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South Atlantic and North Atlantic geomagnetic paleointensity stacks (0–80 ka): implications for inter-hemispheric correlation

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Abstract

Recent coring of high-deposition-rate Atlantic sediments has led to the development of North Atlantic (NAPIS) and South Atlantic (SAPIS) geomagnetic paleointensity stacks. The SAPIS stack comprises five records from the sub-Antarctic South Atlantic (41–47°S, 6–10°E). Four are from piston cores collected during the Ocean Drilling Program (ODP) Leg 177 site survey cruise (Earth Planet. Sci. Lett. 175 (2000) 145). The other is ODP Site 1089 (Leg 177) (J. Geophys. Res., 2001, submitted for publication). All but one (4-PC03) of the SAPIS cores have oxygen isotope records which are used in conjunction with lithologic and geomagnetic variability to derive an optimized correlation to Site 1089. The Site 1089 age model is derived by mapping the benthic and planktic isotope data to those from nearby core RC11-83 which has 14 calibrated radiocarbon ages in the 11-41 ka interval. Below this level, the chronology is derived by matching the Site 1089 benthic oxygen isotope data to the SPECMAP stack. The NAPIS stack comprises six records from a wide area of the North Atlantic (Philos. Trans. R. Soc. Ser. A 358 (2000) 1009). Correlation between cores was based on marine isotopic stage boundaries, augmented by millennial-scale features (Heinrich events and fluctuations in concentration-dependent magnetic parameters). NAPIS was placed on the GISP2 chronology, using the marine to ice-core oxygen isotope correlation proposed by Voelker et al. (Radiocarbon 40 (1998) 517) for one of the NAPIS cores. In the resulting age model, the Laschamp Event, recorded in five of six cores, falls in a very narrow (<1 kyr) age range and coincides with the ¹⁰Be and ³⁶Cl peak measured in the ice cores. Comparison of the two stacks, placed on their own independent age models, indicates that common millennial scale paleointensity features are preserved. Although more work is needed to define the "true" global content of the paleointensity record as well as the precise age of many features, it is readily apparent that paleointensity can provide a global correlation tool at a resolution unattainable from isotope data alone. © 2002 Published by Elsevier Science Ltd.

1. Introduction

Over the last decade, marine climate records from the North Atlantic region have undergone a stratigraphic renaissance due to the recognition of distinct regional lithostratigraphic and climatic markers that define time synchronous events. The Greenland (GRIP/GISP2) ice cores have acted as a catalyst for this renaissance by providing unparalleled templates of climatic variability with robust chronologies. North Atlantic marine sediment records can be tied to ice-core stratigraphies through regional climatic and ash layer tie-points that are supported by traditional marine stratigraphic (δ^{18} O) and dating techniques (14 C) (e.g., Bond et al., 1993;

1999). Correlation of these stratigraphies to those from other areas of the globe presents a chronostratigraphic challenge, that unless overcome, will preclude our understanding of global climate at sub-orbital scales. At present, even under optimal conditions, chronologies based on δ^{18} O are unable to provide sufficient stratigraphic resolution to resolve the phase relationships between millennial-scale climate records. The problem is exacerbated in environmentally sensitive settings where δ^{18} O records may have poor chronostratigraphic value due to local δ^{18} O anomalies that perturb the secular change due to global ice volume. Over the last 50 kyr or so, radiocarbon dating can provide precise temporal constraints, however, because the calibration to calendar years remains imprecise, correlation to non-radiocarbon dated records is often equivocal. In addition,

McManus et al., 1994; Voelker et al., 1998; Kissel et al.,

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variations in ¹⁴C reservoir ages within the ocean may confound potential correlations (e.g. Sikes et al., 2000).

A new method has emerged that may provide at least a partial solution to the problem of sub-Milankovitchscale global correlation. Records of relative geomagnetic paleointensity from marine sediments have been shown to contain a global signal suitable for fine-scale correlation (see Meynadier et al., 1992; Stoner et al., 1995, 1998, 2000; Guyodo and Valet, 1996; Channell et al., 1997, 2000; Laj et al., 2000; Kiefer et al., 2001). Paleointensity records have been applied to stratigraphic correlation in the Labrador Sea for the last 200 kyr (Stoner et al., 1998), the North Atlantic for the last 75 kyr (Laj et al., 2000), and globally for the last 110 kyr (Stoner et al., 2000). As variations in geomagnetic paleointensity are a control on the production of cosmogenic isotopes (e.g., ¹⁰Be and ³⁶Cl), their flux measured in ice cores can be inversely correlated to the paleointensity records from marine sediments. This provides a link between marine sediment and ice-core records (Mazaud et al., 1994; Baumgartner et al., 1998, Laj et al., 2000; Stoner et al., 2000; Wagner et al., 2000). The prominent lows in paleointensity at ~ 40 and \sim 65 ka observed in marine records are identifiable as highs in flux of ¹⁰Be and ³⁶Cl (Raisbeck et al., 1987; Baumgartner et al., 1998) in the Vostok and Grip ice cores, respectively; and many higher frequency features now appear to be temporally correlated (Stoner et al., 2000; Wagner et al., 2000). These observations, and the similarity of globally distributed paleointensity records, indicate that much of the variability within paleointensity records is due to changes in the strength of the global-scale field.

The principal challenge in the development of this very promising method is to define the "true" character of the geomagnetic paleointensity record. Unfortunately, paleointensity cannot be predicted by theory or from numerical simulation as the mechanisms of the geodynamo are not sufficiently constrained. Comparison between relative paleointensity records from sediments and absolute paleointensity from thermally cooled materials (e.g. volcanic rocks and ceramic artifacts) can be used to calibrate the sediment record. In practice, however, the volcanic/sedimentary correlation is often hampered by the discontinuous (stochastic) nature of the volcanic record, and imprecision of available radiometric dating techniques. Comparison of sedimentary paleointensity records from different depositional environments, and detailed investigation of magnetic properties, allows separation of geomagnetic and environmental signals. Distributed records from different parts of the globe are necessary to determine the characteristics of the global (as opposed to local) geomagnetic field. Stacking provides a method for determining the "true" character of the record, as spurious features in individual records should be

averaged out by the stacking process. Due to imprecision of global correlation and the use of low-sedimentation rate records, previously derived global paleointensity stacks (e.g. Sint-200 from Guyodo and Valet (1996)) have averaged out much of the highfrequency variability and, therefore, represent only the long-period variability of the geomagnetic field. Sint-200 depicts the field as smoothly varying with dominant periods > 10 kyr. On the other hand, globally dispersed high-resolution records give a picture of a rapidly varying field with global-scale features at millennial time scales (Stoner et al., 2000).

2. NAPIS

The first paleointensity stack at a resolution high enough to resolve millennial scale variability (NAPIS-75) was based on six high-resolution records from 10-75 ka interval in the North Atlantic (Laj et al., 2000). The cores, distributed from 68°N to 33°N, are all characterized by high average sedimentation rates (Fig. 1; Table 1) and uniform magnetic properties. The dominant remanence carrier is magnetite and titanomagnetite within the pseudo-single domain (PSD) grain size range. The concentration of these minerals changes rapidly as illustrated by high-frequency variations in low-field magnetic susceptibility, anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM) (Kissel et al., 1999). The natural remanent magnetization (NRM) is characterized by a strong stable magnetization component resolved in the 0-60 mT demagnetization interval. Principal component analysis (Kirschvink, 1980) yields maximum angular deviations (MADs) that do not exceed 5° even during the large inclination swings recognized in five of the cores at ~ 40 ka, corresponding to the Laschamp geomagnetic excursion.

To obtain the paleointensity records for five of the six cores, normalized remanence records were generated using values of NRM and ARM after AF demagnetization at 25 mT. This peak field is sufficient for complete removal of secondary components present in the NRM. For ODP Site 983, the sixth core in the stack, we have used the IRM normalized record given by Channell et al. (1997).

In order to derive a high-resolution paleointensity stack, precise stratigraphic control among the six cores is required. Here, a two-step correlation process was used. First, isotopic stage boundaries, and millennialscale stratigraphic features such as Heinrich layers and Ash Layer II were utilized (Rasmussen et al., 1996; Cortijo et al., 1997; Elliot et al., 1998; Manthe, 1998; Voelker et al., 1998; Dokken and Jansen, 1999). Second, oscillations of low-field magnetic susceptibility and ARM intensity between successive Heinrich layers



 -120° -90° -60° -30° 0° 30° 60° Fig. 1. Location map showing the position of the cores used for the NAPIS paleointensity stack (Cores MD95-2009, SU90-33, MD95-2034, SU90-24, PS2644-5 and ODP Site 983) and the SAPIS paleointensity stack (Cores 4-PC03, 5-PC01, 21-PC02, 10-PC03 and ODP Site 1089)

50°S

30

-30°

60°

40

5-PC01

10-PC03

Drift sediments

0°E

Aghulas

ISE

10°

Meteor

were used to refine the correlation. ARM was used preferentially because, unlike susceptibility, it depends on variations in the amount of fine-grained magnetite with no contribution from paramagnetic material (e.g. clay minerals). In practice, the correlation was identical using either susceptibility or ARM. The correlation of ARM intensity (and susceptibility) implies a uniform sedimentation pattern over a large area of the North Atlantic, controlled possibly by uniform fluctuations in bottom current velocity. No isotopic or lithologic stratigraphic constraints are violated by the ARM/

 -120°

60

30

0

-30

-60

.00

susceptibility correlation. When this correlation is used, the directional change associated with the Laschamp event, apparent in five of the six cores, falls within a very short age range of ~ 1 kyr. This provides direct evidence for the accuracy of the correlation, and supports the hypothesis that short-term magnetic variations between Heinrich layers are indeed synchronous. The slight offsets in the timing of the Laschamp event may arise from stratigraphic imprecision or small differences in NRM lock-in characteristics for each core.

Ridge

 20°

Table 1
Basic data for cores used to construct the NAPIS and SAPIS paleointensity stacks

Core used for NAPIS								
Core	Lat (°N) Long (°W)	Core depths used (cm) Water depth (m)	Age estimate (ka)	Average Sed rate (cm/kyr)	Correlation to NAPIS (<i>r</i>)			
MD95-2009	62°44.25 03°59.86	0–1600 1027	10-75	24.6	0.766			
SU90-33	60°03.4 22°00.5	0–500 2400	11.5–75	7.9	0.611			
OPD Site 983	60°27.0 23°36.0	13–851 1984	0–75	11.2	0.812			
PS2644-5	67°52.02 21°45.92	24–915 777	11.5–75	14.0	0.832			
SU90-24	62°40.0 37°22.0	0–1040 2085	11–75	16.2	0.731			
MD95-2034	33°10.0 57°34.0	1500–3500 4461	21–75	37.0	0.831			

Core used for SAPIS

Core	Lat (°S) Long (°E)	Core depths used (cm) Water depth (m)	1089 equivalent (cm)	Age estimate (ka)	Average Sed rate (cm/kyr)	Correlation to 1089 (r)	Correlation to SAPIS (<i>r</i>)
Site 1089	40°56.2 9°53.64	1–1450 4620		0.5-80.7	18		0.893
TTN-057-4-PC03	40°56.04 9°53.65	4–858 4622	96–866	9.6–43.8	25	0.889	0.947
TTN-057-5-PC01	41°00.03 9°53.65	4–1258 4702	76–1192	7.5–63.7	22.3	0.722	0.826
TTN-057-21-PC03	41°08.46 7°48.46	6–1201 4977	1–1450	0.5-80.7	14.9	0.687	0.875
TTN-057-10-PC03	47°05.81 5°54.97	64–1016 4109	421–1450	21.1-80.7	16	0.722	0.923

To report the data on a common age model, we have used the correlation established by Voelker et al. (1998) between the planktic for a miniferal δ^{18} O record of core PS2644-5 and the δ^{18} O record of the GISP2 ice core. Using this correlation, the variations in the magnetic susceptibility and ARM records of the marine cores are in phase with the δ^{18} O record of the GISP2 ice core, with minima (maxima) in the magnetic records coinciding with the cold (warm) Dansgaard/Oeschger oscillations in the ice core. In the marine sedimentary records, the Laschamp event is coeval with interstadial 10. A ¹⁰Be peak, which has been shown to coincide with the Laschamp paleointensity low in a sedimentary core from the North Atlantic (Robinson et al., 1995), also coincides with interstadial 10 in the δ^{18} O record of the GRIP ice core (Yiou et al., 1997). Moreover, a detailed record of the ³⁶Cl flux from the GRIP ice core closely reflects variations of the geomagnetic field intensity during the Laschamp and the younger Mono Lake event. Comparisons between the ³⁶Cl flux and sedimentary paleointensity records indicate a maximum time offsets of around 500 yr (Wagner et al., 2000). This implies that any delay in remanence acquisition due to

the NRM lock-in is both small ($< \sim 10$ cm) and uniform for the different cores. Ideally, the synchronization of marine and ice-core records through geomagnetic field variability provides a climatically independent means of marine/ice-core correlation.

To construct the stack, the six normalized records were first interpolated to a common sampling interval of 100 yr (corresponding to $\sim 1-2$ cm) to give equal weight to each record in the stack (Fig. 2). They were then scaled to obtain a common paleointensity value for the minimum at ~ 40 ka, corresponding to the Laschamp Event, and also to obtain a common average value over the 10-75 ka interval. This technique has the advantage of not being overly sensitive to abrupt variations in individual paleointensity records. The stack was then determined using the arithmetic mean at each interpolated sampling point. The 2σ uncertainties have been calculated using the bootstrap (Tauxe et al., 1991) and jacknife (Caceci, 1989) techniques (Laj et al, 2000). Results obtained with the two techniques are shown in Fig. 3 together with the stacked record. As a consequence of the high degree of internal consistency between individual records, the six stacks of five cores,



Fig. 2. Individual paleointensity records obtained from the six North Atlantic cores used to construct the NAPIS stack (MD95-2009, SU90-33, MD95-2034, SU90-24, PS2644-5 and ODP Site 983).

obtained from the jackknife approach, are almost identical. Each individual record is very similar to the stack itself as indicated by correlation coefficients between the stack and individual records (Fig. 4). The maximum discrepancy is observed for core SU90-33. This record also has the lowest correlation coefficient (0.61) with the stack (Table 1).

3. SAPIS

High-sedimentation rate piston cores from the sub-Antarctic South Atlantic, acquired during the site survey cruise for Ocean Drilling Program (ODP) Leg 177, provide the first high-resolution relative paleointensity and directional secular variation records from the midlatitude southern hemisphere (Channell et al., 2000). These records extended back to 100 ka. During ODP's advanced piston corer which extended the paleomagnetic record from the South Atlantic to approximately 580 ka (Stoner et al., submitted for publication). A highresolution South Atlantic paleointensity stack (SAPIS) for the last 80 kyr is based on paleointensity records from four site survey piston cores and ODP Site 1089 (Table 1). The magnetic properties, directional records and paleointensity estimates obtained from IRM normalized NRM are documented for Cores TTN057-21-PC02, TTN057-10-PC03, TTN057-4-PC03, TTN057-5-PC01 in Channell et al. (2000); and for Site 1089 in



Fig. 3. The North Atlantic paleointensity stack (NAPIS). The shaded/bracketed area corresponds to the 2σ uncertainty derived from bootstrap (top) and from jacknife (bottom) calculations.



Fig. 4. Comparison between the NAPIS stack and the six individual records used to construct the stack (MD95-2009, SU90-33, MD95-2034, SU90-24, PS2644-5 and ODP Site 983).

Stoner et al. (submitted for publication). Four of the records are from north of the Polar Front Zone, while 10-PC03 was located south of the Polar Front during

glacial intervals (Fig. 1). Variable depths and sedimentation rates characterize the records, and not all records cover the entire 80 kyr interval (Table 1). Average sedimentation rates range from 14.9 cm/kyr for 21-PC02 to 25 cm/kyr for 4-PC03, with higher sedimentation rates during glacials and late marine isotopic stage (MIS) 3.

NRM component directions are well-defined for all five cores with MAD values generally below 10° . Inclinations vary about mean values close to those expected (-60 to -65°) for the site latitudes ($41-47^{\circ}S$). Anomalous (positive) inclination values occur at ~ 40 ka in Cores 4-PC03 and 5-PC01 and inclinations become shallow in the same time interval in Cores 21-PC02, 10-PC03 and Site 1089. The anomalous inclinations appear to correspond to the Laschamp Event which has been widely recognized in the North Atlantic region, and is documented in five of the six cores used in the NAPIS stack (Laj et al., 2000). The recognition of the Laschamp Event in two of the five SAPIS cores is the first documentation of this event in the Southern Hemisphere.

In order to develop a SAPIS stack, all records must be placed on a common depth or age framework. As our stratigraphic knowledge of the South Atlantic is immature compared to that of the North Atlantic, the relative stratigraphy of the SAPIS cores, unlike NAPIS, depends partly on geomagnetic records for defining time-synchronous sedimentation. The stratigraphic correlation among SAPIS cores is based on an optimization process using common lithologic features (from magnetic susceptibility), isotopic features (from planktic and benthic oxygen isotopes), and geomagnetic features (from paleointensity and directional secular variation). No stratigraphic constraints are violated by the optimization, which we believe provides the best possible correlation of the SAPIS cores.

As ODP Site 1089 provides the most complete sedimentary sequence for the last 80 kyr, it is used as our reference record. Data from the other cores are



Fig. 5. Comparison of the paleointensity records from ODP Site 1089, and Cores 4-PC03, 5-PC01, 21-PC02 and 10-PC03 on Site 1089 depth equivalents (cm₁₀₈₉)

transferred to Site 1089 depth equivalents (cm₁₀₈₉) using the stratigraphic optimization procedure. Each record was then interpolated and resampled at a common interval of 1 cm₁₀₈₉. All paleointensity records were normalized to a mean of unity. A large remanence drop in the upper 4 m of Cores 4-PC03, 5-PC01 and Site 1089, but not in Cores 21-PC02 or 10-PC03, perturbs the normalized remanence records in the 0-20 ka interval. The magnetic properties of these cores show that the 0– $300 \,\mathrm{cm}_{1089}$ interval above the remanence drop has a high concentration of ultra-fine grained magnetite, possibly of biogenic origin (Channell et al., 2000; Stoner et al., submitted for publication). This fraction is not observed below this interval, suggesting removal when passing through the zone of Fe reduction. Assuming that the high-frequency variations in geomagnetic paleointensity in this interval are accurately recorded, but with an amplitude shift, we have split all records into two parts at a common normalized remanence low (456 cm_{1089}) , then renormalized to unity both above and below this

depth. A constant was added to the records below 456 cm_{1089} to correct for offsets produced by this splicing procedure. The records were then scaled to a common low value at $802 \,\mathrm{cm}_{1089}$, the Laschamp paleointensity low, and then rescaled to a common mean for the overlapping depth interval (Fig. 5). Though this procedure results in a pleasing record, the normalized remanence record above 456 cm_{1089} should be viewed with caution. Table 1 gives the depth intervals used for each core in the stack, and the correlation coefficient (r)of each paleointensity record with that of Site 1089. The stack was determined from the arithmetic mean at each common interpolated sampling point (Fig. 6). The 2σ uncertainties for the SAPIS stack (Fig. 6) are assessed using bootstrap (Tauxe et al., 1991) and jacknife (Caceci, 1989) techniques (see Laj et al., 2000). The SAPIS stack appears to reflect the general character of the individual paleointensity records (Fig. 7) and this is confirmed by the high correlation coefficients between the stack and the individual records (Table 1).



Fig. 6. The South Atlantic paleointensity stack (SAPIS). The shaded/bracketed area corresponds to the 2σ uncertainty derived from bootstrap (top) and from jacknife (bottom) calculations.



Fig. 7. The SAPIS compared with the individual paleointensity records from which it was derived. All records placed on ODP Site 1089 depth equivalents (cm_{1089}).

The age model for the SAPIS stack is based on the age model for ODP Site 1089 (see Hodell et al., 2001; Mortyn et al., in press; Stoner et al., submitted for publication). This was constructed by correlating the planktic and benthic isotope records to those from nearby core RC11-83 which has 14 calibrated radiocarbon ages in the 11–41 ka interval (Charles et al., 1996). For the older part of the record, benthic oxygen isotope data from Site 1089 was matched to the SPECMAP stack (Martinson et al., 1987). This results in a well-constrained chronology for the upper 80 kyr of the Site 1089 record. It should be noted that this chronology differs slightly from previous chronologies used on SAPIS cores by Channell et al. (2000) and Stoner et al. (2000).

4. Inter-hemispheric correlation of SAPIS to NAPIS

Fig. 8 shows SAPIS on the Site 1089 age model compared with the North Atlantic paleointensity stack (NAPIS) on an age model consistent with the Greenland GISP2 ice core (Laj et al., 2000). The records show remarkable similarities between 30 and 65 ka, however, differences exist particularly for the most recent (0–25 ka) interval. For example, NAPIS does not exhibit the decrease in paleointensity observed in SAPIS for the 15–25 ka interval (Fig. 8). As mentioned above, the SAPIS record in this interval, marked by a dashed line in Fig. 8, may be perturbed by the presence of ultra-fine magnetite in the upper part of some of the cores.

Additionally, the NAPIS stack has the appearance of being smoothed when compared with individual NAPIS records and with the SAPIS stack. This reflects the two different approaches used in the correlation of cores to construct the stacks. In NAPIS, the paleointensity records themselves were not used to refine the correlation. This avoids potential problems associated with mis-correlations produced by variable NRM lock-in depths, or spurious correlation of unrelated features in the geomagnetic records, but may also result in a loss of resolution. Note also that the SAPIS stack was derived from cores located in a much more restricted area than those used in NAPIS.

To ascertain the "true" nature of global-scale geomagnetic paleointensity for last 80 kyr, it needs to be determined whether the differences observed in Fig. 8 are due to imprecision in temporal correlation, local geomagnetic field effects, or uncorrected environmental factors. Clearly, additional work is needed to clarify this issue. However, comparison of the two stacks for the 30-65 ka interval show similar millennial-scale features (Fig. 8), implying that global-scale geomagnetic field intensity varies at these time-scales. This is unambiguously demonstrated for the 30-45 ka interval, where SAPIS essentially duplicates NAPIS and, therefore, is inversely correlative with the high resolution ³⁶Cl flux record from the Greenland GRIP ice core (Wagner et al., 2000). If this interval is analogous to the rest of the record, then temporal offsets of time synchronous features and uncorrected environmental factors are the main cause of differences observed in



Fig. 8. The two paleointensity stacks from the North Atlantic (NAPIS) and the South Atlantic (SAPIS), on their independently determined age models. The dashed line and lighter shading in the SAPIS record indicates an interval which may be perturbed by high concentrations of ultra-fine magnetite above a zone of iron reduction in three of the five SAPIS cores. The shaded area corresponds to the 2σ uncertainty derived from bootstrap calculations. The splice in SAPIS (see text) is marked by an arrow.

Fig. 8. Geomagnetic paleointensity if properly documented can, therefore, provide a unique tool for longrange stratigraphic correlation at sub-orbital scale. The development of paleointensity-assisted chronostratigraphies (PAC) will provide global correlation at higher temporal resolution than possible using more traditional stratigraphic techniques.

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References

- Baumgartner, S., Beer, J., Masarik, J., Wagner, G., Meynadier, L., Synal, H.-A., 1998. Geomagnetic modulation of the ³⁶Cl flux in the GRIP ice core, Greenland. Science 279, 1330–1332.
- Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature 365, 143–147.
- Caceci, M.S., 1989. Estimating error limits in parametric curve fitting. Analytical Chemistry 61, 2324–2327.
- Channell, J.E.T., Hodell, D.A., Lehman, B., 1997. Relative geomagnetic paleointensity and δ^{18} O at ODP Site 983 (Gardar Drift, North Atlantic) since 350 ka. Earth and Planetary Science Letters 153, 103–118.
- Channell, J.E.T., Stoner, J.S., Hodell, D.A., Charles, C.D., 2000. Geomagnetic paleointensity from late Brunhes-age piston cores from the subantarctic South Atlantic. Earth and Planetary Science Letters 175, 145–160.
- Charles, C.D., Lynch-Stieglitz, J., Ninnemann, U.S., Fairbanks, R.G., 1996. Climate connections between the hemispheres revealed by deep sea sediment core/ice core correlations. Earth and Planetary Science Letters 142, 19–28.
- Cortijo, E., Labeyrie, L., Vidal, L., Vautravers, M., Chapman, M., Duplessy, J.C., Elliot, M., Arnold, M., Turon, J.L., Auffret, G., 1997. Changes in sea surface hydrology associated with Heinrich event 4 in the North Atlantic ocean between 40 and 60°N. Earth and Planetary Science Letters 146, 29–45.
- Dokken, T., Jansen, E., 1999. Rapid changes in the mechanism of ocean convection during the last glacial period. Nature 401, 458–461.

- Elliot, M., Labeyrie, L., Bond, G., Cortijo, E., Turon, J.L., Tisnerat, N., Duplessy, J.C., 1998. Millenial-scale iceberg discharges in the Irminger Basin during the last glacial period: relationship with the Heinrich events and environmental settings. Paleoceanography 13, 433–446.
- Guyodo, Y., Valet, J.-P., 1996. Relative variations in geomagnetic intensity from sedimentary records: the past 200 thousand years. Earth and Planetary Science Letters 143, 23–26.
- Hodell, D.A., Charles, C.D., Sierro, F.J., 2001. Late Pleistocene evolution of the ocean's carbonate system. Earth and Planetary Science Letters, 192, 109–124.
- Kiefer, T., Sarnthein, M., Erlenkeuser, H., Grootes, P.M., Roberts, A.P., 2001. North Pacific response to millennial-scale changes in ocean circulation over the last 60 kyr. Paleoceanography 16, 179–189.
- Kirschvink, J.L., 1980. The least squares lines and plane analysis of paleomagnetic data. Geophysical Journal of Royal Astronomical Society 62, 699–718.
- Kissel, C., Laj, C., Labeyrie, L., Dokken, T., Voelker, A., Blamart, D., 1999. Rapid climatic variations during marine isotope stage 3: magnetic analysis of sediments from Nordic Seas and North Atlantic. Earth and Planetary Science Letters 171, 489–502.
- Laj, C., Kissel, C., Mazaud, A., Channell, J.E.T., Beer, J., 2000. North Atlantic paleointensity stack since 75 ka (NAPIS-75) and the duration of the Laschamp event. Philosophical Transactions of the Royal Society, Series A 358, 1009–1025.
- Manthe, S., 1998. Variabilité de la circulation thermohaline glaciaire et interglaciaire tracée par les foraminifères planctoniques et de la microfaune benthique. Thèse Univ. Bordeaux I, 289pp.
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quaternary Research 27, 1–29.
- Mazaud, A., Laj, C., Bender, M., 1994. A geomagnetic chronology for Antarctic ice accumulation. Geophysical Research Letters 21, 337–340.
- McManus, J.F., Bond, G.C., Broecker, W.S., Johnsen, S., Labeyrie, L., Higgins, S., 1994. High-resolution climate records from the North Atlantic during the last interglacial. Nature 371, 326–329.
- Meynadier, L., Valet, J.-P., Weeks, R., Shackleton, N.J., Hagee, V.L., 1992. Relative geomagnetic intensity of the field during the last 140 ka. Earth and Planetary Science Letters 114, 39–57.
- Mortyn, P.G., Charles, C.D., Ninnemann, U.S., Hodell, D.A. Deepsea sedimentary analog for the Vostok ice core. Journal of Geophysical Research, in press.
- Raisbeck, G.M., Yiou, F., Bourles, D., Lorius, C., Jouzel, J., Barkov, N.I., 1987. Evidence for two intervals of enhanced ¹⁰Be

deposition in Antarctic ice during the last glacial period. Nature 326, 273–277.

- Rasmussen, T.L., Thompsen, E., Van Weering, T.C.E., Labeyrie, L., 1996. Rapid changes in surface and deep water conditions at the Faeroe margin during the last 58,000 years. Paleoceanography 11, 757–771.
- Robinson, C., Raisbeck, G.M., Yiou, F., Lehman, B., Laj, C., 1995. The relationship between ¹⁰Be and geomagnetic field strength records in central North Atlantic sediments during the last 80 ka. Earth and Planetary Science Letters 136, 551–557.
- Sikes, E.L., Samson, C.R., Guilderson, T.P., Howard, W.R., 2000. Old radiocarbon ages in the southwest Pacific Ocean during the last glacial period and deglaciation. Nature 405, 555–559.
- Stoner, J.S., Channell, J.E.T., Hillaire-Marcel, C., 1995. Late Pleistocene relative geomagnetic paleointensity from the deep Labrador Sea—regional and global correlations. Earth and Planetary Science Letters 134, 237–252.
- Stoner, J.S, Channell, J.E.T., Hillaire-Marcel, C., 1998. A 200 kyr geomagnetic stratigraphy for the Labrador Sea: indirect correlation of the sediment record to SPECMAP. Earth and Planetary Science Letters 159, 165–181.
- Stoner, J.S, Channell, J.E.T., Hillaire-Marcel, C., Kissel, C., 2000. Geomagnetic paleointensity and environmental record from Labrador Sea Core MD95-2024: global marine sediment and ice core chronostratigraphy for the last 110 kyr. Earth and Planetary Science Letters 183, 161–177.
- Stoner, J.S., Channell, J.E.T., Hodell, D.A., Charles, C. ~570 kyr paleomagnetic record from the sub-Antarctic South Atlantic (ODP Site 1089). Journal of Geophysical Research, submitted for publication.
- Tauxe, L., Kylstra, N., Constable, C., 1991. Bootstrap statistics for paleomagnetic data. Journal of Geophysical Research 96, 11– 11,740.
- Voelker, A., Sarnthein, M., Grootes, P.M., Erlenkeuser, H., Laj, C., Mazaud, A., Nadeau, M.J., Schleicher, M., 1998. Correlation of marine ¹⁴C ages from the Nordic Sea with GISP2 isotope record: implication for ¹⁴C calibration beyond 25 ka BP. Radiocarbon 40, 517–534.
- Wagner, G., Beer, J., Laj, C., Kissel, C., Mazarik, J., Muscheler, R., Synal, H.-A., 2000. Chlorine-36 evidence for the Mono Lake event in the Summit GRIP ice core. Earth and Planetary Science Letters 181, 1–6.
- Yiou, F.G., Raisbeck, M., Baumgartner, S., Beer, J., Hammer, C., Johnsen, S., Jouzel, J., Kubik, P.W., Lestringuez, J., Stiévenard, M., Suter, M., Yiou, P., 1997. Beryllium 10 in the Greenland Ice Core Project ice core at Summit, Greenland. Journal of Geophysical Research 102, 26–26,794.