Stratigraphic correlation in sediment drifts

White Paper for INVEST (relevant to WG 2.1, WG 3.1, WG 3.2, WG 3.3)

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Abstract

The quest for improved stratigraphic correlation remains one of the great challenges in paleoceanography. Benthic $\delta^{18}O$ is the hallmark of marine stratigraphy, however, $\delta^{18}O$ changes in seawater are not globally synchronous on (millennial) timescales associated with the mixing time of the oceans (e.g. Skinner and Shackleton, *Quat. Sci. Rev.*, 2005, 2006) and the rate of change of global ice volume (the basis for $\delta^{18}O$ stratigraphy) is gradual other than at Terminations, limiting the correlation potential of the record.

There would be great advantage in coupling oxygen isotopes with an independent stratigraphic tool that is global in nature and devoid of environmental influences. Traditional magnetic polarity stratigraphy has become the backbone of geologic timescales partly because polarity reversal is a geophysical phenomenon attributable to the main dipole field, and therefore provides global timelines for precise correlation at the time of reversal. The accumulation of relative paleointensity (RPI) data in the last 10 years holds the promise of stratigraphic correlation within polarity chrons, possibly at millennial scale.

A first step in the utilization of paleointensity (RPI) records in stratigraphy has been the development of RPI stacks (e.g. Valet et al., *Nature*, 2005; Yamazaki and Oda, *G-cubed*, 2005) and an RPI stack based on the tandem correlation of RPI and $\delta^{18}O$ data (Channell et al., *EPSL*, 2009). An objective in the next phase of IODP should be the mining of sediment drifts not only to exploit the high resolution environmental/climate records associated with them, but also to utilize the stratigraphic tools ($\delta^{18}O$ and RPI) to place this record in a stratigraphic framework appropriate for the study of rapid climate change.

In addition, RPI records are critical to ground-truth numerical simulations of the geodynamo, and to promote understanding of the enigmatic mechanisms associated with polarity reversals and magnetic excursions.

Background

The ice core records from Greenland and Antarctica are perhaps the most valuable climate records yet recovered, in large part because of their high temporal resolution. In many respects, they have become the de facto "type sections" of Pleistocene climate variability to which other records are compared. Those from Greenland cover the last glacial cycle (~125 kyr) and those from Antarctica now reach back to marine isotope stage (MIS) 20 at ~800 kyr. Future plans call for extending the record from Greenland to the penultimate glaciation (MIS 6) and to recover the oldest ice (~1.5 Ma) on Antarctica (IPICS white papers at www.pages.unibe.ch/ipics/whitepapers.html).

Although ice cores are extremely powerful paleoclimatic archives, understanding the Earth's climate system requires a coupled ocean-atmosphere approach where ice core data are integrated with marine sediment core records. For example, the mechanism for atmospheric CO_2 changes on timescales longer than decades must lie in the ocean. Ice core records must therefore be integrated with analogous marine sediment records to understand glacial-interglacial pCO_2 variations. To accomplish this, the temporal resolution of the oceanic record should rival the resolution of the climate records derived from Antarctic/Greenland ice-cores. One of the challenges in the next phase of IODP will be the search for such marine records with appropriate resolution, continuity and age control.

For comparison with ice core records, sediment drifts from the deep-sea provide the combination of high sedimentation rates and uniform fine-grained silty-clay lithologies (relative to less uniform continental margin deposits) that are suitable for extracting climate records. In the North Atlantic, sediment drifts have been sampled during ODP Legs 162 and 172 and during IODP Expedition 303/306. The recovered cores from these drilling expeditions have provided high resolution environmental records with mean sedimentation rates in the 5-20 cm/kyr range over the last ~2 Myr.

The combination of oxygen isotope data and magnetic relative paleointensity (RPI) data have provided the stratigraphic tools to export these environmental records outside the North Atlantic, and correlate them to ice core records. At the onset of drilling of drift deposits in the North Atlantic using the Advanced Piston Corer (APC), 14 years ago during ODP Leg 162, it was not known whether the deposits would provide continuous sedimentary records or whether they would be riddled with disconformities that would limit their usefulness. It has now been demonstrated that the principal North and Central Atlantic sediment drifts, including Eirik, Gardar, Bjorn, Feni and Faro-Albufeira provide unique high resolution, rather continuous, records of environmental change over the last few Myr, providing some of our best records of the abrupt millennial-scale climatic and paleoceanographic change.

Millennial-scale correlations using RPI data are potentially achievable due to the rapid rate of change of geomagnetic field intensity (presently about 5% /century). A number of RPI stacks from the North Atlantic (Laj et al., *Trans. Roy. Soc.*, 2000), South Atlantic (Stoner et al., *Quat. Sci. Rev.,* 2002), Pacific (Yamazaki and Oda, *G-cubed*, 2005) and global oceans (Laj et al., *AGU Monograph*, 2004) attest to the consistency of marine RPI records. The satisfying correlation of marine RPI records to lacustrine RPI records (e.g. Peck et al., *JGR*, 1996), to RPI records based on marine magnetic anomalies

(Gee et al., *Nature*, 2000), and to cosmogenic isotope records from ice cores (e.g. Wagner et al., *EPSL*, 2000) have strengthened the case that the RPI records represent a global signal. Apart from the similarity of RPI records from different environments, the argument in favor of RPI records representing a global signal comes from analysis of non-axial-dipole components in the historical field that vary on centennial timescales (Hulot and Le Mouel, *PEPI*, 1994; Hongre et al., *PEPI*, 1998; Valet et al., *G-cubed*, 2008). If similar repeat times hold in the geologic past, RPI records from cores with sedimentation rates less than ~15-20 cm/kyr are unlikely to record anything but the axial dipole field. Although standing non-axial-dipole (NAD) components have been detected in the 5 Myr time-averaged field, the distribution of these NAD features remains controversial (Carlut and Courtillot, *GJI*, 1998) and any effects on RPI records have not been detected.

The modulation of cosmogenic isotope flux by geomagnetic field intensity has provided a means for correlating ice-core and marine records during the last glacial cycle (e.g., Muscheler et al., *Quat. Sci. Rev.*, 2005), during the longer-term (200 kyr) (e.g., Christl et al., *Quat. Sci. Rev.*, 2003) and in the vicinity of the Matuyama-Brunhes boundary in the EPICA (Antarctic) ice core record (e.g., Dreyfus et al., *EPSL*, 2008). These correlations between RPI records and cosmogenic isotope flux indicate that the RPI record is for the most part a global signal.

A new stack of RPI data for the last 1.5 Myr (Fig. 1) utilizes 13 records, mainly from the North Atlantic, but also including records from the South Atlantic and Pacific oceans (Channell et al., *EPSL*, 2009). IODP Site 1308 from the North Atlantic (re-drill of DSDP Site 609) was used as the correlation target as it possesses both high quality isotope and RPI records over the entire 1.5 Myr interval (Channell et al., *EPSL*, 2008; Hodell et al., *Paleocean.*, 2008). The RPI stack differs from previous stacks in that it utilizes only RPI records that have accompanying oxygen isotope data. The “Match” protocol of Lisiecki and Lisiecki (*Paleocean.*, 2002) was used to simultaneously optimize the correlation of RPI and isotope records thereby reducing the degree of freedom associated with correlation of RPI (or isotope) records alone. The resulting oxygen isotope stack (Fig. 1) has comparable resolution to the LR04 stack (Lisiecki and Raymo, *Paleocean.*, 2005), and the accompanying RPI stack (Fig. 1) provides a useful reference template that can be applied to global stratigraphic correlations. Power at orbital periods that has been detected in many RPI records is virtually absent in the stack, supporting the contention that orbital power in RPI records is due to lithologic contamination in some RPI records (see Xuan and Channell, *PEPI*, 2008). In this new stack, excursions occupy times of low geomagnetic paleointensity, in fact, all the more extreme RPI minima correspond to ages of adequately documented excursions or reversals implying that geomagnetic intensity has a threshold that triggers both excursions and reversals. The coupling of RPI and oxygen isotope records, and the recognition of RPI minima that feature excursions, provides a new template for global stratigraphic correlation that promises not only to improve the resolution of stratigraphic correlation, into the realm of interest for the study of “abrupt” climate change, but also to liberate (benthic) oxygen isotope data from its chronological role and allow its regional environmental characteristics to be fully utilized.

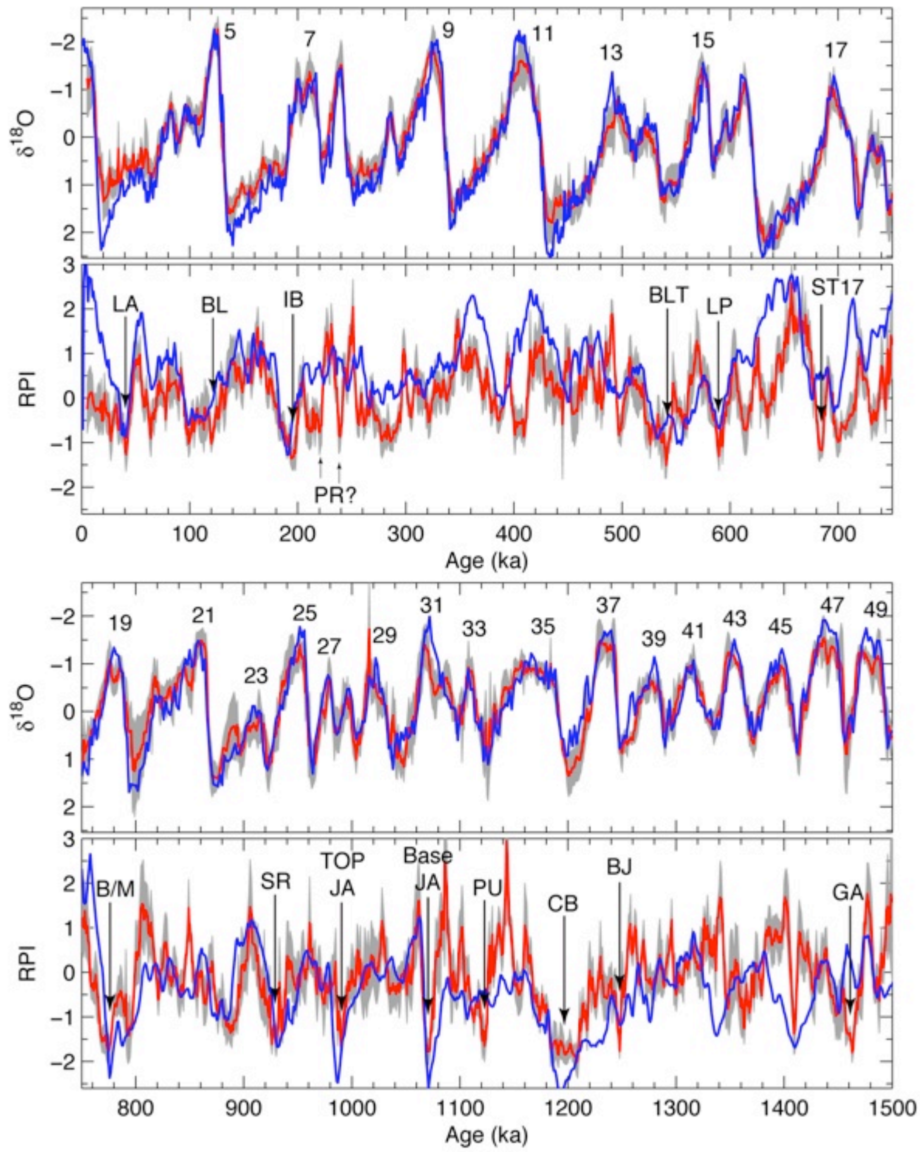

Fig. 1. Oxygen isotope and relative paleointensity (RPI) stacks (both in red) for the last 1.5 Myrs from Channell et al. (*EPSL*, 2009) based on 13 coupled RPI and isotope records from the world's oceans. Half-width of the error envelope in both cases is 2σ determined using the bootstrap method for 1 million samplings. The oxygen isotope stack (red) is compared with the LR04 benthic isotope stack (blue) (Lisiecki and Raymo, *Paleocean.*, 2005), and the RPI stack (red) provides an improvement in resolution over the Sint-2000 stack (blue) (Valet et al., *Nature*, 2005). RPI minima in the stack correspond to established ages of magnetic excursions, and chron/subchron boundaries: LA-Laschamp, BL-Blake, IB-Iceland Basin, PR-Pringle Falls, BLT-Big Lost, LP-La Palma, ST17-Stage 17, JA-Jaramillo Subchron, SR-Santa Rosa, PU-Punaruu, CB-Cobb Mt. Subchron, BJ-Bjorn, GA-Gardar, B/M-Brunhes-Matuyama boundary.

The sediment drifts off the Antarctic peninsula (IODP Proposal 732)

There is intense interest in the response of the Antarctic Peninsula and West Antarctica to global warming because recent observations suggest this region may be undergoing rapid changes including warming, ice-shelf disintegration and ice-sheet thinning and retreat. These recent changes can be considered in a longer geologic perspective by studying ice and marine sediment cores to decode the paleoceanographic and climatic changes, as well as evaluate the past history and stability of the West Antarctic Ice Sheet (WAIS) and Antarctic Peninsula Ice Sheet (APIS).

The lack of precise chronological control that has dogged paleoceanographic interpretations of sediment cores from high southerly latitudes (due to a lack of foraminiferal carbonate for isotopic analyses) can now be partially offset using RPI records and by placing sites west of the Antarctic Peninsula at water depths less than 2800 m, where carbonate preservation is enhanced (Hillenbrand et al., *Mar. Geol.*, 2003) allowing stable isotope analyses on foraminifera tests. The paleomagnetic data from the ODP sites collected from the sediment drifts off the Antarctic Peninsula (Guyodo et al., *EPSL*, 2001; Acton et al., *PEPI*, 2006) and from conventional gravity cores collected from Drift 7 (Sagnotti et al., *EPSL*, 2001; Macri et al., *EPSL*, 2006) indicate that the drift sediments carry a high fidelity record of the direction and paleointensity of the Earth's magnetic field. These data indicate that the drift deposits carry a magnetic signal that can not only be used for chronological control but also for understanding the behavior of the geomagnetic field at high southerly latitudes. In the 10 years since ODP Leg 178, RPI records from the world's oceans have proved to be valuable for high-resolution global correlation.

IODP Proposal 732 is designed to drill a series of sites on sediment drifts (contourites) located on the continental rise west of the Antarctic Peninsula and West Antarctica. The proposed sites contain continuous sections with high sedimentation rates that can be dated using RPI and, at shallow-water sites, oxygen isotope stratigraphy. Six proposed sites target expanded Pliocene-Quaternary sequences, with two sites targeting the pre-Pliocene record at locations characterized by thinned younger sediment cover.

Previous cores collected in the region, including those recovered during ODP Leg 178 (1998), have indicated that these drift deposits carry a rich high-resolution archive of Antarctic margin paleoceanography and history of the APIS and WAIS. The potential of existing ODP cores is compromised by two factors: (1) incomplete composite sections and (2) lack of precise chronological control.

There are few targets in the circum-Antarctic region that rival the potential offered by the sediment drifts off West Antarctica. The recovery of these sediment cores and integration of these data with polar ice cores will contribute significantly our understanding of the role of the WAIS and APIS and the adjacent Southern Ocean in global atmospheric and oceanographic processes. In addition, the proposed drilling will contribute critical information regarding the past stability of the APIS/WAIS and its implications for sea-level change.

'Rapid Climate Change' was named as a special research initiative in the IODP Initial Science Plan (ISP). The initiative should be continued in the next phase of IODP with drilling of sediment drifts utilizing RPI and $\delta^{18}O$ in tandem to provide appropriate means for global correlation of high-resolution environmental records.