that is, in turn, tied to the Greenland ice-core chronology. The natural remanent magnetization (NRM) is represented by a single magnetization component carried by a low-coercivity mineral (magnetite), although reflectance and bulk magnetic properties indicate the presence of a high-coercivity (hematitic) magnetic phase, possibly from eolian dust. The presence of fine-grained hematite means that the sediments are not ideal for RPI studies, however the detrital hematite does not appear to contribute to the NRM or anhysteretic remanent magnetization (ARM). In order to test the usefulness of the RPI data, we construct a stack of 12 RPI records from the SW Iberian Margin for the 0-45 ka interval and compare it with a stack of 12 globally distributed marine and lake records, chosen on the basis of mean sedimentation rates (>15 cm/kyr) and superior age models. The two stacks are similar, but different from published RPI stacks, particularly for the 10-30 ka interval, and imply a virtual axial dipole moment (VADM) high at ~15-18 ka followed by a drop in field strength from ~15 to 13 ka. A revised VADM estimate calculated from Greenland ^{10}Be ice-core flux using a contemporary age model is remarkably consistent with the new overall RPI stack, based on Iberian Margin and global RPI records. The elevated atmospheric ^{14}C levels of the last ice age cannot, however, be fully explained by this RPI stack although relative changes such as the long-term drop in atmospheric ^{14}C from 30 to 15 ka are reproduced, supporting the hypothesis of a combined influence of production rate and ocean ventilation on ^{14}C during the last ice age.

Keywords: Relative geomagnetic paleointensity, latest Quaternary, SW Iberian Margin, carbon cycle, ice-core ^{10}Be, "Mystery Interval".

1. Introduction

Consistent correlation of sedimentary relative paleointensity (RPI) proxies to oxygen isotope data over the last 1-2 Myrs (e.g., Channell et al., 2009; Xuan et al., 2016) has shown that RPI proxies in sediments can reflect the Earth's axial dipole (AD) field and therefore provide a signal suitable for global stratigraphic correlation. This conclusion is supported by the consistent picture of dipole field strength from RPI and from sedimentary ^{10}Be/^{9}Be ratios back to 850 ka (e.g., Simon et al., 2016). Because the strength of the AD field is an important control on atmospheric cosmogenic isotope production, RPI records have implications for the calibration of radiocarbon dates and for the carbon cycle including the apparent drop in atmospheric Δ^{14}C in the "mystery interval" at 17.5-14.5 kyr (Broecker and Barker, 2007).

The Holocene (0-11.5 ka) record of paleointensity has been modeled from archeomagnetic and lava-flow data (Korte et al., 2009, 2011; Pavon-Carrasco et al., 2014) indicating a pattern of AD field intensity changes characterized by a broad high in intensity at ~1-3 ka, preceded by a broad low in the 5-7 ka interval (Fig. 1b). Beyond the range of archeomagnetic data, latest Pleistocene (11.5-45 ka) sedimentary RPI data have been compiled into regional and global stacks (Laj et al., 2000, 2004; Stoner et al., 2002; Valet et al., 2005; Channell et al., 2009; Ziegler et al., 2011), but with little agreement between stacks, or individual records, for the 10-30 ka interval (Fig. 1a). The poor consistency of sedimentary RPI data since the time of the Mono Lake (~34 ka) and Laschamp (~41 ka) excursions (Fig. 1a) is attributed to drilling disturbance in the uppermost few meters of recovered sediment sequences.

Absolute paleointensity data from volcanics have not contributed significantly to the paleointensity time-series for the 10-30 ka interval for several reasons: lava sequences are plagued by unknown time-gaps between flows, ^{40}Ar/^{39}Ar dating has poor precision for young (<40 ka) ages, scarcity of robust radiocarbon age control, and scatter in absolute paleointensity determinations when plotted versus age particularly for the 10-30 ka interval (e.g., Teanby et al., 2002; Pressling et al., 2006; Genevey et al., 2008; Laj et al., 2014).

Using models of cosmogenic nuclide production (Masarik and Beer, 1999), Muscheler et al. (2005) calculated the virtual axial dipole moment (VADM) corresponding to the flux of cosmogenic isotopes in ice cores for ^{36}Cl (Baumgartner et al., 1998; Wagner et al., 2000) and ^{10}Be (Yiou et al., 1997; Finkel and Nishiizumi, 1997). Estimates of atmospheric ^{14}C activity have been derived from independent age control on radiocarbon ages from stalagmites (Beck et al., 2001; Wang et al., 2001; Southon et al., 2011), corals (Fairbanks et al., 2005), lake varves (Bronk Ramsey et al., 2012) and from the correlation of marine sediment cores to Greenland ice (Hughen et al., 2004; Peterson et al., 2000; Bard et al., 2004). VADM estimates derived from atmospheric ^{14}C (Muscheler et al., 2005) are not consistent with estimates from ^{36}Cl and ^{10}Be from Greenland ice, particularly for 10-30 ka (Fig. 1b). Discrepancies may be due to differing transport pathways for ^{36}Cl and ^{10}Be from the atmosphere to ice, diffusion of ^{36}Cl in firn (not likely in Greenland), and changes in the carbon cycle, particularly changes in ocean ventilation (e.g. Skinner and Shackleton, 2004; Muscheler et al., 2004; Robinson et al., 2005; Skinner et al., 2010; Chen et al., 2015). Furthermore, revisions in ice-core timescales directly impact the radionuclide flux calculation. For the last glacial maximum (LGM) interval, the latest Greenland ice core timescale (Svensson et al., 2008) results in adjustments to the ^{10}Be-based VADM estimates of Muscheler et al. (2005).

Magnetic concentration parameters in sediments, such as susceptibility or anhysteretic remanent magnetization (ARM) intensity, are less affected by subtle drilling disturbance than natural remanent magnetization (NRM) intensities. Sedimentary NRM intensities depend on magnetic grain alignment, and are an essential entity in RPI proxies. Published RPI stacks (Fig. 1a) rely largely on cores collected from the *Marion Dufresne* (MD) using the Calypso corer, and cores collected using the Advanced Piston Corer (APC) of the Ocean Drilling Program and Integrated Ocean Drilling Program (ODP/IODP). The stretching (oversampling) of the upper part of sediment cores collected by the Calypso corer has been well documented (Skinner and McCave, 2003; Széréméta et al., 2004). Deformation of the upper part of APC cores is less well documented although familiar to shipboard scientists who regularly observe poorly consolidated or "soupy" conditions in the topmost few meters of recovered sediment. Drilling disturbance of APC cores down-section has been associated with shearing of the sediment as the APC core-barrel rips through the sediment and physically deflects the ancient magnetization particularly at core edges (Acton et al., 2002). This secondary magnetization component tends to have a coercivity spectrum that overlaps with the ancient (primary) magnetization, being largely produced by magnetic grain deflection, and therefore the primary magnetization is often not recoverable through laboratory demagnetization (Acton et al., 2002).

The influence of drilling disturbance can be mitigated to some extent by choosing sites with elevated mean sedimentation rates, so that the uppermost few meters of the sediment sequence have a more restricted (younger) age range, and by choice of coring and sampling methods. With these factors in mind, we investigated the RPI record for the latest Quaternary (0-45 ka) from a suite of short (NIOZ-type) piston cores and Kasten cores (Zangger and McCave, 1990) collected from the SW Iberian Margin during cruise JC089 of the RSS *James Cook* in August 2013 (Hodell et al., 2014). The coring methods used during JC089 are not immune to drilling disturbance; however, traditional piston cores and especially square barrel Kasten cores are expected to be less susceptible to drilling disturbance than Calypso or APC cores (Skinner and McCave, 2003). The JC089 sites are located on a spur on the continental slope of the Iberian Margin (Promonotorio dos Principes de Avis) that is elevated above the abyssal plain and the influence of turbidites (Fig. 2). Uppermost Quaternary sediments comprise greenish-gray hemipelagic nannofossil mud and clays with mean sedimentation rates in the 10-20 cm/kyr range

(Table 1). Our discussion includes JC089 cores collected from water depths >2500 m (Table 1); cores collected at shallower water depth during the same cruise display more significant heterogeneity in both lithology and magnetic properties.

The site locations are in the vicinity of Core MD95-2042 (Fig. 2) made famous by Shackleton et al. (2000, 2004) due to their observation that planktic and benthic $\delta^{18}O$ records mimic Greenland and Antarctic ice-core air-temperature records, respectively. As a result, sediment cores from this part of the Iberian Margin have potential for precise age control over the last glacial cycle through correlation to ice-core chronologies. One of the sites discussed here (Station 6, Table 1) is at the same location as Core MD01-2444 (Fig. 2), and is close to (1.8 km from) IODP Site U1385. At MD01-2444 and Site U1385, precise age models have been constructed by correlation of oxygen isotope and X-ray fluorescence (XRF) core-scanning data to Core MD99-2334K and ice-core chronologies (Skinner et al., 2003; Skinner and Shackleton, 2004; Hodell et al., 2013, 2015; Freeman et al., 2016). The SW Iberian Margin has distinct chronological advantages relative to most marine sites where traditional oxygen isotope stratigraphy usually has limited resolution, even at glacial terminations, resulting in poor stratigraphic control within the last glacial cycle. Core MD95-2042 was one of several cores used to build the Portuguese Margin RPI stack (Thouveny et al., 2004) that was accompanied by sedimentary $^{10}Be/^{9}Be$ data (Carcaillet et al., 2004; Ménabréaz et al., 2011). Although magnetite dominates the magnetic properties of Cores MD95-2042 and MD01-2444, the suitability of these sediments for RPI studies is compromised by the presence of a high-coercivity magnetic phase (Moreno et al., 2002), believed to be hematite sourced from eolian dust, or possibly from riverine input (Channell et al., 2013; Hodell et al., 2013).

2. XRF methods and age control

The JC089 cores were scanned at the University of Cambridge using an Avaatech XRF core scanner (3rd generation) to obtain semi-quantitative elemental data. The surface of the cores was scraped clean then covered with 4 µm thick SPEXCertiPrep Ultralene foil to avoid contamination and to prevent the cores drying out and cracking. Each section was measured at three different voltages and currents: 10 kV and 750 mA, 30 kV and 500 mA, and at 50 kV and 1000 mA. The entire length of each core was analyzed at

5-mm resolution with an irradiated surface length and width of 5 mm (downcore) and 12 mm (cross core). The count time was 60 s for each measurement. Element intensities were obtained by post-processing of the XRF spectra using the Canberra WinAxil software with standard software settings and spectrum-fit models.

Sediments deposited on the SW Iberian Margin were particularly responsive to Quaternary climate on both millennial and orbital timescales, being optimally positioned to respond to fluctuations in sea-surface and bottom-water temperatures (Shackleton et al., 2000, 2004; Skinner et al., 2003, 2007; Hodell et al., 2013, 2015). Variations in carbonate concentrations in sediments from this region have been associated with changes in terrigenous supply (Thomson et al., 1999, 2000), although surface-water productivity and sea-surface temperatures affect carbonate content on millennial timescales (Hodell et al., 2013). For Core MD01-2444, same location as JC089-06 (Fig. 2), the Ca/Ti ratio from XRF core-scanning provides a reliable proxy for wt % $CaCO_3$, and largely reflects the mixing ratio of biogenic (Ca) and detrital (Ti) components (Hodell et al., 2013). The Ca/Ti ratio at MD01-2444 mimics planktic $\delta^{18}O$ and can be correlated to the Greenland ice-core $\delta^{18}O$ record for the last glacial cycle (Hodell et al., 2013).

For this study, age models for JC089 cores were constructed by correlating Ca/Ti and Zr/Sr signals to the L* reflectance record from Cariaco Basin (Deplazes et al., 2013). The Cariaco age model is a hybrid of layer counting, radiocarbon, and correlation of the L* record to the ice core $\delta^{18}O$ record of NGRIP using the GICC05 age scale for 0-60 ka (see supplement of Deplazes et al., 2013). Peaks in Ca/Ti mark interstadials whereas Zr/Sr values are generally higher during stadials, particularly Heinrich stadials (Fig. 3; Figs. S1-S4). We used the Cariaco Basin record as the intermediary to Greenland because Heinrich stadials are well expressed in the Cariaco color record, whereas they are muted in the Greenland ice core $\delta^{18}O$ and dust record. There are only very minor differences between our age models constructed via Cariaco and those of Freeman et al. (2016) in which the same JC089 cores were correlated directly to Greenland (Figs. S5 and S6).

Precise age control from correlation to ice-core chronologies is a result of heterogeneity in geochemistry and lithology as a result of the high fidelity response of these sediments to climatic change. The heterogeneity that facilitates the age control is, on the other hand, not advantageous for relative paleointensity determinations that rely on uniformity in magnetic properties.

3. Magnetic measurements and methods

Magnetic measurements using a 2G Enterprises pass-through cryogenic magnetometer (Weeks et al., 1993) were made on u-channel samples (2 x 2 x 150 cm^3) collected from the split face of piston cores and the scraped side of Kasten cores. Cleaning/scraping of the surfaces prior to u-channel sampling is particularly critical for Kasten cores because of the likelihood of coring disturbance close to core-walls and hence close to the u-channel sample. NRM was measured prior to alternating field (AF) demagnetization and after demagnetization at peak fields of 10-30 mT in 5mT steps, 30-60 mT in 2.5 mT steps and 60-70 mT in 5 mT steps, and 80 mT. All magnetometer measurements were carried out at 1-cm spacing, with a 10-cm leader and trailer at the ends of the u-channel sample. NRM component magnetizations were determined in a uniform 20-80 mT demagnetization range, and maximum angular deviation (MAD) values were determined using the standard method (Kirschvink, 1980) and the software of Xuan and Channell (2009). Volume magnetic susceptibility was then measured at 1-cm spacing using a susceptibility track designed for u-channel samples (Thomas et al., 2003). ARM was then imposed along the long-axis of u-channel samples using a 50 μT DC field and a 100 mT alternating field. The ARM was then AF demagnetized at peak fields of 10-60 mT in 5 mT steps, and 60-80 mT in 10 mT steps. ARM was then incrementally imposed along the axis of each u-channel sample using a uniform (50 μT) DC field and stepwise increasing alternating fields, using the same AF increments as for ARM demagnetization. Next, an isothermal remanent magnetization (IRM) was imposed along the axis of each u-channel using a DC field of 300 mT, and the $IRM_{0.3T}$ was then demagnetized at the same peak field used for ARM demagnetization. Finally, an IRM_{1T} was imposed using a DC field of 1 T, and again demagnetized using the same alternating fields used for ARM and $IRM_{0.3T}$.

Relative paleointensity (RPI) proxies in sediments are determined by normalization of NRM intensity by the intensity of a laboratory-induced magnetization designed to activate the same magnetic grains that contribute to the NRM (Levi and

Banerjee, 1976; Tauxe, 1993). The most commonly used normalizers are ARM and IRM. The NRM and the normalizer should be carried by magnetite in a restricted grain size and concentration range (see Tauxe, 1993). Here we acquire potential paleointensity proxies for the 20-60 mT demagnetization/acquisition interval using four slopes: NRM demagnetization versus ARM demagnetization, NRM demagnetization versus ARM acquisition, NRM demagnetization versus IRM$_{0.3T}$ demagnetization, and NRM demagnetization versus IRM$_{1T}$ demagnetization. The software of Xuan and Channell (2009) allows linear correlation coefficients (r) to be determined for slopes determined at each 1-cm spaced measurement position.

A Princeton Measurements Corp. vibrating sample magnetometer (VSM) was used to determine hysteresis ratios and first order reversal curves (FORCs) on sediment samples encased in #4 gel-caps. No FORCs are reproduced in this paper as the FORC results and conclusions are very similar to those for Core MD01-2444 (Channell et al., 2013).

4. Magnetic properties

NRM has low coercivity in Core MD01-2444 (Channell et al., 2013) and at neighboring sites including MD95-2042 (Thouveny et al., 2004). The magnetic properties of Core MD01-2444 are dominated by biogenic and detrital magnetite with a greater proportion of biogenic magnetite in interglacial stages (Channell et al., 2013). Fine-grained hematite in Core MD01-2444 is indicated by S-ratios and a* (570-560 nm) reflectance data, and it was associated with eolian Saharan dust due to precessional power in a* reflectance data (Hodell et al., 2013; Channell et al., 2013). In JC089 cores, the NRM component directions have low coercivity, are associated with low (<5°) MAD values, and inclinations are consistent with site latitude although with shallower inclinations at depth (Fig. 4) possibly associated with sediment compaction. The characteristic (primary) NRM magnetization components are not obviously correlated amongst the cores, and the Laschamp or Mono Lake magnetic excursions are not observed in any of the JC089 cores, or in Core MD01-2444, although the Laschamp excursion is apparently represented by divergent declinations for several adjacent u-channel measurement positions in Core MD95-2042 (Thouveny et al., 2004). Recordings of directional aberrations associated with Laschamp and Mono Lake excursions are rare in sediments with similar (~15 cm/kyr) sedimentation rates, presumably due to filtering of the directional signal by non-instantaneous remanence-acquisition, the stochastic nature of sediment accumulation on short timescales, and the centennial-scale duration of these two directional excursions (see Laj and Channell, 2015).

Orthogonal projections of u-channel AF demagnetization data of JC089 Kasten cores (Fig. 5a) are displayed at sediment depths of 100 cm, 200 cm, 250 cm, and ~350 cm (300 cm corresponds to a section break). For one core (06-5K), the projection at 330 cm is shown because the core does not reach 350 cm (Table 1). A single NRM magnetization component appears to be present throughout the suite of cores, and the maximum peak field (80 mT) implies low coercivity NRM carrier(s). Orthogonal projections from samples at these depths in JC089 piston cores are shown in Figure S7.

Volume susceptibility shows subdued variability other than during HS4 (Fig. 6d) Variations in the magnetite grain-size parameter κ_{arm}/κ indicate coarser magnetite during Heinrich stadials (HS), a progressive fining of grain size at Termination I, and fine magnetite grain sizes in the early Holocene (Fig. 6c). The change in κ_{ARM}/κ at Termination I is controlled by an increase, by a factor of ~2, of ARM intensity as the concentration of fine-grained biogenic magnetite increases relative to coarser detrital magnetite in the Holocene. The plot of κ_{arm} versus susceptibility (κ) indicates fine magnetite grain sizes apart from during HS4 (Fig. 6a), and the range of magnetite grain sizes is consistent with estimates from the hysteresis (Day et al., 1977) plot (Fig. 6b). Our interpretation of the magnetic properties of JC089 cores is consistent with the interpretations from Core MD01-2444 where magnetic properties are controlled by variations in the proportion of biogenic and detrital magnetite (Channell et al., 2013) with interglacial stages, including the Holocene, characterized by enhanced concentration of biogenic magnetite, whereas Heinrich stadials have enhanced detrital input associated with sea level low-stands. High susceptibility and coarse magnetite grain size during HS4 (Fig. 6) are consistent with the presence of ice-rafted debris (IRD). Heinrich stadials tend to be associated with lower values of κ_{arm}/κ (coarser magnetite grain size), higher susceptibility and higher S-ratios, but only HS4 has the prominent susceptibility signal denoting IRD (Fig. 6).

In Cores MD95-2042 and MD[illegible]r[illegible] magnetic mineral was detected by Moreno et al. (2002) and Channell et al. (2013), respectively, and attributed to eolian dust (Hodell et al., 2013). In Core MD01-2444, isothermal remanent magnetization acquired in magnetizing fields of 300 mT ($IRM_{0.3T}$) and 1 T (IRM_{1T}) yield S-ratios (determined as $IRM_{0.3T}$ / IRM_{1T} after demagnetization of both IRMs at peak fields of 30 mT) with values in the 0.8-0.95 range with lower values (high coercivities) associated with glacial and stadial climatic episodes (see Fig. 5 in Channell et al., 2013). For JC089 cores, the values of $IRM_{0.3T}$ and IRM_{1T} yield S-ratios in a similar (0.8-0.95) range although values are variable from core to core (Fig. 6e). Using two of the sediment depths (100 cm and 200 cm) used for orthogonal projections of NRM (Fig. 5a), normalized intensities (Jr/Jo) of NRM indicate higher coercivity in the 20-80 mT peak field demagnetization range than for ARM (Fig. 5b). Both $IRM_{0.3T}$ and IRM_{1T} have higher coercivity in the 60-80 mT range than NRM and ARM (Fig. 5b). The progressive bifurcation with increasing peak fields for $IRM_{0.3T}$ and IRM_{1T} denotes the high-coercivity signal of the hematitic dust that is apparently less important in NRM and ARM (Fig. 5b).

5. Relative paleointensity (RPI) proxies

RPI proxies in these sediments are complicated by the presence of biogenic magnetite (see Roberts et al., 2012), and by the presence of detrital hematite, as RPI proxies traditionally require magnetite to be the sole remanence carrier with uniformity in magnetite grain size and concentration (Tauxe, 1993). On the other hand, the hematite in Core MD01-2444 is from eolian dust, or possibly from riverine input, and therefore detrital (Hodell et al., 2013), and therefore may not contribute to the NRM due to the low intrinsic magnetization (alignment efficiency) of hematite. The possibility of acquiring useful RPI proxies depends on the extent to which the detrital hematite contributes to the NRM and to the normalizers used to acquire the RPI proxies.

Core MD01-2444 and Cores 06-4K and 06-5K were collected at the same location (Fig. 2), and yet the MD01-2444 apparent sedimentation rates are about twice those at 06-4K and 06-5K (Fig. 7), presumably because of relative stretching of the MD core. The two Kasten cores (06-4K and 06-5K) have similar but not identical sedimentation rates with differences attributable to differential compaction (Figs. S5 and S6). Clearly, cores collected at nominally the same location are not identical, and depend on the coring method, and perhaps on the precise location of core penetration. RPI proxies from the three cores differ, particularly in the 12-15 ka interval (Fig. 7). The Ca/Ti and Zr/Sr ratios for 06-4K (Fig. 3; Figs. S2 and S4) imply a hiatus that apparently removed part or all of the Younger Dryas, which appears to be recorded in 06-5K (Fig. 3). Note that all four RPI proxies (NRM/ARM, NRM/ARMAQ, NRM/$IRM_{0.3T}$, NRM/IRM_{1T}) are similar in the glacial interval, but differ in the Holocene, although correlation coefficients (r) associated with all slopes are close to unity, implying well-defined slopes (Fig. 7). A similar difference in the four RPI proxies was observed in the Holocene at MD01-2444 and was attributed to under-normalization by IRM due to high concentration of ultra-fine biogenic magnetite (Channell et al., 2013). A fine-grained high-coercivity hematitic phase would be expected to affect the four proxies differently, and the general similarity of the RPI proxies implies that the hematite does not contribute significantly to NRM intensity or to the normalizers used to generate the RPI proxies.

For other JC089 cores (Table 1), linear sedimentation rates are not identical for Kasten and piston cores from the same location, attributable to differential coring disturbance, with the piston cores having generally higher linear sedimentation rates (Fig. 8; Figs. S5 and S6). The four RPI proxies (NRM/ARM, NRM/ARMAQ, NRM/$IRM_{0.3T}$, NRM/IRM_{1T}) are generally similar although again there is the tendency, as in Cores 06-4K and 06-5K (Fig. 7), for under-normalization by IRM in the Holocene where the concentration of ultra-fine biogenic magnetite is greater (Fig. 8). The linear correlation coefficients (r) are generally >0.98, indicating that the slopes (RPI proxies) are well defined. Note that all RPI proxies (slopes) were determined for the 20-60 mT demagnetization/acquisition range in an effort to exclude the enhanced influence of hematite at peak fields >60 mT (Fig. 5b).

6. Relative paleointensity (RPI) stacks

In order to test the fidelity of the RPI proxies, we constructed a RPI stack for the SW Iberian Margin for the 0-45 ka interval for comparison with other records. The Iberian Margin Stack (Fig. 9a) includes the ten JC089 cores (Table 1, Fig. 9b), the RPI record from Core MD01-2444 (Table 2, Channell et al., 2013) and the Portuguese Margin Stack (Table 2, Thouveny et al., 2004). All records are on their individual age models, with no age adjustments or record matching. The JC089 and MD01-2444 RPI proxies that are incorporated in the stack are the slopes of NRM/ARM. Each record was interpolated to a uniform 0.5-kyr sampling spacing, and set to a common mean and common standard deviation. The stack is the mean at each 0.5-kyr data step, giving equal weight to each of 12 records (Fig. 9a).

The choice of records for inclusion in the stack from outside the Iberian Margin for 0-45 ka (Table 2) was based on mean sedimentation rate (>15 cm/kyr) and deemed adequacy of age models. The vast majority of marine cores do not have adequate sedimentation rates, nor do they have age control in the last glacial other than identification from $\delta^{18}O$ of the last glacial termination. The twelve records that are included in the stack from outside the Iberian Margin (Fig. 9c) are listed in Table 2. Each record was placed on its published age model, was interpolated to a uniform 0.5-kyr sampling spacing, and set to a common mean and common standard deviation. The stack is the arithmetic mean at each 0.5-kyr data step (Fig. 9a).

The lacustrine records included in the 0-45 ka stack from outside the Iberian Margin (Table 2) are the Lac du Bouchet (France) record of Thouveny et al. (1993), the Lake Biwa (Japan) record of Hayashida et al (2007), the Lake Potrok Aike (Patagonia) record of Lisé-Pronovost et al. (2013), the Lake Van (Turkey) record of Vigliotti et al. (2014), and the Lake Towuti (Indonesia) record of Kirana et al. (2018). Lisé-Pronovost et al. (2013) offered a “corrected” NRM/ARM RPI proxy record, designed to compensate for the influence on RPI of magnetic grain-size changes. The correction method was originally applied to NRM/IRM data from Lake Pepin (Brachfeld and Banerjee, 2000), and has rarely been used since. We utilize the Potrok Aike RPI record before “correction” because we have concerns about the veracity of the correction, particularly for NRM/ARM data. Age models for lacustrine RPI data incorporated in the stack are as published, and are based on radiocarbon, tephrochronology, and for Lake Van, correlation of XRF core-scanning records to ice-core chronologies.

The marine RPI records included in the 0-45 ka stack from outside the Iberian Margin (Table 2) are the Black Sea record of Nowaczyk et al. (2013), the Rockall Trough record of Channell et al. (2016), the ODP Site 1063 record of Channell et al. (2012), the Bermuda Rise record of Schwartz et al. (1996), the Philippine Sea record of Stott et al. (2002), the ODP Site 1089 (South Atlantic) record of Stoner et al. (2003), and the Scotia Sea record of Xiao et al. (2016). Age models are as published apart from the ODP Site 1063 age model where a single additional age-depth point has been added to the published age model (Channell et al., 2012). Age models are based on combinations of orbitally-tuned oxygen isotope data, radiocarbon, tephrochronology and correlation to ice-core chronologies.

For the stack from outside the Iberian Margin, the 12 records were interpolated to a uniform 0.5-kyr sampling spacing, and set to a common mean and common standard deviation. The stack is the mean at each 0.5-kyr time-step, giving equal weight to each of the twelve records (Fig. 9a).

Finally an overall stack (Fig. 9a) was constructed by combining the individual records from outside the Iberian Margin with a stack of all 10 JC089 records, the Portuguese Margin Stack of Thouveny et al. (2004) and the MD01-2444 record of Channell et al. (2013), giving equal weight to each record. Again, all records are on their individual (published) age models, with no age adjustments (apart from a single extra age tie-point for Site 1063) or record matching.

7. Discussion

Individual RPI records in the SW Iberian Margin stack (Fig. 9b) and in the stack from outside the Iberian Margin (Fig. 9c) show considerable variability. Age model discrepancies account for some of this variability, and the saw-tooth character of some of individual records reflects low resolution at the 0.5 kyr sampling step. Rather than emphasizing individual higher resolution records, we assign equal weight to each record in the two stacks, and construct an overall stack as described above, that comprises a combination of three Iberian Margin records and 12 records from outside the Iberian Margin. The resulting stacks are similar to one another (Fig. 9a), but are very different from the published stacks for this time interval (Fig. 1a). The Holocene part of the RPI stacks can be only broadly matched to the Holocene compilations, CALS10k.1b and SHA.DIF.14k of Korte et al. (2011) and Pavon-Carrasco et al. (2014) (Fig. 9a). The scaling of the stacks to VADM was accomplished by matching the stacks to CALS10k.1b and SHA.DIF.14k and assuming a VADM of ~3 x10^{22} Am^2 for the Laschamp RPI minimum (Fig. 9a). The pre-Holocene part of the RPI stacks are characterized by a RPI shoulder (notch) at ~13-14 ka, that is represented in some individual records by a RPI minima (Figs. 9 b,c), and is preceded by a RPI high at ~15-18 ka (Fig. 9a). The decrease in RPI from ~20 ka to the Laschamp excursion at ~41 ka is marked by two poorly defined minima at ~26-30 ka and 34 ka. These RPI minima occur in some individual records, and are smoothed by the stacking process. In one of the cores included in the stack from outside the Iberian Margin (Core MD04-2822 from Rockall Trough), a directional excursion was recorded within a RPI minimum at 26.5 ka (Channell et al., 2016).

Previously published estimates of geomagnetic field intensity (VADM) since 30 ka from Greenland ^{36}Cl and ^{10}Be records, and from estimated atmospheric ^{14}C concentrations (Muscheler et al., 2005) do not resemble one another (Fig. 1b) or previously published RPI stacks (Fig. 1a), or the stacks resolved here (Fig. 9a). The resemblance amongst the previously published cosmogenic-based estimates of VADM is improved prior to 30 ka (Fig. 1b), possibly because cosmogenic isotope production is more sensitive to low field intensity, and is relatively insensitive to field intensities higher than modern (Masarik and Beer, 2009).

The peak in RPI stacks at 15-18 ka (Fig. 9a) may partially explain the well-documented drop in atmospheric $\Delta^{14}C$ in the "mystery interval" at 17.5-14.5 kyr (Broecker and Barker, 2007). The apparent lag of a peak in RPI at ~15-18 ka relative to the peak VADM at 14.5 ka inferred from ^{14}C production (Fig. 10) may be attributable to lock-in delay in acquisition of the remanent magnetization, with a ~2 kyr lag at a 10-15 cm/kyr sedimentation rate being equivalent to ~20-30 cm lock-in depth. On the other hand, no such offset is observed at the Laschamp excursion where ages from lavas and sediments agree rather well (e.g., Laj et al., 2014). Immediately after the RPI high at ~15-18 ka, a RPI minimum at ~13.5 ka is observed in some individual records (Fig. 9), notably in Core MD01-2444 where it is accompanied by a directional magnetic excursion (Channell et al., 2013). This excursion has not been observed elsewhere, and it is not present in any of the JC089 cores, although an excursion of similar age from $^{40}Ar/^{39}Ar$

methods (at ~17 ka) has been documented in the Tianchi Volcanics in China (Singer et al., 2014).

The new overall VADM stack from Figure 9a, combined with the CALS10k.1b model for the Holocene (Korte et al., 2011), is now compared with updated calculations of VADM from Intcal13 atmospheric ^{14}C (Reimer et al., 2013) and Greenland ^{10}Be using a current Greenland ice core timescale (Svensson et al., 2008). The updated VADM calculation based on ^{10}Be (Fig. 10a), using recent ^{10}Be production models (Poluianov et al., 2016; Herbst et al., 2017), is different from those shown in Figure 1b (from Muscheler at al., 2005) since the timescale update results in corresponding revisions in accumulation rates and ^{10}Be flux. Here we based the ^{10}Be flux calculation on the average GRIP and GISP2 ^{10}Be record (Muscheler at al., 2005) and adjusted the accumulation rate and ^{10}Be flux to be consistent with the most recent Greenland ice core timescale (Svensson et al., 2008). This procedure may lead to a significant climate signal in the ^{10}Be flux (e.g., Adolphi et al., 2014), however; it is not clear how such potential climate influence can be identified and corrected over longer timescales. The new calculations indicate that although the ^{10}Be-based VADM fits rather well with the overall VADM stack, the ^{14}C-based VADM does not (Fig. 10), presumably due to changes in carbon cycling over the last Termination and probably also due to an underestimated ^{14}C production rate. Nevertheless, the overall VADM stack can explain the atmospheric ^{14}C trend from about 25 to 15 ka as indicated by the similar trends in the VADM stack and ^{14}C-based geomagnetic field during this period (Fig. 10).

8. Conclusions

Based on 24 sedimentary RPI records from the SW Iberian Margin and elsewhere (Tables 1 and 2), we make the case for a revised view of geomagnetic field intensity in the latest Pleistocene (10-30 ka). We construct a stack of RPI data from 10 sediment cores recovered during Cruise JC089 (Table 1). This stack is combined with two previously published records from the Iberian Margin (Thouveny et al., 2004; Channell et al., 2013) and with 12 RPI records from outside the Iberian margin (Table 2) to produce an overall RPI stack (Fig. 9a). The RPI stacks feature a high in RPI at ~15-18 ka that is followed by a shoulder (notch) at 13-15 ka as RPI decreases to a minimum at ~9 ka. In some individual records (Fig. 9), the notch at 13-15 ka is manifest as a low in RPI that is largely smoothed out by stacking. In one record, MD01-2444 (Table 2), a RPI low at 13.5 ka is associated with a directional magnetic excursion (Channell et al., 2013).

The overall stack indicates a progressive increase in RPI from the low in RPI at ~41 ka associated with the Laschamp magnetic excursion to a high at 15-18 ka corresponding to late HS1 (Fig. 10). A low in RPI at ~34 ka, associated with the Mono Lake magnetic excursion, and at ~26-30 ka are manifest by more pronounced RPI minima in some individual records. A prominent RPI minimum at 26.5 ka is accompanied by a directional excursion in the Rockall Trough record (Table 2, Channell et al., 2016).

The inconsistent picture of RPI in the 10-30 ka interval from published RPI stacks (Fig. 1a) is attributed to poor preservation of recovered sediment in the uppermost part of sediment sequences, particularly those recovered by Calypso cores and the APC used by ODP/IODP. The cores incorporated into our stacks are not immune to drilling disturbance, but we minimize disturbance by preferentially selecting cores recovered using conventional piston and Kasten (gravity) coring, and cores with mean sedimentation rates >15 cm/kyr.

The new overall RPI stack is supported by a revised calculation of VADM from Greenland ^{10}Be flux (Fig. 10) using a recent ice-core timescale (Svensson et al., 2008) although a possible climate influence on the ^{10}Be flux is hard to assess. The overall RPI stack is, on the other hand, inconsistent with the estimated VADM from atmospheric ^{14}C (Fig. 10). The new overall RPI stack, even with 2 kyr magnetization lock-in delay, cannot explain atmospheric ^{14}C levels (Reimer et al., 2013), not only during the "Mystery Interval" but also back to 45 ka although it can explain the atmospheric ^{14}C trend from ~25 to 15 ka (Fig. 11). An increase in marine radiocarbon ventilation in late HS1 and/or the onset of the Bølling-Allerød has been observed in numerous records (e.g. Skinner and Shackleton, 2004; Robinson et al., 2005; Skinner et al., 2010, 2014, 2015; Burke and Robinson, 2012; Chen et al., 2015; de la Fuente et al., 2015; Umling and Thunell, 2017). If the timing of the observed RPI maximum is accurate, at ~15-18 ka (Fig. 10), this would raise the bar for the magnitude of marine radiocarbon ventilation change that would be needed to fully account for the atmospheric Δ^{14}C record, as it would imply an increasing trend in radiocarbon production while atmospheric radiocarbon activity was decreasing. Offsets between observed atmospheric Δ^{14}C changes and modeled atmospheric Δ^{14}C changes (e.g. derived from ^{10}Be- or RPI-based reconstructions of variable radiocarbon production rates, using an ocean outcrop-diffusion box-model), can provide an indication of how much atmospheric Δ^{14}C variability might be attributed to carbon cycle changes rather than ^{14}C production rate changes (Figure 11a). Across the deglaciation, these offsets track atmospheric CO_2 closely (Figure 11c), and share many features with available marine radiocarbon ventilation records, suggesting an ocean ventilation influence on atmospheric Δ^{14}C and CO_2. However, it is also notable that the existing marine radiocarbon ventilation records exhibit smaller changes than would seem to be required to fully reconcile the observed atmospheric Δ^{14}C record and the revised ^{10}Be and RPI records (Figure 11b). Therefore, while several independent records strongly support the combined influence of ocean ventilation and ^{14}C production changes on atmospheric Δ^{14}C and CO_2 during the last ice age and over the last Termination, a complete solution to the mystery of deglacial radiocarbon and carbon cycling remains elusive.

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The overall RPI stack, scaled to VADM, is in Table S1. The ^{10}Be-based estimate of geomagnetic field intensity is in Table S2. This work was made possible by NERC support (NE/J00653X/1) for Cruise 089 aboard the RSS *James Cook* that permitted collection of the cores for this study. JETC acknowledges support from US NSF grants EAR-1014506 and OCE-0850413, LCS from UK NERC grant NE/L006421/1, and RM from Swedish Research Council grant DNR2013-8421. We thank Kainian Huang for laboratory assistance, Nicolas Thouveny, Agathe Lisé-Pronovost, Wenshen Xiao and Kartika Kirana for sending requested data, and Claude Hillaire-Marcel for editorial guidance.

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Figure Captions

Fig. 1 (a) Relative paleointensity stacks: NAPIS (blue, Laj et al., 2000), GLOPIS (orange, Laj et al., 2004), SAPIS (dark green, Stoner et al., 2003), Sint-2000 (dashed red, Valet et al., 2005), PISO-1500 (dashed black, Channell et al., 2009) and PADM2M (dashed light green, Ziegler et al., 2011). (b) Modeled Holocene axial dipole field intensity (brown, Korte et al., 2011; black, Pavon-Carrasco et al., 2014), virtual axial dipole moment (VADM) determined from ^{10}Be flux (blue) and ^{36}Cl flux (green) in Greenland ice cores (Muscheler et al., 2005), and from Δ^{14}C (red dashed, Muscheler et al., 2005).

Fig. 2. Location of stations (3-8) occupied during cruise JC089 (Table 1), and neighboring cores (MD95-2042 and MD01-2444, Table 2). Core MD01-2444 and Station 6 are nominally at the same location.

Fig. 3. (a) Ca/Ti ratio from XRF core scans of piston cores (blue) and Kasten cores (red) correlated to the L* reflectance from Cariaco Basin (black) from Deplazes et al. (2013) for the 0-50 ka interval. (b) Ca/Ti ratio from XRF core scans for the 12-18 ka interval. (c) Zr/Sr ratio from XRF core scans for the 12-18 ka interval. Piston cores shown in blue, Kasten cores shown in red with labeled records from core 06-4K (light green), 06-5K (dark green) and 05-3K. Younger Dryas (YD), Bølling-Allerød (BA), Heinrich stadials (HS1-HS5) are marked.

Fig. 4. Component declination, inclination and associated maximum angular deviation (MAD) values determined for a uniform 20-80 mT peak field demagnetization interval. Piston cores 05-3P (green) and 03-1P (black) show variable declinations in the upper part. Other piston cores shown in blue, and Kasten cores in red. Cores were not oriented in azimuth, and the declinations were set by uniform rotation of the mean declination for each core to 0°.

Fig. 5 (a) Examples of orthogonal projection of AF demagnetization of natural remanent magnetization (NRM) for u-channel samples from JC089 Kasten cores. Examples from piston cores are shown in Figure S7. Projections are shown for core depths of 100 cm, 200 cm, 250 cm and 350 cm (300 cm usually corresponds to a section break). Peak fields are 0, 10-30 mT in 5mT steps, 30-60 mT in 2.5 mT steps and 60-80 mT in 5 mT steps. Intensities are given in mA/m. (b) Normalized intensities for NRM (black), ARM (blue), $IRM_{0.3T}$ (orange), and IRM_{1T} (red) at core depths of 100 cm and 200 cm in Cores 03-6K, 04-2K and 05-3K.

Fig. 6. (a) Plot of anhysteretic susceptibility (κ_{arm}) versus susceptibility (κ) with lines indicating lines of equal magnetite grain-size after King et al. (1983). (b) Hysteresis ratio plot for JC089 piston core data (blue) and JC089 Kasten core data (red) after Day et al. (1977) with magnetite grain size mixing line (green) from Carter-Stiglitz et al. (2001), and data for unannealed sized magnetite (Dunlop, 2002; Carter-Stiglitz and Dunlop, 2006). (c) Susceptibility (κ) versus age for JC089 piston cores (blue) and JC089 Kasten cores (red) with core 07-4P labeled. (d) κ_{arm}/κ versus age for JC089 piston cores (blue) and JC089 Kasten cores (red) with cores 06-4K and 07-4P labeled. (e) S-ratios determined as the ratio of $IRM_{0.3T}$ over IRM_{1T} (both after AF demagnetization at peak fields of 30 mT) for a selection of JC089 Kasten cores (red) and piston cores (blue). Labeling of Younger Dryas (YD) and Heinrich stadials: see caption of Figure 3.

Fig. 7. Sedimentation rates, and relative paleointensity (RPI) proxies for Cores 06-4K, 06-5K and MD01-2444. Slopes and accompanying linear correlation coefficients (r): NRM/ARM (dark blue), NRM/ARMAQ (light blue), NRM/$IRM_{0.3T}$ (orange), NRM/IRM_{1T} (red). Core MD01-2444 RPI proxy (black) and sedimentation rates (red) from Channell et al. (2013). Yellow shading indicates RPI minimum at ~13.5 ka. Grey shading indicates last 2 kyr (unreliable surface sediment).

Fig. 8. Sedimentation rates, and relative paleointensity (RPI) proxies for (a) Cores 03-1P and 03-6K, (b) Cores 04-2P and 04-2K, (c) Cores 05-3P and 05-3K, (d) Cores 07-4P and 08-5P. Slopes and accompanying linear correlation coefficients (r): NRM/ARM (dark blue), NRM/ARMAQ (light blue), NRM/$IRM_{0.3T}$ (orange), NRM/IRM_{1T} (red). Yellow

shading indicates RPI minimum at ~13.5 ka. Grey shading indicates last 2 kyr (unreliable surface sediment).

Fig. 9. Relative paleointensity data: (a) Iberian Margin stack (red), the stack from outside the Iberian Margin (blue) and an overall stack (black, see text for details) with the Holocene models of Korte et al. (2011) (brown) and Pavon-Carrasco et al. (2014) (black). Error bars on stacks are standard errors (2σ). (b) Individual Iberian Margin records from piston cores (blue) and Kasten cores (red) with Core MD01-2444 data (black continuous line, Channell et al., 2013) and the Portuguese Margin Stack (green, Thouveny et al., 2004). The black dashed line represents the Iberian Margin stack. (c) Individual records from outside the Iberian Margin (Table 2) including records from the South Atlantic realm (red), western Pacific realm (green), North Atlantic (blue) and Europe/Mediterranean (black). Black dashed line is the resulting stack for records from outside the Iberian Margin. Yellow shading marks RPI minima at ~13.5 ka, 26.5 ka (Rockall excursion), 34 ka (Mono Lake excursion) and 41 ka (Laschamp excursion). Grey shading indicates last 2 kyr (unreliable surface sediment).

Fig. 10. The overall virtual axial dipole (VADM) geomagnetic stack from Figure 9a (black with 2σ error) with the Holocene model of Korte et al. (2011) (green) plotted with an updated calculation of the ^{10}Be-based VADM (blue) and ^{14}C-based VADM (red). The updated VADM calculations from ^{14}C and ^{10}Be, in contrast to Figure 1b (from Muscheler at al., 2005), are based on the most recent Greenland ice-core time scale (Svensson et al., 2008). The ^{10}Be-based curve was calculated after low-pass filtering (cut-off 1/3000 yrs) the revised ^{10}Be flux, and by using the most recent ^{10}Be production models (Poluianov et al., 2016; Herbst et al., 2017).

Fig. 11 (a) Comparison of the Intcal13 ^{14}C data (black, Reimer et al., 2013) and modeled Δ^{14}C based on the overall VADM stack (labeled PI), and the ^{10}Be-based VADM, using a box-diffusion carbon cycle model (Siegenthaler, 1983) where the solid blue curve includes no magnetization lock-in delay and the dashed light blue curve includes a 2 kyr lock-in delay. The conversion of geomagnetic field into ^{14}C production rates was achieved using the local interstellar cosmic ray spectrum of Herbst et al. (2017) and the cosmogenic radionuclide yield functions of Poluianov et al. (2016). (b) Selected published marine radiocarbon ventilation records from the North Atlantic (red line and stars; Skinner et al., 2014), South Atlantic (black line and crossed diamonds; Skinner et al., 2010), South Pacific (purple filled diamonds; Skinner et al., 2015), and Eastern Equatorial Pacific (purple line and crossed squares; de la Fuente et al., 2015) compared with the ‘expected’ mean ocean ventilation age derived from the observed and modeled atmospheric radiocarbon activities in (a), assuming that their offset up to 5 ka is accounted for by mass balance of radiocarbon in the ocean-atmosphere system. (c) Comparison of atmospheric pCO_2 (Monnin et al., 2001; Lemieux-Dudon et al., 2010) and offsets between the observed and modeled $\Delta^{14}C$ records shown in (a). The mass balance calculation assumes that changes in the marine and atmospheric radiocarbon inventories form a closed and conservative system such that:

$$-\Delta R_a . XCO_2 . M_a = \Delta R_o . C_o . V_o$$

where ΔR_a and ΔR_o are incremental changes in the atmospheric- and average ocean radiocarbon activities, XCO_2 is the molar mixing ratio of the atmosphere (assumed equivalent to partial pressure at a nominal pressure of 1 atm), M_a is the molar mass of the atmosphere, C_o is the average carbon concentration of the ocean (assumed invariant at ~2.28352 mol/m^3), and V_o is the volume of the ocean (assumed to equal to 1.3 x 10^8 m^3). Incremental changes in R_a were derived at 200 yr time-steps and summed up forward in time.

Supplementary Fig. S1. Log(Ca/Ti) of JC089 cores from the Iberian Margin cores correlated to L* of Cariaco Basin for 0 to 80 ka (Deplazes et al., 2013). Individual records have been offset by a constant for illustration purposes.

Supplementary Fig. S2. Log(Ca/Ti) of JC089 cores from the Iberian Margin cores correlated to L* of Cariaco Basin for 0 to 25 ka (Deplazes et al., 2013). Individual records have been offset by a constant for illustration purposes.

Supplementary Fig. S3. Log(Zr/Sr) of JC089 cores from the Iberian Margin cores correlated to L* of Cariaco Basin for 0 to 80 ka (Deplazes et al., 2013). Individual records have been offset by a constant for illustration purposes.

Supplementary Fig. S4. Log(Zr/Sr) of JC089 cores from the Iberian Margin cores correlated to L* of Cariaco Basin for 0 to 25 ka (Deplazes et al., 2013). Individual records have been offset by a constant for illustration purposes.

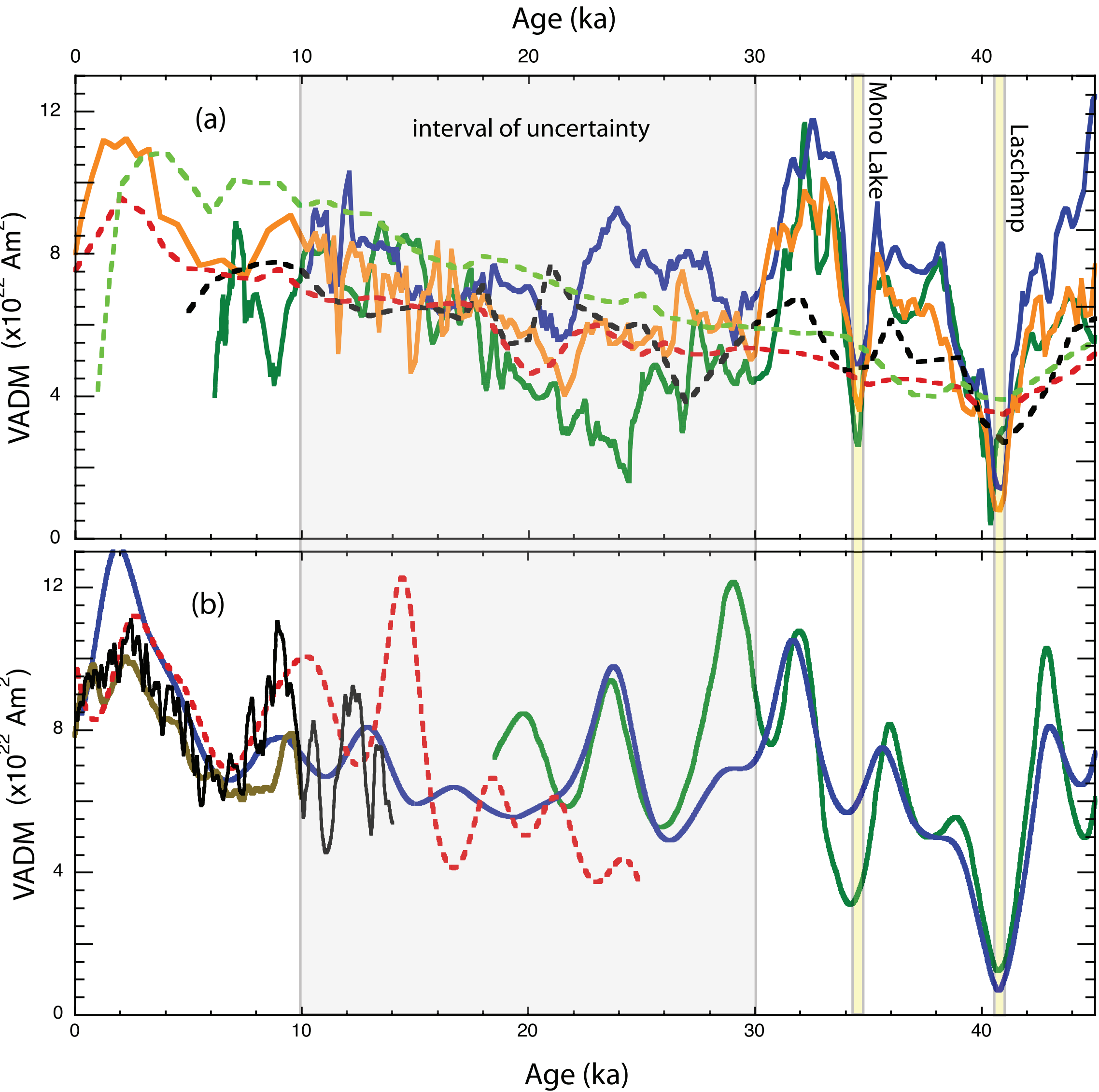
Supplementary Fig. S5. Tie points and sedimentation rates for piston (filled circles) and kasten (filled squares) cores from the Iberian Margin based on correlating XRF Ca/Ti and Zr/Sr to Cariaco L* for 0 to 80 ka. Open squares are the tie points used by Freeman et al. (2016).

Supplementary Fig. S6. Tie points and sedimentation rates for piston (filled circles) and kasten (filled squares) cores from the Iberian Margin based on correlating XRF Ca/Ti and Zr/Sr to Cariaco L* for 0 to 25 ka. Open squares are the tie points used by Freeman et al. (2016).

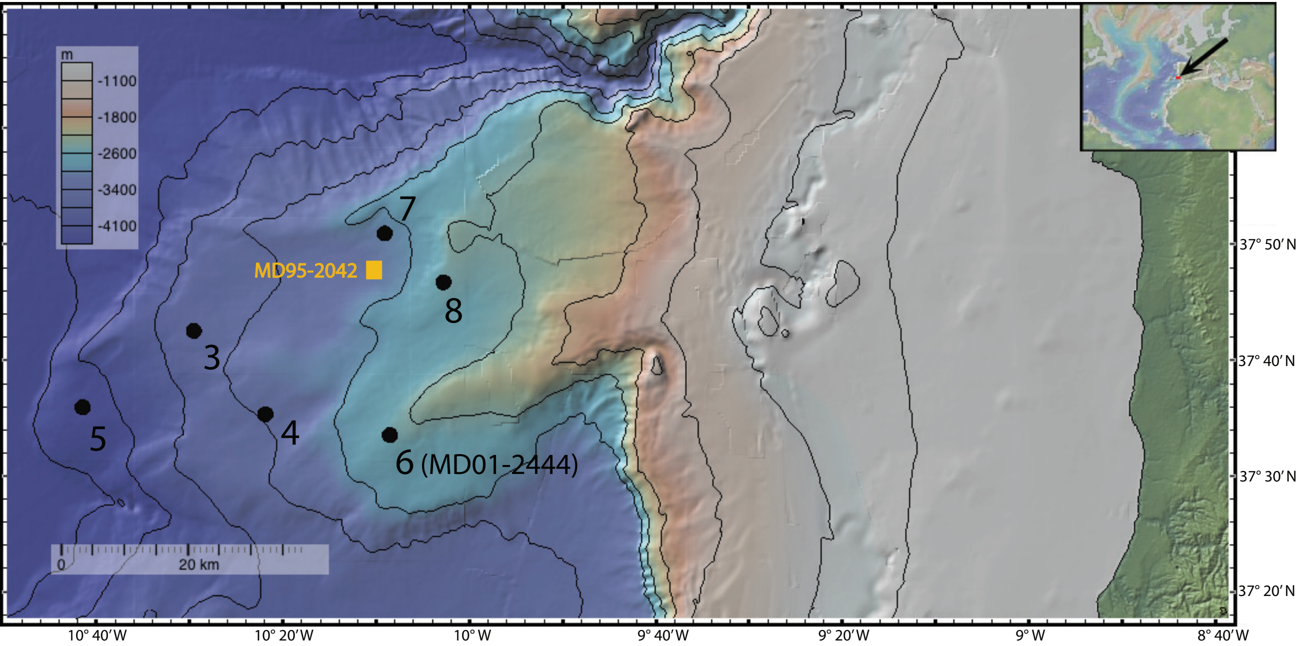
Supplementary Fig. S7. Examples of orthogonal projections of AF demagnetization of natural remanent magnetization (NRM) for JC089 piston cores. Projections for core depths of 100 cm, 200 cm, 250 cm and 350 cm (300 cm usually corresponds to a section break). Peak fields are 0, 10-30 mT in 5mT steps, 30-60 mT in 2.5 mT steps and 60-80 mT in 5 mT steps. Intensities are given in mA/m.

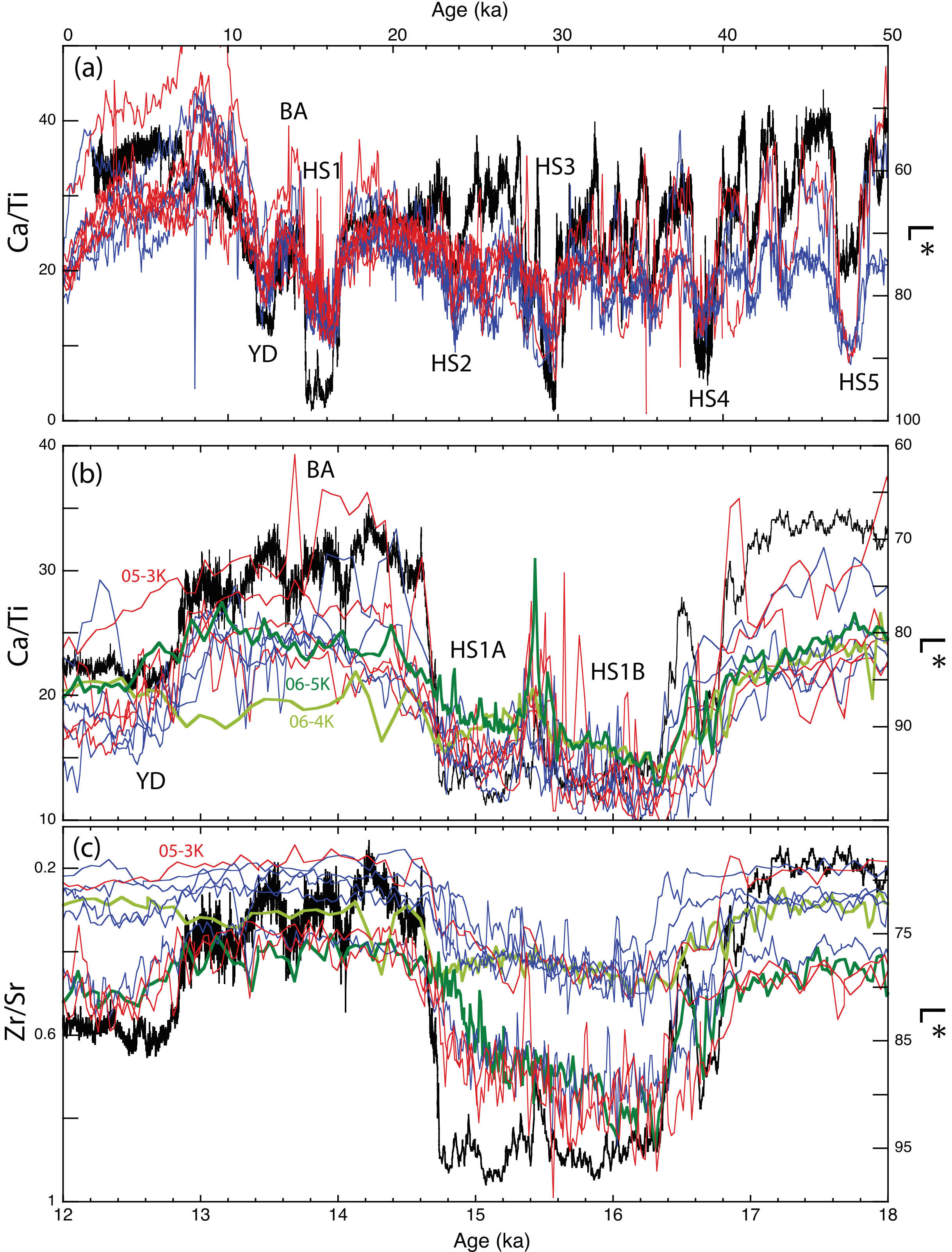
Supplementary Table 1. The overall relative paleointensity (RPI) stack, scaled to virtual axial dipole moment (VADM).

Supplementary Table 2. Geomagnetic intensity proxy based on ^{10}Be flux in Greenland ice cores, resampled at 0-5 kyr intervals, using the GICC05 timescale of Svensson et al. (2008).

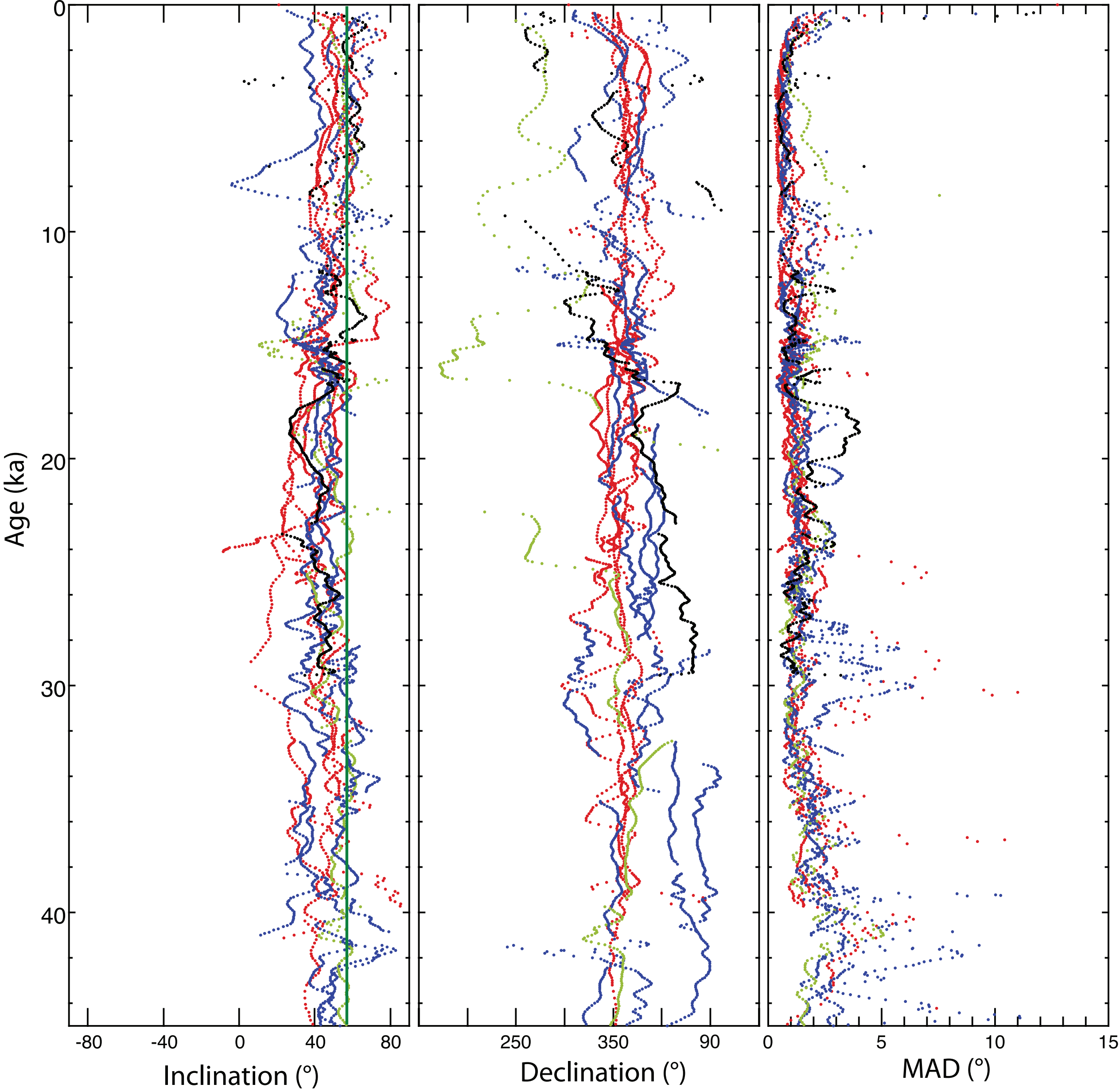


Age (ka)
0
10
20
30
40
(a)
interval of uncertainty
Mono Lake
Laschamp
12
8
4
0
VADM (x10^22 Am^2)
(b)
12
8
4
0
VADM (x10^22 Am^2)
0
10
20
30
40
Age (ka)

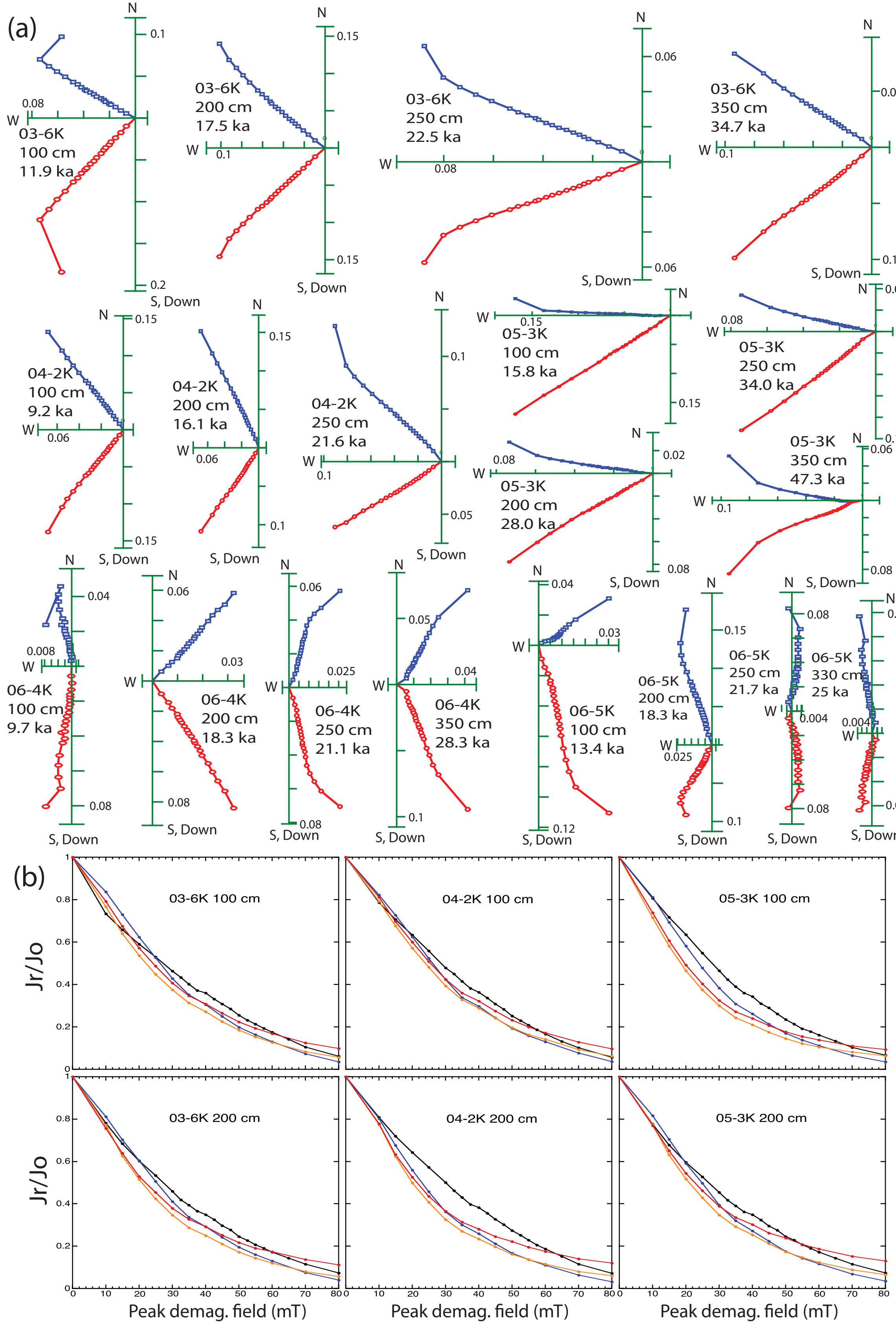

m
-1100
-1800
-2600
-3400
-4100
7
MD95-2042
8
3
5
4
6 (MD01-2444)
0
20 km
37° 50′ N
37° 40′ N
37° 30′ N
37° 20′ N
10° 40′ W
10° 20′ W
10° W
9° 40′ W
9° 20′ W
9° W
8° 40′ W

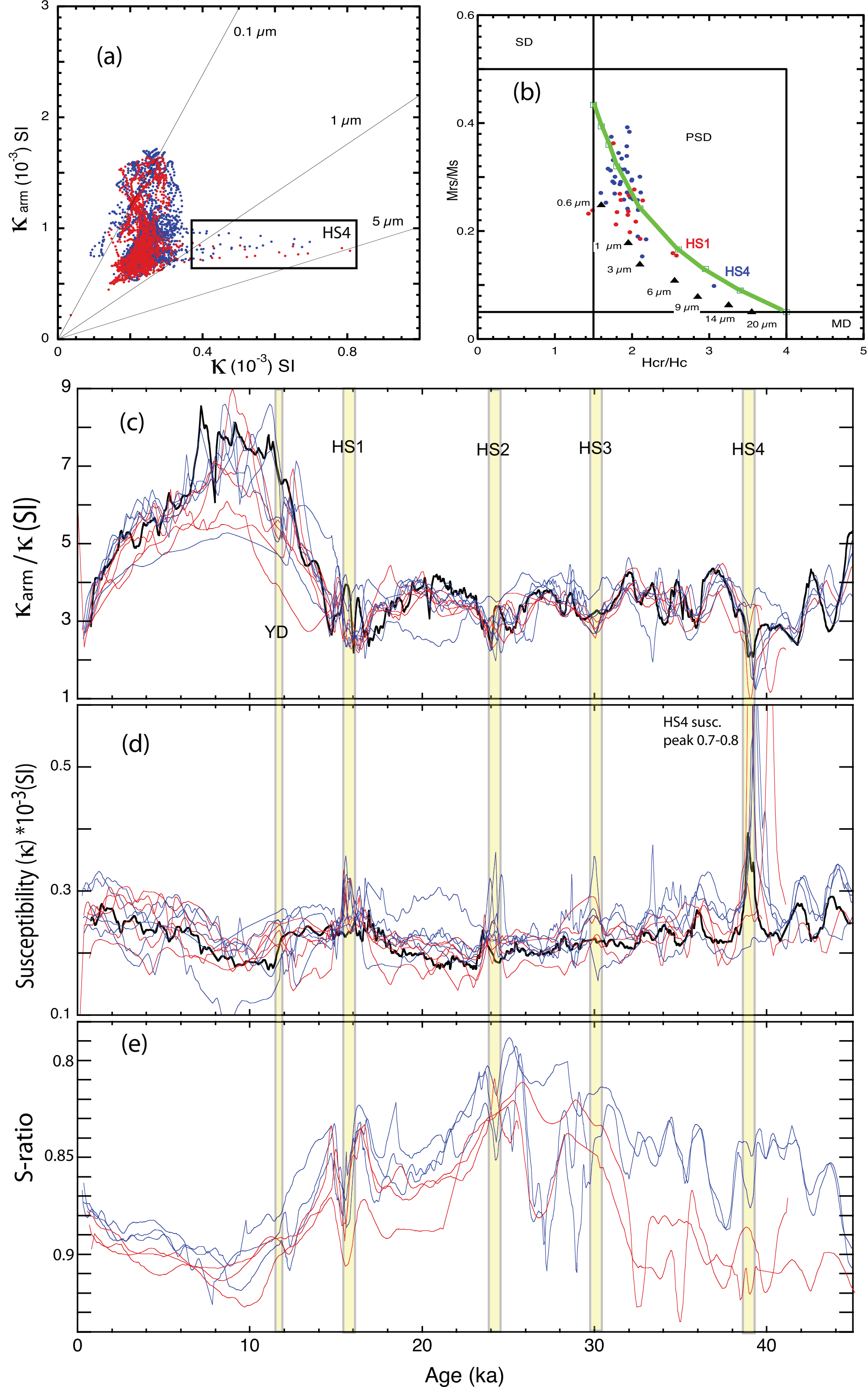


Age (ka)
(a)
Ca/Ti
BA
HS1
HS3
YD
HS2
HS4
HS5
L*
(b)
Ca/Ti
BA
05-3K
HS1A
HS1B
06-5K
06-4K
YD
L*
(c)
Zr/Sr
05-3K
L*
Age (ka)

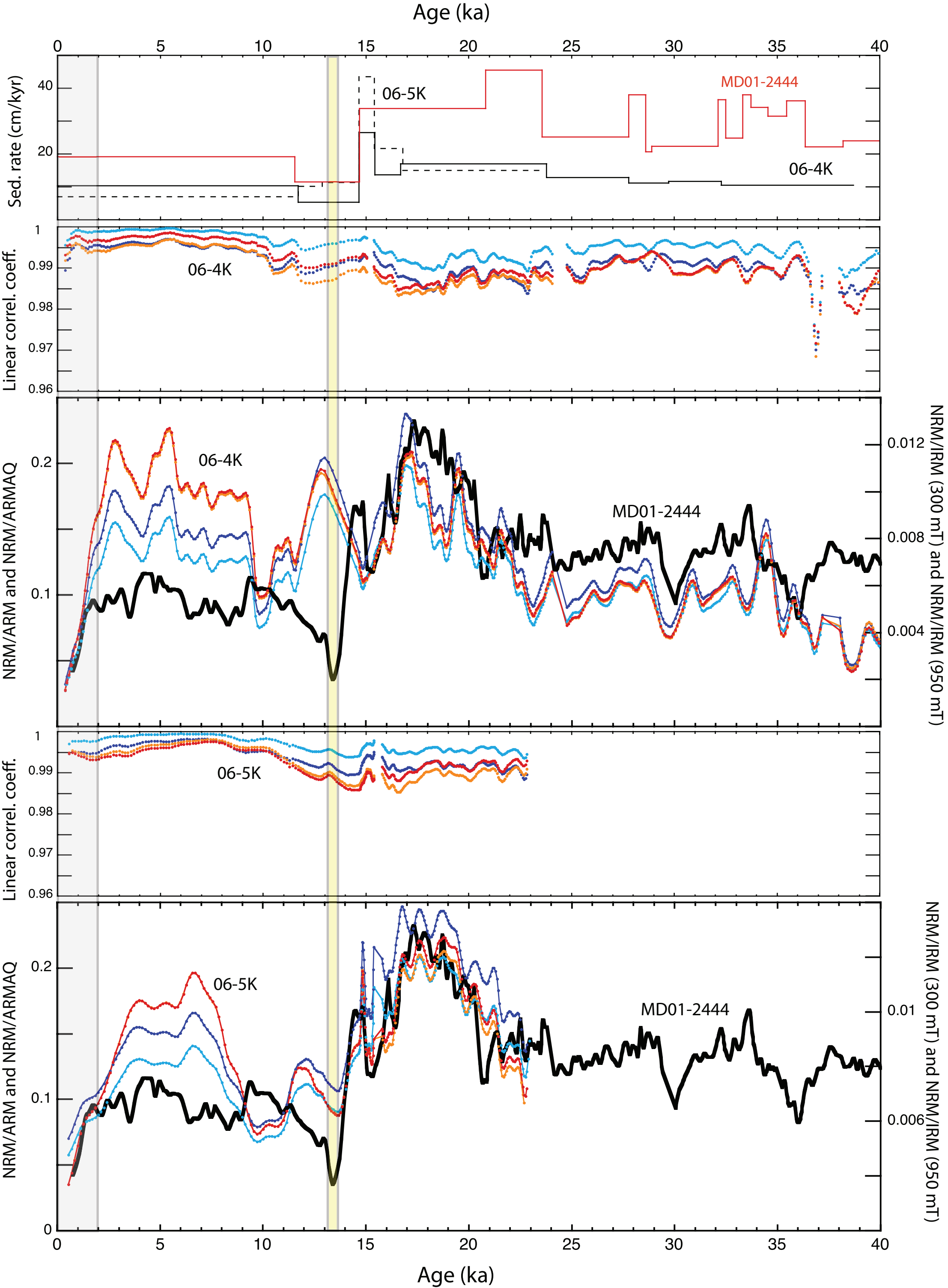


Age (ka)
0
10
20
30
40
-80
-40
0
40
80
Inclination (°)
250
350
90
Declination (°)
0
5
10
15
MAD (°)

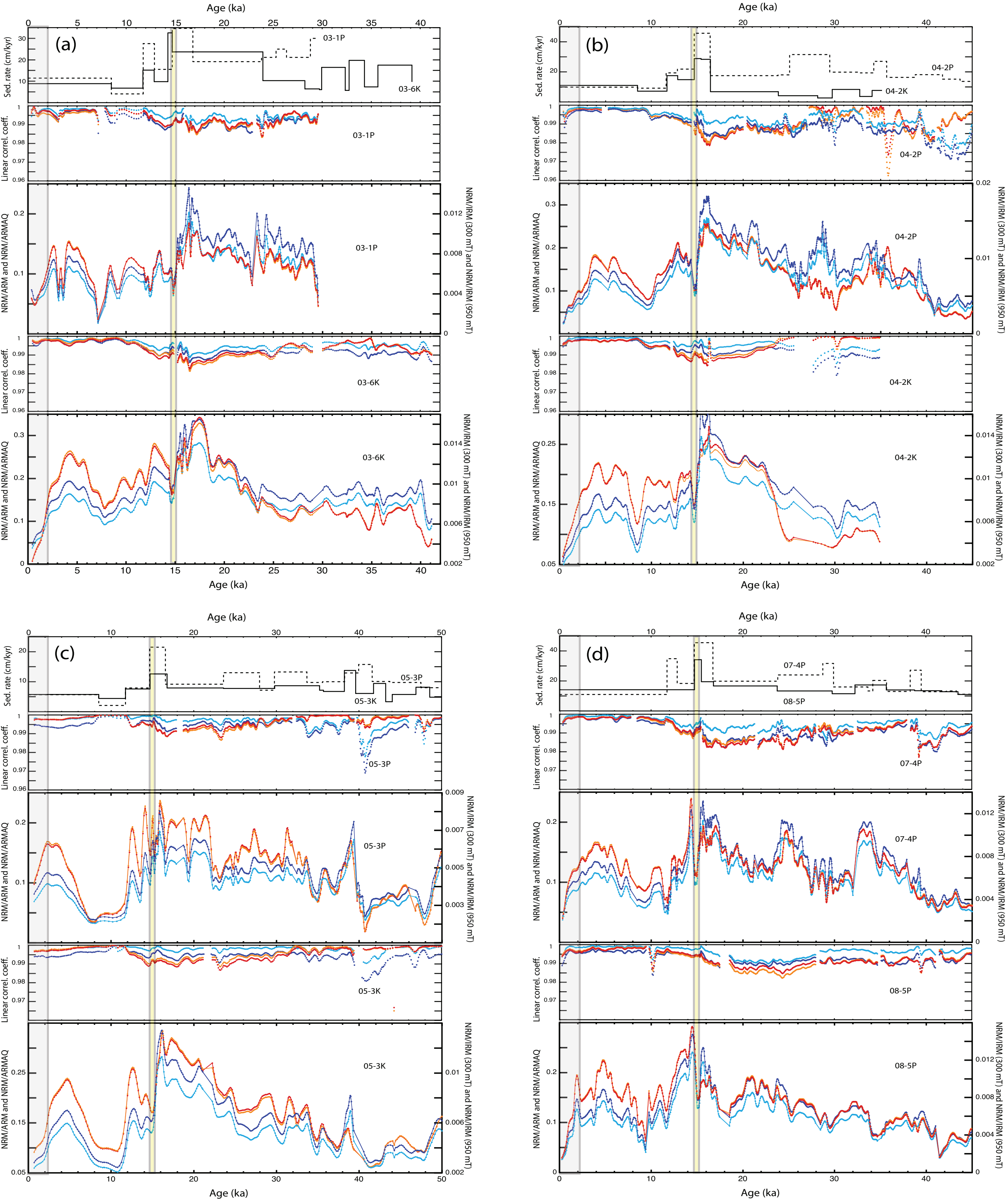

(a)
03-6K 100 cm 11.9 ka
03-6K 200 cm 17.5 ka
03-6K 250 cm 22.5 ka
03-6K 350 cm 34.7 ka
04-2K 100 cm 9.2 ka
04-2K 200 cm 16.1 ka
04-2K 250 cm 21.6 ka
05-3K 100 cm 15.8 ka
05-3K 250 cm 34.0 ka
05-3K 200 cm 28.0 ka
05-3K 350 cm 47.3 ka
06-4K 100 cm 9.7 ka
06-4K 200 cm 18.3 ka
06-4K 250 cm 21.1 ka
06-4K 350 cm 28.3 ka
06-5K 100 cm 13.4 ka
06-5K 200 cm 18.3 ka
06-5K 250 cm 21.7 ka
06-5K 330 cm 25 ka
N
W
S, Down
(b)
03-6K 100 cm
04-2K 100 cm
05-3K 100 cm
03-6K 200 cm
04-2K 200 cm
05-3K 200 cm
Jr/Jo
Peak demag. field (mT)



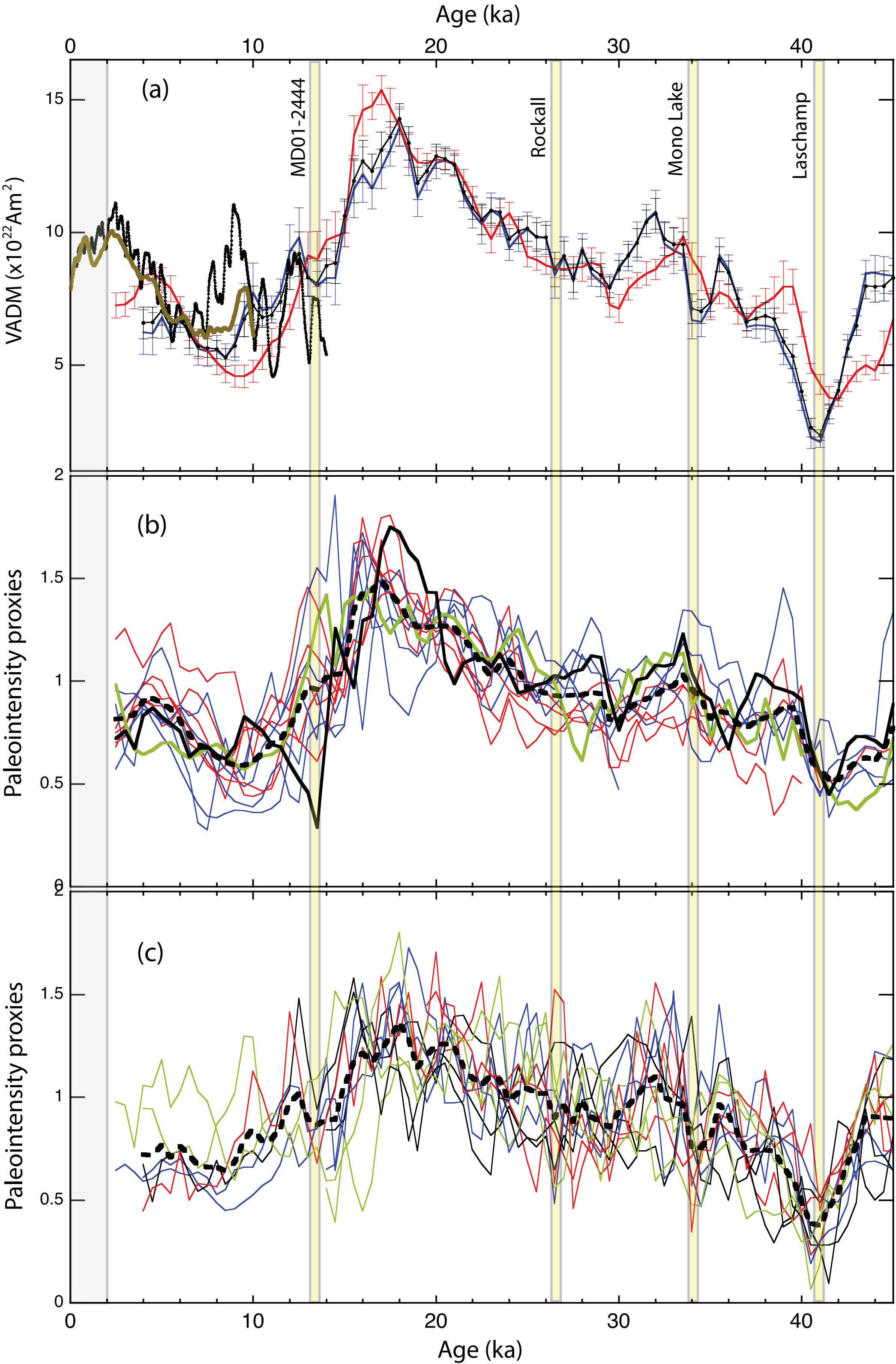
(a)
0.1 μm
1 μm
5 μm
HS4
κarm (10^-3) SI
κ (10^-3) SI
(b)
SD
PSD
MD
HS1
HS4
0.6 μm
1 μm
3 μm
6 μm
9 μm
14 μm
20 μm
Mrs/Ms
Hcr/Hc
(c)
HS1
HS2
HS3
HS4
YD
κarm / κ (SI)
(d)
HS4 susc.
peak 0.7-0.8
Susceptibility (κ) *10^-3(SI)
(e)
S-ratio
Age (ka)



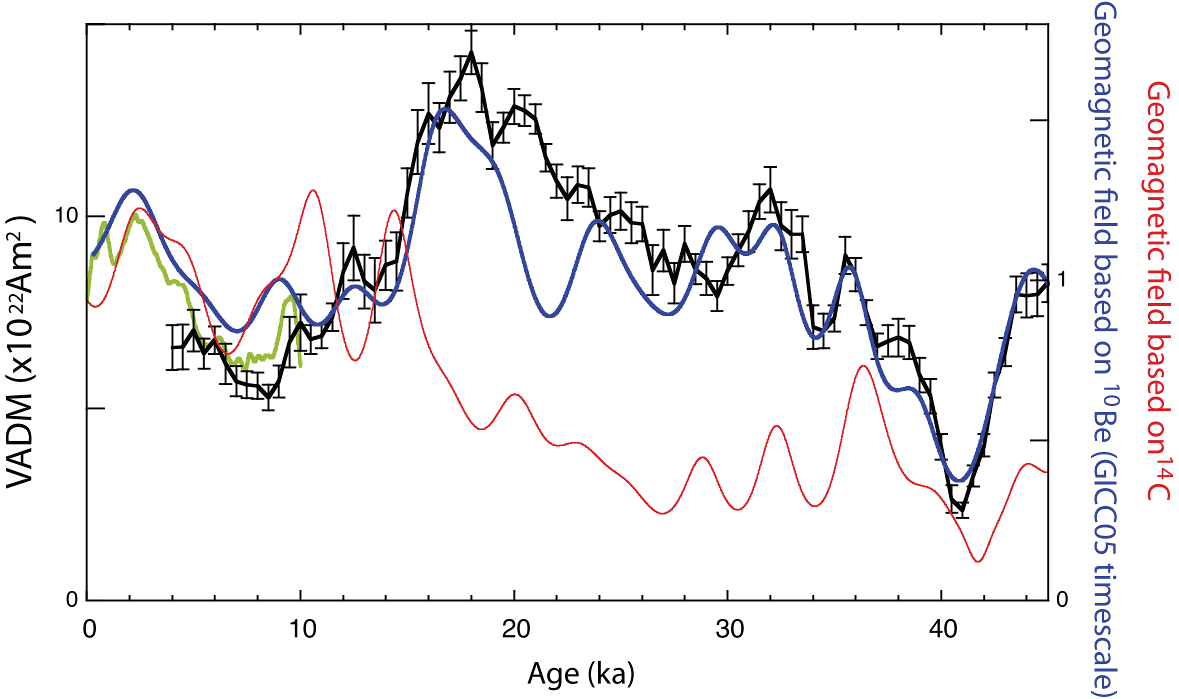
Age (ka)
Sed. rate (cm/kyr)
06-5K
06-4K
MD01-2444
Linear correl. coeff.
06-4K
NRM/ARM and NRM/ARMAQ
NRM/IRM (300 mT) and NRM/IRM (950 mT)
06-4K
MD01-2444
Linear correl. coeff.
06-5K
NRM/ARM and NRM/ARMAQ
NRM/IRM (300 mT) and NRM/IRM (950 mT)
06-5K
MD01-2444
Age (ka)



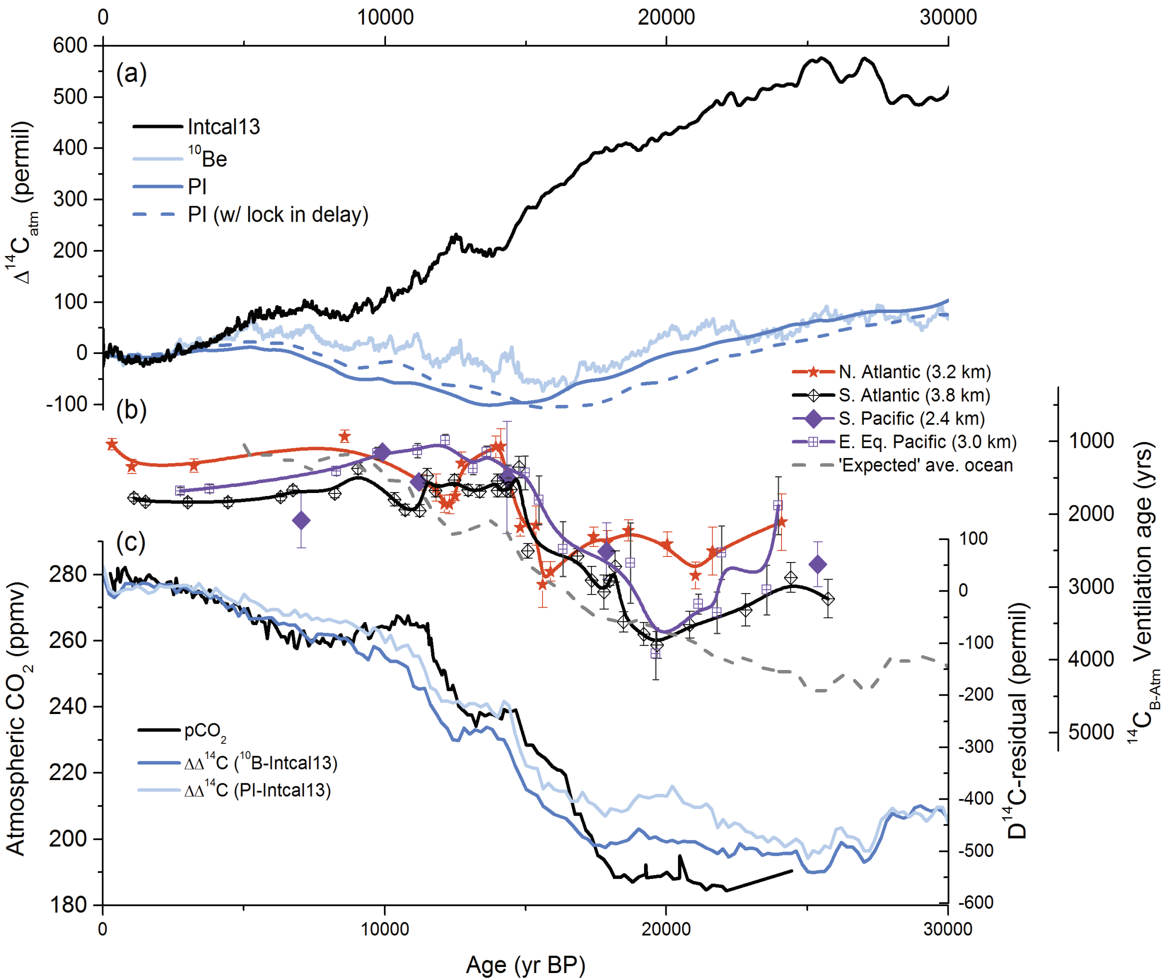
(a)
(b)
(c)
(d)
Age (ka)
Sed. rate (cm/kyr)
Linear correl. coeff.
NRM/ARM and NRM/ARMAQ
NRM/IRM (300 mT) and NRM/IRM (950 mT)
03-1P
03-6K
04-2P
04-2K
05-3P
05-3K
07-4P
08-5P



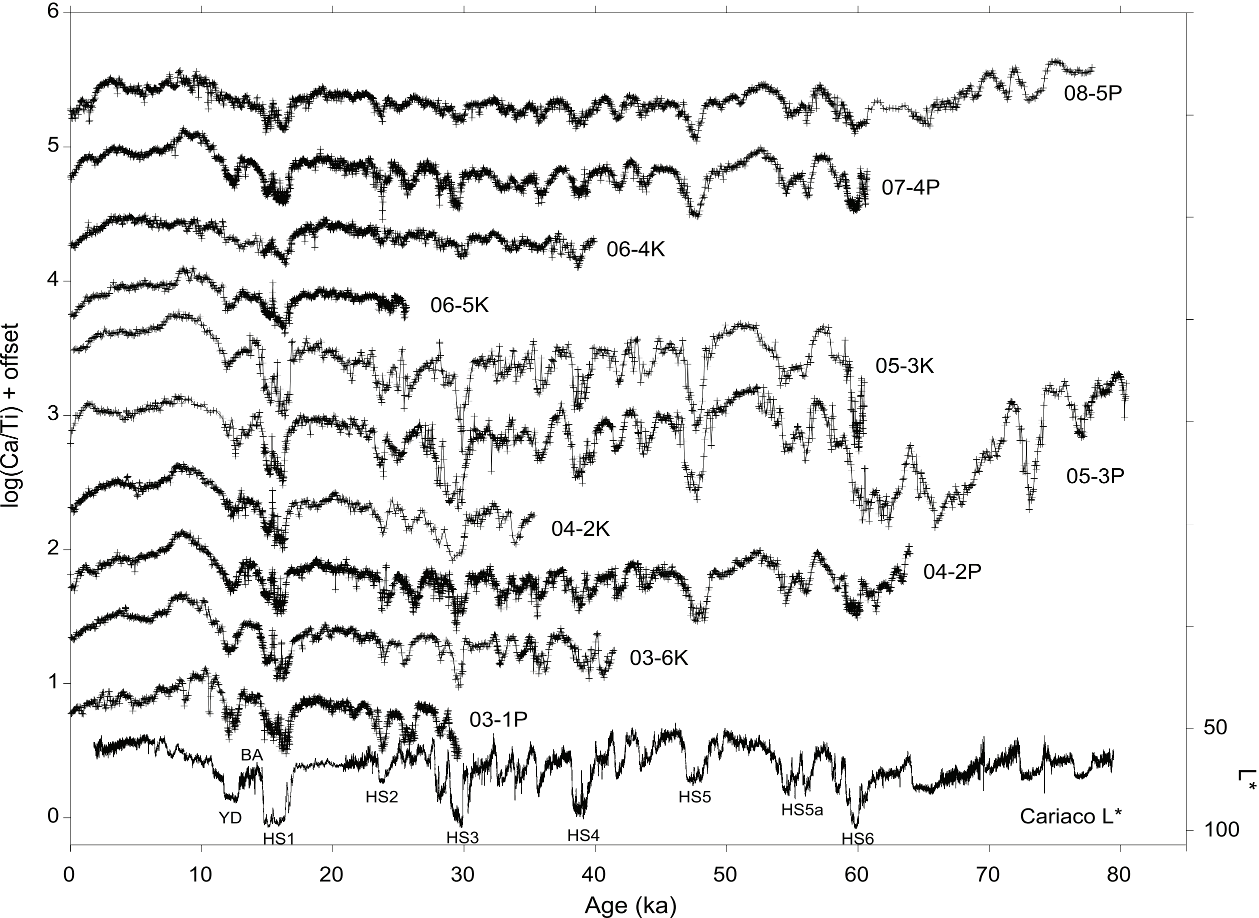
Age (ka)
0
10
20
30
40
VADM (x10^{22}Am^2)
15
10
5
2
(a)
MD01-2444
Rockall
Mono Lake
Laschamp
Paleointensity proxies
2
1.5
1
0.5
0
(b)
Paleointensity proxies
(c)
Age (ka)



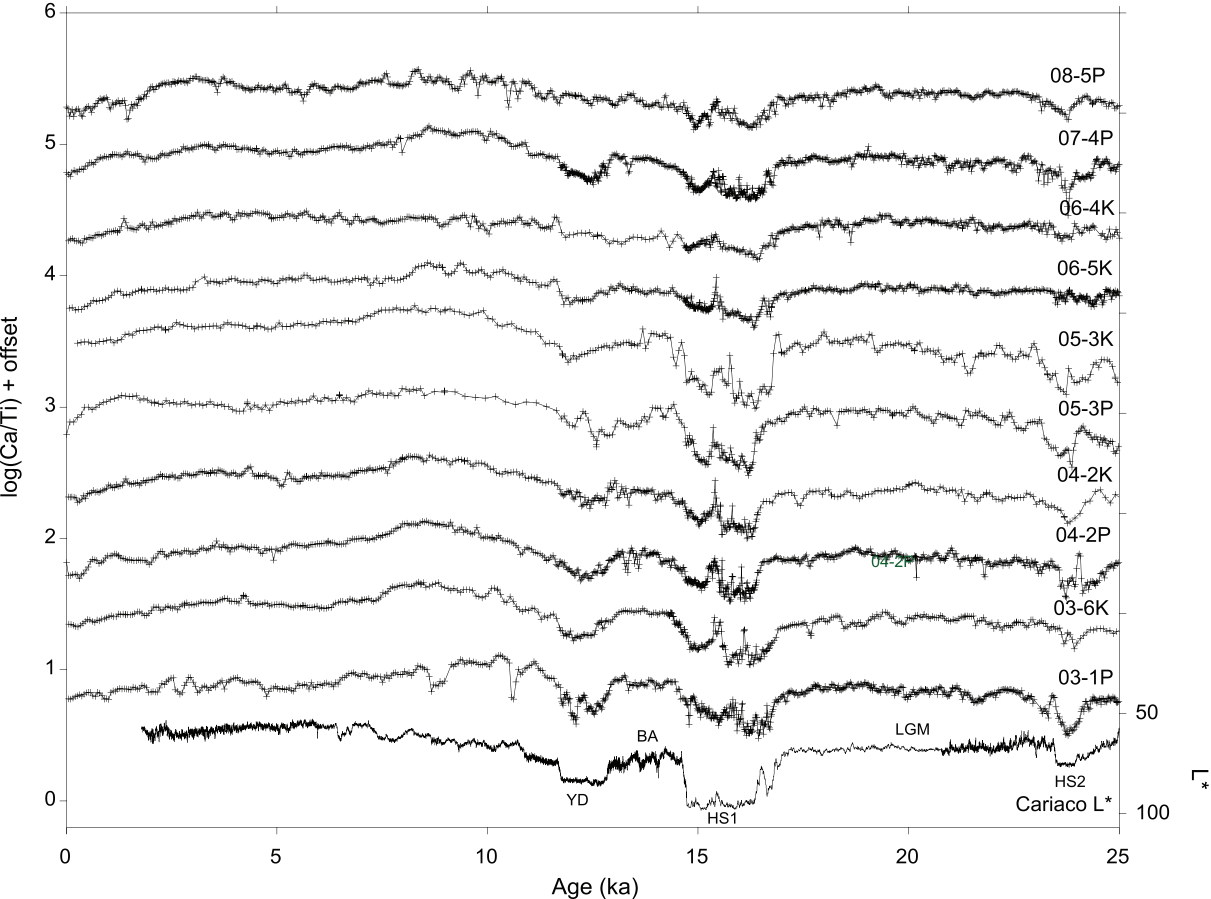
VADM (x10²²Am²)
10
0
0
10
20
30
40
Age (ka)
1
0
Geomagnetic field based on ¹⁰Be (GICC05 timescale)
Geomagnetic field based on ¹⁴C



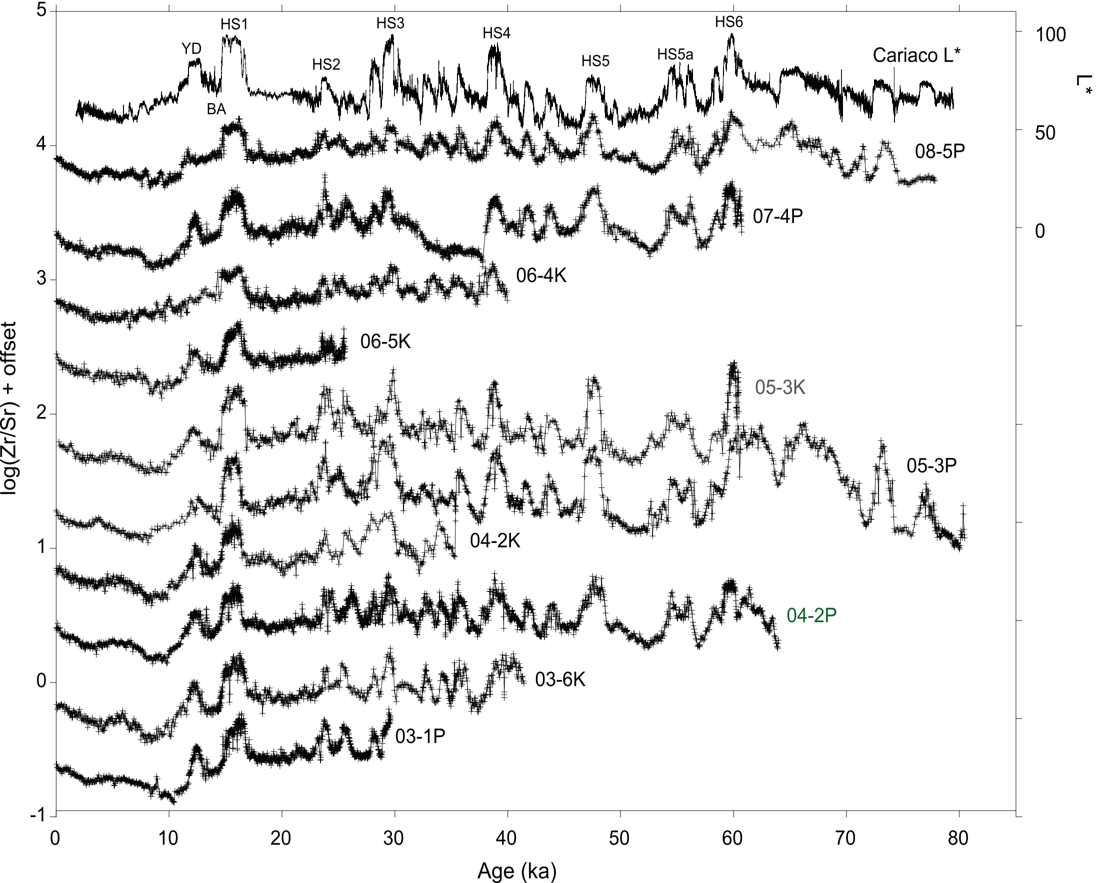
(a)
(b)
(c)
Intcal13
10Be
PI
PI (w/ lock in delay)
N. Atlantic (3.2 km)
S. Atlantic (3.8 km)
S. Pacific (2.4 km)
E. Eq. Pacific (3.0 km)
'Expected' ave. ocean
pCO2
ΔΔ14C (10B-Intcal13)
ΔΔ14C (PI-Intcal13)
Δ14Catm (permil)
Atmospheric CO2 (ppmv)
D14C-residual (permil)
14CB-Atm Ventilation age (yrs)
Age (yr BP)



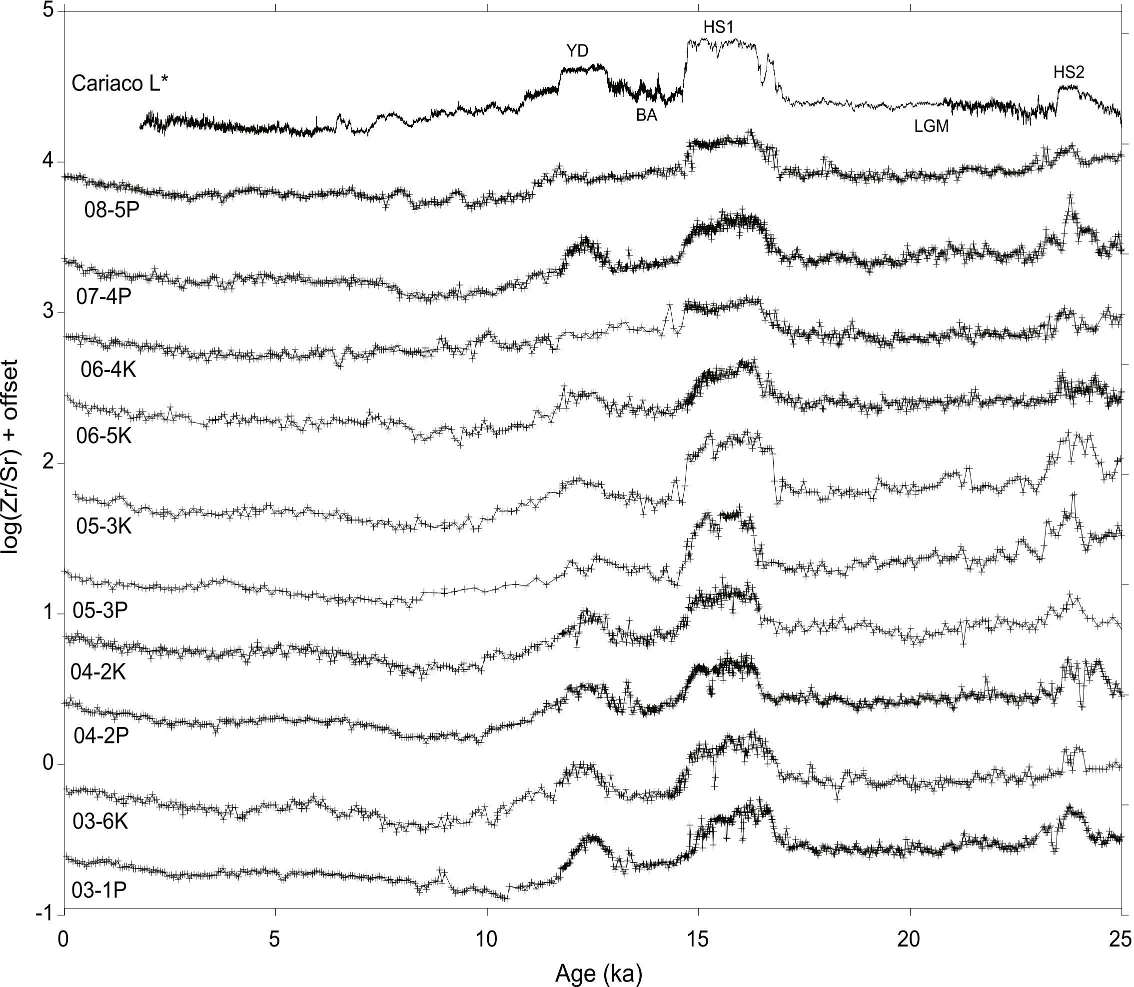
log(Ca/Ti) + offset
0
1
2
3
4
5
6
08-5P
07-4P
06-4K
06-5K
05-3K
05-3P
04-2K
04-2P
03-6K
03-1P
Cariaco L*
BA
YD
HS1
HS2
HS3
HS4
HS5
HS5a
HS6
50
100
L*
0
10
20
30
40
50
60
70
80
Age (ka)



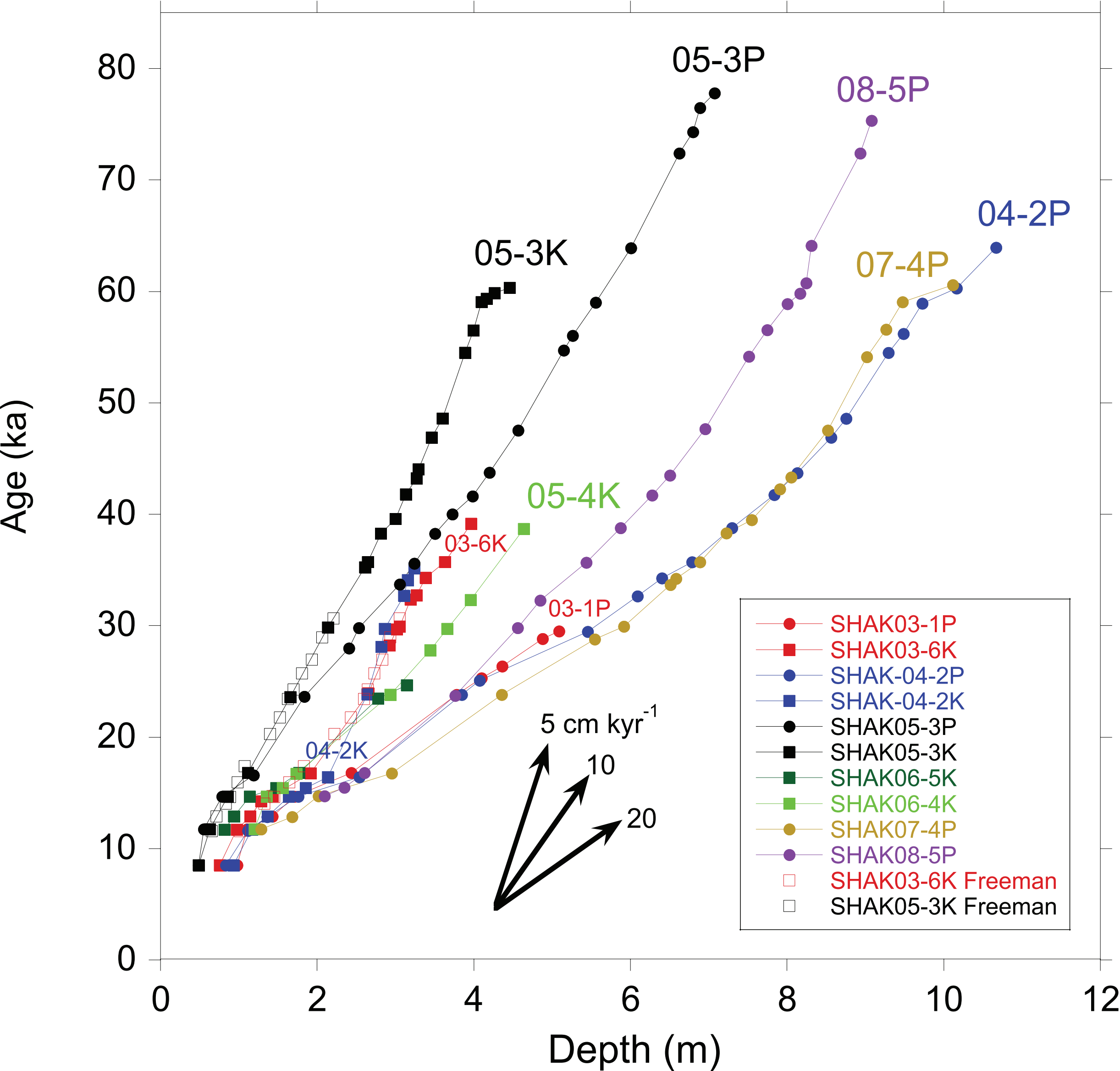
log(Ca/Ti) + offset
Age (ka)
08-5P
07-4P
06-4K
06-5K
05-3K
05-3P
04-2K
04-2P
04-2P
03-6K
03-1P
BA
LGM
YD
HS1
HS2
Cariaco L*
L*
50
100
0
1
2
3
4
5
6
0
5
10
15
20
25



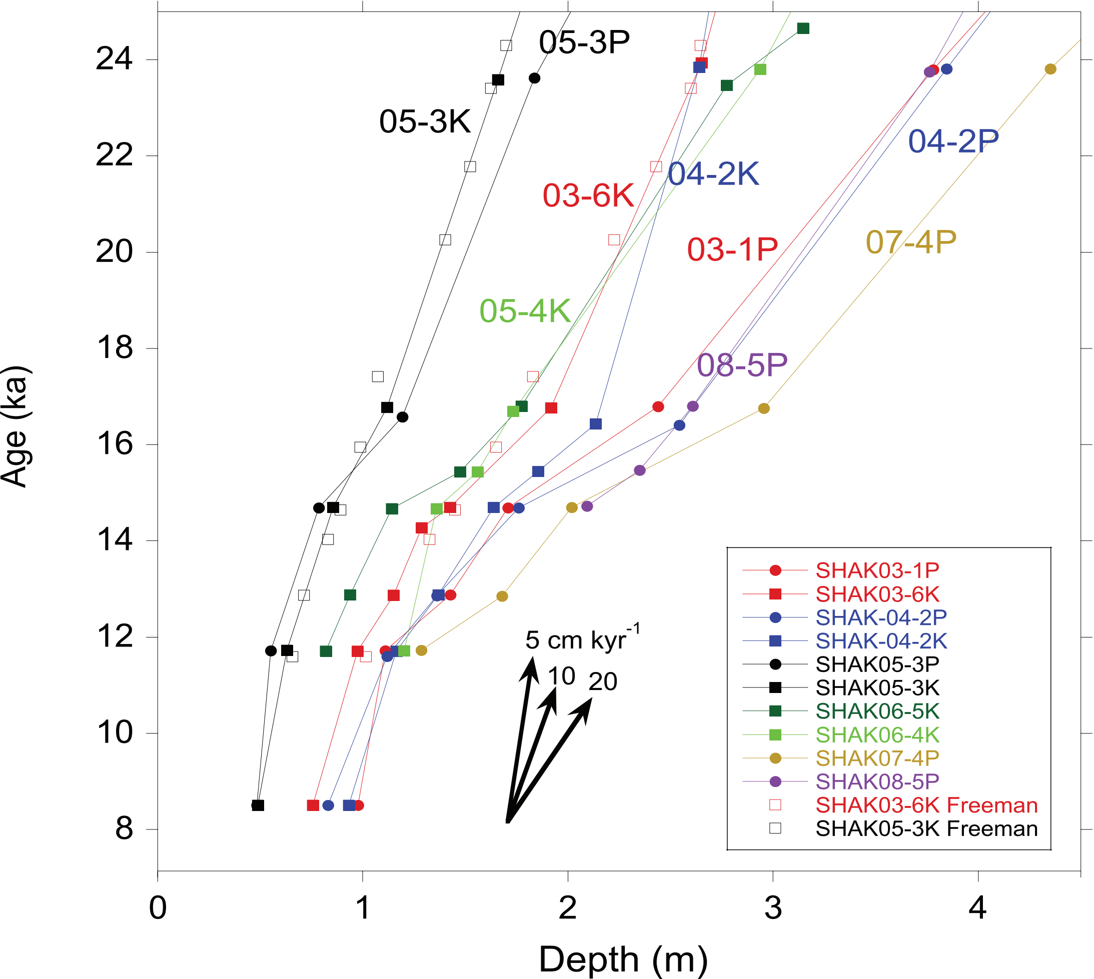
YD
HS1
BA
HS2
HS3
HS4
HS5
HS5a
HS6
Cariaco L*
08-5P
07-4P
06-4K
06-5K
05-3K
05-3P
04-2K
04-2P
03-6K
03-1P
log(Zr/Sr) + offset
L*
Age (ka)



Cariaco L*
YD
HS1
BA
LGM
HS2
L*
100
50
0
08-5P
07-4P
06-4K
06-5K
05-3K
05-3P
04-2K
04-2P
03-6K
03-1P
log(Zr/Sr) + offset
5
4
3
2
1
0
-1
0
5
10
15
20
25
Age (ka)



Age (ka)
Depth (m)
0
10
20
30
40
50
60
70
80
0
2
4
6
8
10
12
05-3P
08-5P
04-2P
05-3K
07-4P
05-4K
03-6K
03-1P
04-2K
5 cm kyr-1
10
20
SHAK03-1P
SHAK03-6K
SHAK-04-2P
SHAK-04-2K
SHAK05-3P
SHAK05-3K
SHAK06-5K
SHAK06-4K
SHAK07-4P
SHAK08-5P
SHAK03-6K Freeman
SHAK05-3K Freeman



05-3P
05-3K
03-6K
04-2K
04-2P
03-1P
07-4P
05-4K
08-5P
5 cm kyr-1
10
20
SHAK03-1P
SHAK03-6K
SHAK-04-2P
SHAK-04-2K
SHAK05-3P
SHAK05-3K
SHAK06-5K
SHAK06-4K
SHAK07-4P
SHAK08-5P
SHAK03-6K Freeman
SHAK05-3K Freeman
Age (ka)
Depth (m)

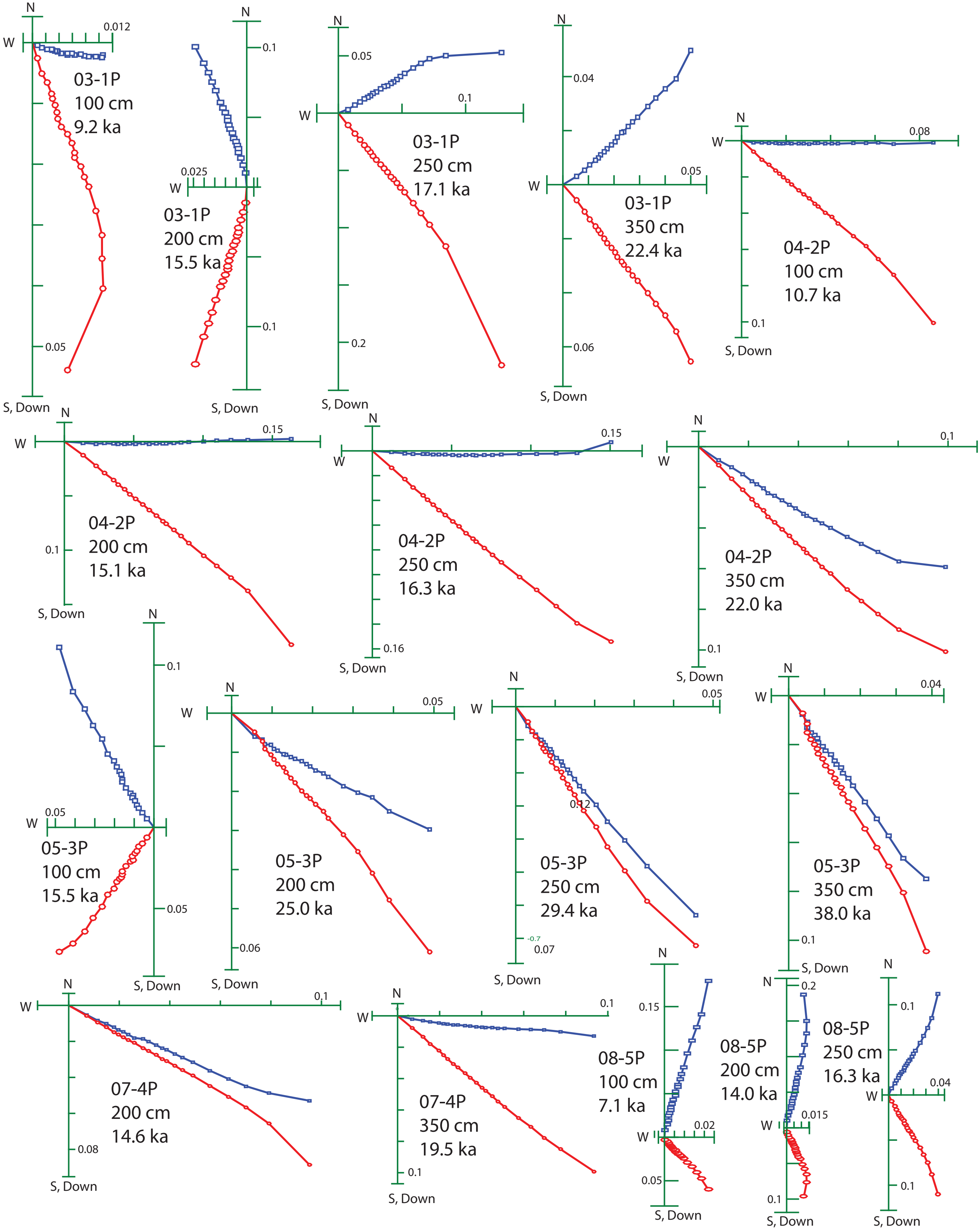

03-1P
100 cm
9.2 ka
03-1P
200 cm
15.5 ka
03-1P
250 cm
17.1 ka
03-1P
350 cm
22.4 ka
04-2P
100 cm
10.7 ka
04-2P
200 cm
15.1 ka
04-2P
250 cm
16.3 ka
04-2P
350 cm
22.0 ka
05-3P
100 cm
15.5 ka
05-3P
200 cm
25.0 ka
05-3P
250 cm
29.4 ka
05-3P
350 cm
38.0 ka
07-4P
200 cm
14.6 ka
07-4P
350 cm
19.5 ka
08-5P
100 cm
7.1 ka
08-5P
200 cm
14.0 ka
08-5P
250 cm
16.3 ka
N
W
S, Down

Table 1. JC089 cores included in the SW Iberian Margin stack

Station (Fig. 2)	Core	Core type	Lat. (°N)	Long. (°W)	WD (m)	Max. age (ka)	Recovery (m)	Mean sed. rate 10-45 ka (cm/kyr)
3	03-6K	Kasten	37.71	10.49	3740	41	4.16	10.2
3	03-1P	Piston	37.71	10.49	3731	30	5.14	17.2
4	04-2K	Kasten	37.59	10.36	3459	35	3.25	9.25
4	04-2P	Piston	37.59	10.36	3470	>45	10.69	18.3
5	05-3K	Kasten	37.60	10.69	4690	>45	4.68	7.5
5	05-3P	Piston	37.60	10.69	4662	>45	7.45	9.8
6	06-4K	Kasten	37.56	10.14	2646	40	4.75	12.2
6	06-5K	Kasten	37.56	10.14	2646	26	3.44	12.8
7	07-4P	Piston	37.85	10.15	3100	>45	10.19	18.4
8	08-5P	Piston	37.78	10.05	2619	>45	9.20	15.1

Table 2. Records other than from JC089 (Table 1) included in the RPI stacks for 0-45 ka

Site	Core type	Lat. (°)	Long. (°)	Water depth (m)	Mean sed rate (10-45 ka) cm/kyr	Ref.
MD01-2444 (SW Iberia)*	CAL	37.6 N	10.1 W	~3162	28	1
Portuguese Margin Stack*	CAL	39.0 N	10.2 W	2344	~25	2
Lac du Bouchet (France)	LC	4.9 N	3.8 E		22.2	3
Lake Biwa (Japan)	PC	35.2 N	136.1 E	67	40	4
Lake Potrok Aike (Patagonia)	PC	52.0 S	70.4 W	100	66	5
Lake Van (Turkey)	PC	38.6 N	42.7 E	360	40	6
Lake Towuti (Indonesia)	KPC	2.8 S	121.5 E	154	19	7
Black Sea	GC	42.0 N	37.0 E	200-800	60	8
MD04-2822 (Rockall Trough)	PC	56.8 N	11.4 W	2637	54	9
ODP 1063 (Bermuda Rise)	APC	33.7 N	57.6 W	4584	61	10
CH88-10p (Bermuda Rise)	PC	29.6 N	19.3 W	3818	23	11
MD98-2181 (Philippines)	CAL	6.3 N	125.8 E	2114	43	12
ODP 1089 (South Atlantic)	APC	40.9 S	9.9 E	4620	20	13
PS67-197-1 (Scotia Sea)	PC	55.1 S	44.1 W	3837	31	14

* included in SW Iberian Margin stack

Core type: LC Livingstone corer; KPC Kullenberg piston corer; PC piston corer; GC gravity corer; CAL Calypso corer (MD), APC Advanced piston corer (ODP).

References: (1) Channell et al. (2013), (2) Thouveny et al. (2004), (3) Thouveny et al. (1993), (4) Hayashida et al. (2007); (5) Lisé-Pronovost et al. (2013); (6) Vigilotti et al. (2014), (7) Kirana et al. (2018), (8) Nowaczyk et al. (2013), (9) Channell et al. (2016), (10) Channell et al. (2012), (11) Schwartz et al. (1996), (12) Stott et al. (2002), (13) Stoner et al. (2003), (14) Xiao et al. (2016).

Age (ka)	VADM ($x10^{22}$ Am^2)	Std. error		Age (ka)	VADM ($x10^{22}$ Am^2)	Std. error
4.00	6.585	0.592		25.00	10.136	0.478
4.50	6.604	0.585		25.50	9.833	0.537
5.00	7.032	0.541		26.00	9.800	0.450
5.50	6.432	0.391		26.50	8.600	0.648
6.00	6.777	0.354		27.00	9.112	0.538
6.50	6.162	0.522		27.50	8.257	0.520
7.00	5.705	0.391		28.00	9.283	0.462
7.50	5.625	0.350		28.50	8.627	0.389
8.00	5.587	0.343		29.00	8.384	0.430
8.50	5.284	0.334		29.50	7.926	0.396
9.00	5.708	0.417		30.00	8.581	0.360
9.50	6.728	0.655		30.50	9.119	0.419
10.00	7.238	0.728		31.00	9.601	0.535
10.50	6.798	0.374		31.50	10.386	0.445
11.00	6.881	0.308		32.00	10.695	0.587
11.50	7.380	0.355		32.50	9.746	0.620
12.00	8.573	0.725		33.00	9.533	0.636
12.50	9.179	0.835		33.50	9.533	0.472
13.00	8.303	0.703		34.00	7.120	0.566
13.50	8.078	0.847		34.50	7.016	0.452
14.00	8.731	0.641		35.00	7.346	0.335
14.50	8.830	0.764		35.50	8.984	0.481
15.00	10.615	0.646		36.00	8.483	0.430
15.50	11.935	0.828		36.50	7.497	0.326
16.00	12.676	0.796		37.00	6.617	0.327
16.50	12.309	0.647		37.50	6.758	0.409
17.00	13.101	0.667		38.00	6.847	0.497
17.50	13.593	0.569		38.50	6.719	0.425
18.00	14.267	0.570		39.00	5.875	0.450
18.50	13.356	0.632		39.50	5.326	0.450
19.00	11.847	0.613		40.00	4.006	0.329
19.50	12.314	0.387		40.50	2.639	0.356
20.00	12.867	0.458		41.00	2.354	0.201
20.50	12.756	0.396		41.50	3.244	0.270
21.00	12.537	0.378		42.00	4.045	0.296
21.50	11.528	0.359		42.50	5.612	0.331
22.00	10.918	0.435		43.00	6.472	0.369
22.50	10.462	0.555		43.50	7.964	0.467
23.00	10.823	0.476		44.00	7.942	0.570
23.50	10.752	0.503		44.50	7.970	0.568
24.00	9.744	0.389		45.00	8.266	0.494
24.50	10.034	0.462				

Age (ka)	^{10}Be-based intensity	Age (ka)	^{10}Be-based intensity
0.50	1.098	23.00	1.068
1.00	1.163	23.50	1.158
1.50	1.234	24.00	1.186
2.00	1.278	24.50	1.146
2.50	1.270	25.00	1.077
3.00	1.211	25.50	1.011
3.50	1.133	26.00	0.960
4.00	1.066	26.50	0.921
4.50	1.019	27.00	0.897
5.00	0.985	27.50	0.900
5.50	0.949	28.00	0.944
6.00	0.904	28.50	1.028
6.50	0.862	29.00	1.120
7.00	0.841	29.50	1.166
7.50	0.858	30.00	1.143
8.00	0.910	30.50	1.097
8.50	0.973	31.00	1.085
9.00	1.004	31.50	1.124
9.50	0.978	32.00	1.170
10.00	0.918	32.50	1.145
10.50	0.871	33.00	1.026
11.00	0.865	33.50	0.894
11.50	0.901	34.00	0.825
12.00	0.953	34.50	0.844
12.50	0.981	35.00	0.937
13.00	0.967	35.50	1.031
13.50	0.935	36.00	1.014
14.00	0.928	36.50	0.885
14.50	0.977	37.00	0.750
15.00	1.094	37.50	0.673
15.50	1.262	38.00	0.657
16.00	1.428	38.50	0.663
16.50	1.523	39.00	0.635
17.00	1.529	39.50	0.552
17.50	1.487	40.00	0.452
18.00	1.442	40.50	0.386
18.50	1.410	41.00	0.377
19.00	1.370	41.50	0.427
19.50	1.295	42.00	0.533
20.00	1.179	42.50	0.673
20.50	1.049	43.00	0.820
21.00	0.945	43.50	0.943
21.50	0.892	44.00	1.018
22.00	0.900	44.50	1.031
22.50	0.966	45.00	0.991