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The “Shackleton Site” (IODP Site U1385) on the Iberian Margin

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Abstract. Nick Shackleton’s research on piston cores from the Iberian margin highlighted the importance of this region for providing high-fidelity records of millennial-scale climate variability, and for correlating climate events from the marine environment to polar ice cores and European terrestrial sequences. During the Integrated Ocean Drilling Program (IODP) Expedition 339, we sought to extend the Iberian margin sediment record by drilling with the D/V *JOIDES Resolution*. Five holes were cored at Site U1385 using the advanced piston corer (APC) system to a maximum depth of ~ 155.9 m below sea floor (m b.s.f.). Immediately after the expedition, cores from all holes were analyzed by core scanning X-ray fluorescence (XRF) at 1 cm spatial resolution. Ca/Ti data were used to accurately correlate from hole-to-hole and construct a composite spliced section, containing no gaps or disturbed intervals to 166.5 m composite depth (mcd). A low-resolution (20 cm sample spacing) oxygen isotope record confirms that Site U1385 contains a continuous record of hemipelagic sedimentation from the Holocene to 1.43 Ma (Marine Isotope Stage 46). The sediment profile at Site U1385 extends across the middle Pleistocene transition (MPT) with sedimentation rates averaging ~ 10 cm kyr^{-1}. Strong precession cycles in colour and elemental XRF signals provide a powerful tool for developing an orbitally tuned reference timescale. Site U1385 is likely to become an important type section for marine–ice–terrestrial core correlations and the study of orbital- and millennial-scale climate variability.

1 Introduction

Few marine sediment cores have played such a pivotal role in paleoclimate research as those from the southwestern Iberian margin (Fig. 1; hereafter referred to as the “Shackleton sites”). Nick Shackleton’s original interest in the Iberian margin was to correlate marine sediment cores with European pollen stratigraphies, but the unexpected correlation of core MD95-2042 to the polar ice cores proved to be an exceptional windfall. Shackleton et al. (2000, 2004) showed that the planktic oxygen isotopic record could be correlated precisely to temperature variations (i.e. δ^{18}O) in Greenland ice cores, especially during MIS3 (Fig. 2). By comparison, the benthic δ^{18}O signal in the same cores resembles the temperature record from Antarctica. Moreover, the narrow continental shelf and proximity of the Tagus River results in the rapid delivery of terrestrial material, including pollen, to the deep-sea environment, thereby permitting direct correlation to European terrestrial sequences (e.g. Sánchez-Goñi et al., 1999; Shackleton et al., 2003; Tzedakis et al., 2004, 2009). Few places exist in the world ocean where such detailed and unambiguous marine–ice–terrestrial correlations are possible.

In November 2009, an ECORD-sponsored Magellan workshop was held in Lisbon, Portugal, to develop plans for

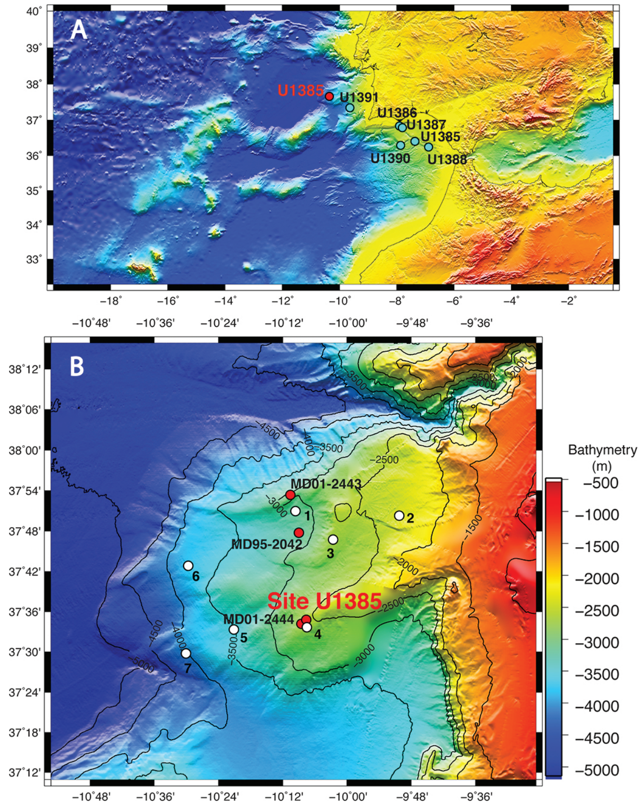

Figure 1. Maps of **(A)** west Iberian margin showing the location of sites drilled during the IODP Expedition 339 **(B)** Detailed bathymetry (Zitellini et al., 2009) of the Promonotorio dos Principes de Avis, including the locations of selected *Marion Dufresne* (MD) piston cores, the IODP Site U1385 (37°34.285′ N, 10°7.562′ W; 2578 m b.s.l.), and proposed drilling site in the proposal IODP 771-Full. Modified after Expedition 339 Scientists (2013b).

obtaining a long sediment record from the Iberian margin (Abrantes et al., 2010). A full proposal (771-Full) and Ancillary Program Letter (APL 763) were submitted to the Integrated Ocean Drilling Program (IODP), with the latter requesting four days of ship time to drill one of the “Shackleton sites” to 150 m b.s.f. APL-763 was approved for drilling and scheduled as part of the IODP Expedition 339, whose main purpose was to study the history of Mediterranean Outflow Water (see Hernández-Molina et al., this issue).

2 Recovery

IODP Site U1385 (37°34.285′ N, 10°7.562′ W) was drilled in November 2011 (Fig. 1). The site is located on a spur, the Promonotorio dos Principes de Avis, along the continental slope of the southwestern Iberian margin, which is elevated above the abyssal plain and influence of turbidites. The site is near the position of piston core MD01-2444, which has provided a remarkable record of millennial-scale climate variability of the last 190 ka (Vautravers and Shackleton, 2006; Skinner et al., 2007; Margari et al., 2010; Martrat et al., 2007; Hodell et al., 2013). The water depth (2578 m b.s.l.) of Site U1385 places it under the influence of Northeast Atlantic Deep Water today, although it was influenced by southern-sourced waters during glacial periods.

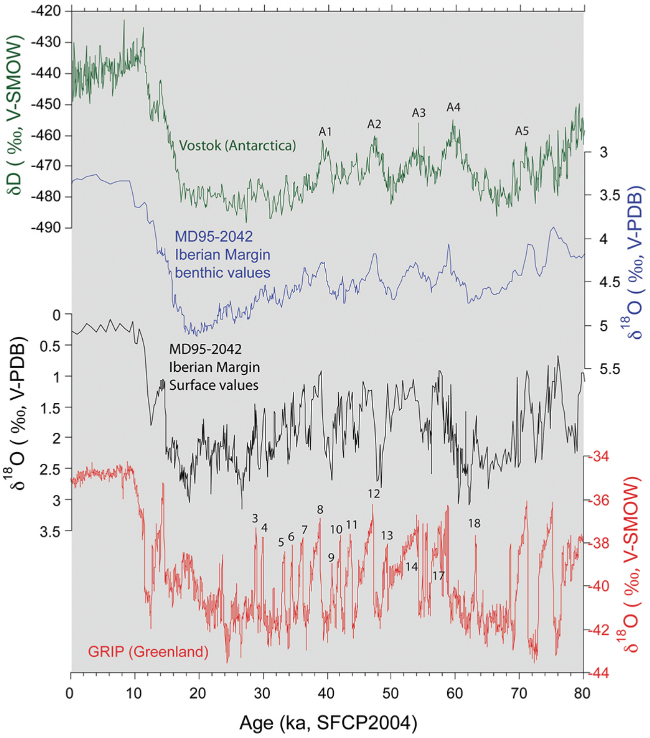

Figure 2. Correlation of δ^{18}O record of Greenland ice core (red) to δ^{18}O of *Globigerina bulloides* (black) in Core MD95-2042 (Shackleton et al., 2000). Resulting correlation of Vostok δD (green) and benthic δ^{18}O of Core MD95-2042 (blue) is based on methane synchronization. VPDB = Vienna Peedee belemnite, VSMOW = Vienna standard mean ocean water. Modified after Expedition 339 Scientists (2013a).

Five holes were cored at Site U1385 using the advanced piston corer (APC) system to a maximum depth of ~ 155.9 m b.s.f. A total of 67 cores were recovered representing 621.8 m of sediment with a nominal recovery of 103.2 % (> 100 % due to post-recovery core expansion). The sediment lithology consists of uniform, nannofossil muds and clays, with varying proportions of biogenic carbonate and terrigenous sediment (Expedition 339 Scientists, 2013a).

Following the cruise, split cores from all holes were analyzed by core scanning X-ray fluorescence (XRF) at the University of Cambridge and the Royal Netherlands Institute for Sea Research (NIOZ) to obtain semi-quantitative elemental data at 1 cm spatial resolution (Fig. 3). These data were used to accurately correlate among holes and construct a complete spliced stratigraphic section, containing no notable gaps or disturbed intervals to 166.5 mcd.

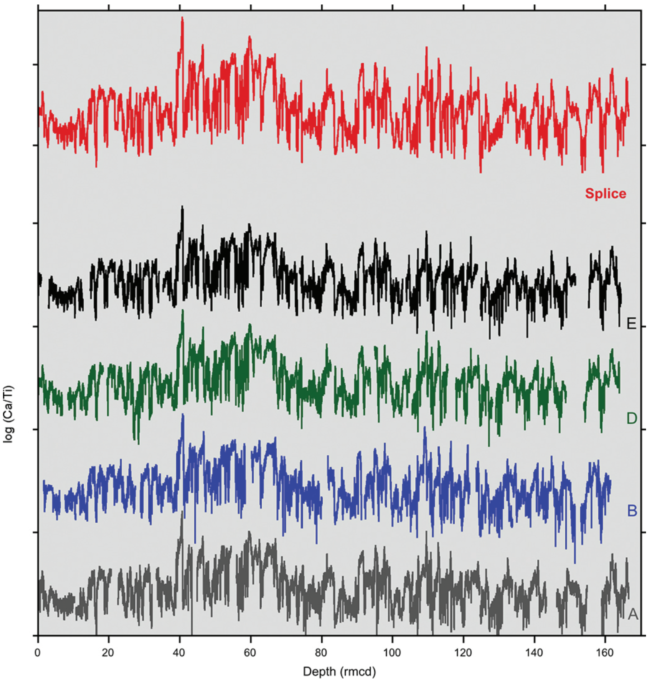

Figure 3. Log Ca/Ti measured by scanning XRF in Holes A (grey), B (blue), D (green), and E (black) from Site U1385. The spliced Ca/Ti record (red) is comprised of segments from Holes A, B, D, and E. Ca/Ti is a proxy for weight %$CaCO_3$ content and reflects the relative proportion of biogenic carbonate and detrital sediment (Hodell et al., 2013).

3 Developing an accurate chronology

A pre-requisite for all future paleoclimatic studies utilizing Site U1385 will be developing an accurate timescale. A low-resolution (20 cm) benthic oxygen isotope record (Fig. 4) demonstrates that Site U1385 contains a complete record from the Holocene to 1.43 Ma (Marine Isotope Stage 46). The record can be correlated unambiguously to the LR04 benthic δ^{18}O stack (Lisiecki and Raymo, 2005) to provide an initial age model. Variations in sediment colour contain very strong precession signals at Site U1385 (Fig. 5), which will be used for orbital tuning.

For the last 800 kyr, it may also be possible to fine-tune the chronology by correlation of millennial events to ice core and speleothem records. The Ca/Ti signal at Site U1385 displays fine-scale millennial variations that mirror planktic δ^{18}O and are highly correlated with alkenone-based sea surface temperature (SST) estimates (Fig. 6). As Shackleton et al. (2000, 2004) demonstrated, these variations could be correlated to the Greenland ice core record. Similarly, Chinese speleothem records also contain millennial-scale “weak monsoon events” that have been correlated to cold phases in the North Atlantic (Cheng et al., 2009). A potential approach for further refining the absolute timescale of Site U1385 will be to correlate the prominent minima in Ca/Ti (corresponding to severe cold events) to weak monsoon events in the speleothem records (Hodell et al., 2013). For the last 800 ka, a “synthetic Greenland” record has been produced by extracting and differentiating the high-frequency variability from the Antarctic EPICA-Dome C ice core record (Barker et al., 2011). Ca/Ti shows a good match with the real and synthetic Greenland ice core δ^{18}O record for the last 120 kyr (Fig. 6), and this correlation could be exploited for fine-tuning the Site U1385 over the past 800 kyr.

4 A marine sediment analog to the polar ice cores

The polar ice cores have provided unrivaled records of climate change that have become benchmarks for Pleistocene climate variability; however, the oldest continuous ice cores recovered to date in Greenland and Antarctica is ~ 124 and 800 ka, respectively. An important challenge is to identify complementary marine sections with sufficiently high sedimentation rates and climate signals suitable for comparison with the polar ice core records. If we assume the correlation between rapid temperature changes on the Iberian margin and over Greenland has held for older glacial periods, then a long millennially resolved record from Site U1385 might serve as a marine sediment proxy record for the Greenland ice core beyond the age of the oldest undisturbed ice (~ 124 ka). Comparing surface water signals at Site U1385 with the synthetic Greenland reconstruction (Barker et al., 2011) and methane record from Antarctica (Loulergue et al., 2008) will test the strengths and weaknesses of using these records as proxies for Greenland temperature change. Similarly, millennial-scale variability in benthic δ^{18}O at Site U1385 will be compared to EPICA δD to determine if the correlation observed for the last glacial cycle holds for the last 800 kyr.

5 Co-evolution of orbital and suborbital climate variability

Although much progress has been made towards understanding the orbital effects on climate, a complete theory of the ice ages still remains elusive (Raymo and Huybers, 2008). A missing piece of the puzzle may be understanding how climate change on shorter timescales (i.e. suborbital) interact with the effects of orbital forcing to produce the observed patterns of glacial–interglacial cycles through the Pleistocene. For example, millennial-scale climatic perturbations may play an important role in longer-term climate transitions, such as glacial terminations (Wolff et al., 2009; Cheng et al., 2009; Denton et al., 2010). Studying the co-evolution of orbital and suborbital variability requires a new calibre of sediment archive with a high level of chronological precision. Our objective is to develop Site U1385 into such a marine reference section for studying the interaction

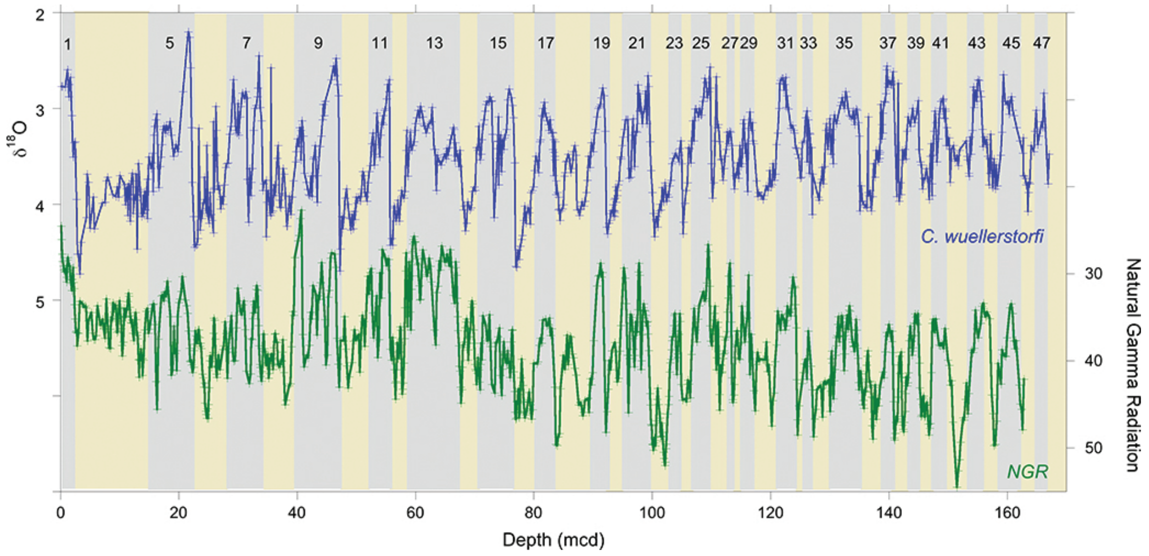

Figure 4. Benthic oxygen isotope record of *Cibicidoides wuellerstorfi* (blue) and natural gamma radiation (green) with identification of marine isotope stages at Site U1385.

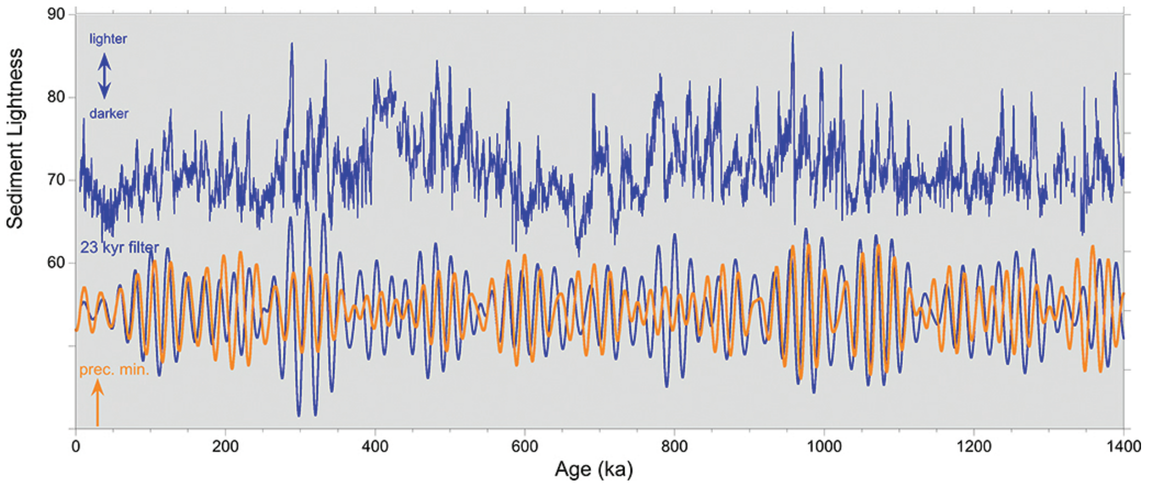

Figure 5. Variations in sediment lightness (L^*) at Site U1385. The 23 kyr filtered signal of lightness (blue) compared to the precession index ($e \times \sin(\omega)$; orange). The potential exists for tuning colour variations at Site U1385 to orbital precession.

of millennial- and orbital- scale climate variability, and for comparing marine, ice, and terrestrial records.

6 Middle Pleistocene transition

The Site U1385 sediment record extends across the middle Pleistocene transition when the climate system evolved from a more linear response to insolation forcing in the "41 kyr world" to one that was decidedly non-linear in the "100 kyr world" (Imbrie et al., 1992). Smaller ice sheets in the 41 kyr world gave way to larger ice sheets in the late Pleistocene with an accompanying change in ice sheet dynamics (Clark et al., 2006; Hodell et al., 2008). Ice volume surpassed a critical threshold across the MPT that permitted ice sheets to survive boreal summer insolation maxima, thereby lengthening glacial cycles and activating the dynamical processes responsible for Laurentide Ice Sheet instability in the region of Hudson Strait (i.e. Heinrich events) (Hodell et al., 2008).

Site U1385 provides an opportunity to examine how millennial-scale climate variability evolved across the MPT as glacial boundary conditions changed. Raymo et al. (1998) provided clear evidence from Site 983 in the North Atlantic that millennial-scale variability was a persistent feature during some glacial periods during the "41 kyr world". Did the nature, timing and frequency of millennial-scale climate variability differ for the "41 kyr world" versus the "100 kyr world"? What are the implications for fresh-water forcing and Atlantic meridional overturning circulation (AMOC)?

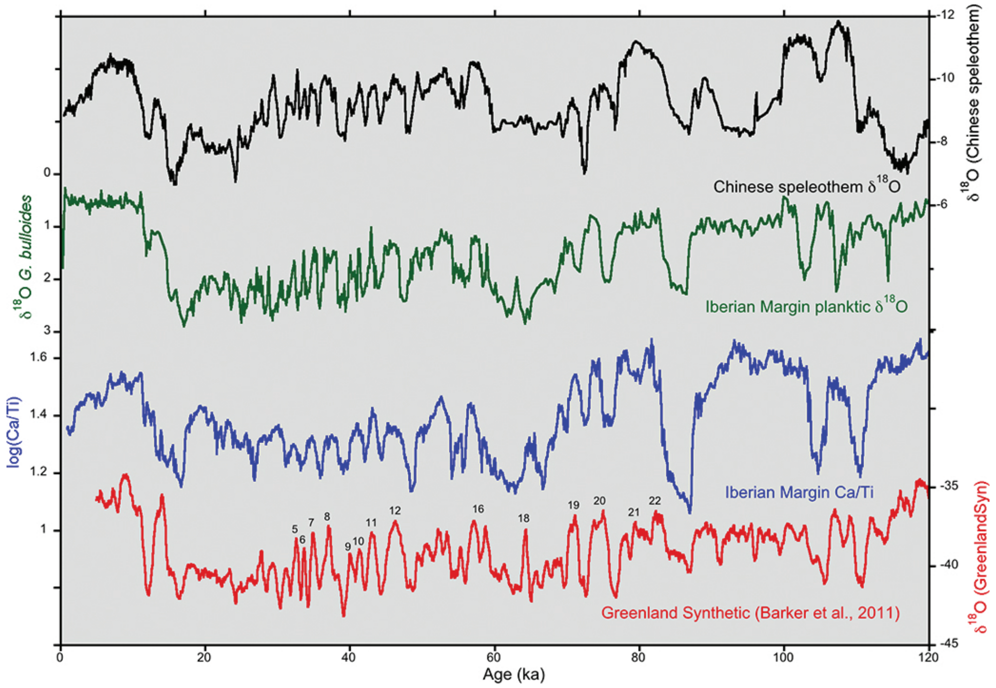

Figure 6. Comparison of Ca/Ti (blue) and planktic δ^{18}O (green) from piston core MD01-2444 (same location as Site U1385) with the Greenland synthetic δ^{18}O record (Barker et al., 2011) and a composite of Chinese spelothem records. The similarity of some of the millennial-scale events offer the opportunity of synchronizing the records and transferring the U-Th-dated chronology of the speleothem record to the ice core and marine sediment archives. Figure reproduced with permission from the American Geophysical Union (Hodell et al., 2013).

7 Testing the bipolar seesaw in glacial periods

The leading cause to explain millennial climate variability recorded in Greenland and Antarctic ice cores during the last glacial period is changes in the strength of AMOC, which alters interhemispheric heat transport and results in opposite temperature responses in the two hemispheres. However, we know little about whether this “bipolar seesaw” was a persistent feature of older glacial periods. A great strength of the Iberian margin sediment record is the fact that it contains signals of both Greenland and Antarctic ice cores in a single archive. Shackleton et al. (2000, 2004) demonstrated it is possible to determine the relative phasing of changes in Greenland and Antarctic climate by comparing planktic and benthic δ^{18}O signals in Core MD95-2042 (Shackleton et al., 2000, 2004). This phasing of surface and deep-water signals on the Iberian margin is consistent with the bipolar seesaw; moreover, millennial-scale warmings in Antarctica preceded the onset of Greenland warmings and the onset of rapid warming in Greenland coincided with cooling in Antarctica. Site U1385 can be used to test if similar phasing existed in older glacial periods, consistent with the operation of a bipolar-seesaw (e.g. Margari et al., 2010). Determining the phase relationships of signals in a single core circumvent many of the problems associated with core-to-core correlation and developing age models that are accurate on millennial timescales.

8 Linking marine and European terrestrial sequences

Marine archives recovered adjacent to the continents have the potential to link continental and marine climate records as they are affected directly by continental inputs, such as sediment from rivers and winds. The western Iberian margin has emerged as a critical area for studying continent–ocean connections because of the combined effects of major river systems and a narrow continental shelf that lead to the rapid delivery of terrestrial material (e.g. pollen, organic biomarkers) to the deep-sea environment (Sánchez Goñi et al., 2000; Shackleton et al., 2003; Tzedakis et al., 2004, 2009; Margari et al., 2010). By comparing marine stable isotopes and pollen records in the same core, the relative timing of land–sea climate change can be determined. Palynological studies of Site U1385 will evaluate how major vegetation changes in southern Europe over the last 1.43 Ma related to changes in global climate as expressed in the marine oxygen isotope record. Site U1385 provides the material needed to significantly improve the precision to which marine climate records can be linked to European terrestrial sequences.

9 Sampling strategy and multi-proxy studies

Two nearly complete secondary splices were constructed, one using intervals from Holes U1385A and U1385B (the

“AB splice”) and the other using intervals from Holes U1385D and U1385E (the “DE splice”). The Ca/Ti data permits precise correlation among the holes to within a few centimeters. We have undertaken a highly coordinated sampling effort of Site U1385 cores to produce the widest range of proxy measurements possible on the same set of samples. With an average sedimentation rate of 10 cm $\mathrm{kyr^{-1}}$, we sampled the composite section of Site U1385 at 1 cm intervals to resolve millennial climate events. With Site U1385, we aim to accept the challenge posed by Alley (2003) that “paleoceanographers should consider following the ice-core community’s lead and organise a research effort to generate a few internationally coordinated, multiply replicated, multiparameter, high time resolution-type sections of oceanic change.”

10 Future drilling

Site U1385 demonstrates the great promise of the Iberian margin to yield long records of millennial-scale climate change and land–sea comparisons. Site U1385 was the fulfillment of APL-763, but a Full Proposal (771) is pending with the IODP for a complete 56-day expedition to the Iberian margin. Drilling additional sites will allow us to both extend the record beyond the base of Site U1385 (1.43 Ma) and recover a full depth transect of sites spanning a range of subsurface water masses. Together with Expedition 339 sites drilled at intermediate water depths (from 560 to 1073 m), the sites would constitute the most complete depth transect drilled on any continental margin. Surface signals are expected to be similar among sites and can be used for site-to-site correlation, whereas benthic signals will reflect the range of subsurface water mass properties. Building on the success of Site U1385 and given the seminal importance of the Iberian margin for paleoclimatology and marine–ice–terrestrial correlations, additional drilling of this region by the IODP is warranted.

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