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Earth and Planetary Science Letters 242 (2006) 390–405
EPSL
www.elsevier.com/locate/epsl

Holocene centennial to millennial-scale climatic variability: Evidence from high-resolution magnetic analyses of the last 10 cal kyr off North Iceland (core MD99-2275)

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Received 30 November 2004; received in revised form 8 July 2005; accepted 25 July 2005
Available online 24 January 2006
Editor: V. Courtillot

Abstract

High-resolution magnetic analysis has been performed on the top ~25 m of core MD99-2275 (66°33.06′N, 17°41.59′W; 440 m water depth) from the mid-outer shelf off North Iceland. This is a key boundary region for climate changes related to atmospheric and oceanographic variations influenced by the moving limit between the cold and warm water masses at the Polar Front and the low depression track with its associated westerlies situated across Iceland. An age model based on tephrochronology was previously reported for this core and has allowed precise timing of significant variations in the magnetic mineral concentration and grain size over the last 10 cal kyr. The 'Holocene climatic optimum' identified in North Iceland between ~10 and 6 cal kyr BP is characterized by minor variations in the magnetic record, while there is a clear increase in oceanographic instability from ~6 cal kyr BP to the present. At large scale, a decreasing trend in the magnetic mineral content toward the present is presumably associated with a change in the circulation pattern and coincides in time with decreasing North Atlantic Deep Water formation. Short-term intervals of decreased magnetic mineral content are also identified at 5.2–4.9, 3.77–3.41, 3.01–2.7 and 0.93–0.62 cal kyr BP, the youngest one (AD 1020 to 1330) corresponding in time to the Medieval Warm Period. These events are interpreted to reflect periods of increased activity of the relatively warm, high salinity surface Irminger Current related to stronger input of North Atlantic waters into the Nordic Seas. In addition, spectral analysis of selected magnetic parameters demonstrates centennial-scale periodicities of ~715, 240, 170 and 100 yr, which are more clearly expressed in the last 6 cal kyr BP than in the previous period. These periodicities might be attributed to intervals of persistence in the North Atlantic Oscillation (NAO) mode at centennial timescales. This record, therefore, indicates that the Holocene climate was more unstable than is often assumed, and it demonstrates the importance of high-resolution climatic studies for this recent time period to improve climate model predictions.

Keywords: Holocene; thermohaline circulation; Irminger Current; magnetic properties

1. Introduction

On the basis of temperature estimates from the Greenland summit, the Holocene climate (11,500 cal yr BP to the present) has long been considered as fairly

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doi:10.1016/j.epsl.2005.07.030

stable by comparison with the extreme climate fluctuations of the last glacial interval. Nevertheless, significant climate variations also occurred during most of the Holocene (e.g. [1]). In the mid to high latitudes of the northern hemisphere, various past climatic records — for example from Greenland ice cores [2], deep-sea Holocene sediments from the North Atlantic [3,4], speleothems data from SW Ireland [5], Holocene glacier fluctuations [6–8] and eolian soil deposits from Iceland [9] — have revealed the occurrence of abrupt shifts notwithstanding the conventional concept of a stable Holocene climate. Several of the Holocene cold events, including the 'Little Ice Age' and the cooling at about 8.2 cal kyr BP, have also been recognized outside the circum-North Atlantic region [1,10], suggesting a more global extent [11,12]. If it is widely accepted that climate variability on timescales of 10^3 to 10^5 years is driven primarily by orbital, or so-called Milankovitch forcing, the causes of the observed Holocene centennial to millennial-scale variability are still less well understood. Yet, understanding these higher frequencies may be important for predicting future climate changes and anthropogenic induced effects.

It is now well accepted that the North Atlantic Ocean exerts a major influence on global climate change through formation of North Atlantic Deep Water (NADW), which is a major component of the thermohaline circulation (THC) associated with transport of heat poleward from the Equator. The North Atlantic Oscillation (NAO), which might be a manifestation of the Arctic Oscillation in the Atlantic regions [13], has been recognized as one of the dominant atmospheric modes of northern Hemisphere climate variability (e.g. [14]). The NAO winter index is the pressure difference between Iceland and the Azores during the winter months [15–18]. During a positive state of the NAO winter index, a strong pressure gradient exists between these two areas with a pronounced atmospheric Iceland low driving strong mid-latitude westerlies. An air temperature cooling trend of ~0.5 °C/yr on average since the 1960s in the region bounded by Baffin Island and Canada in the west and the Shetland Islands in the east has been linked to long-term stability in the positive mode of the NAO [16]. On a decadal timescale, the signature of the NAO variability in the ocean north of Iceland is imprinted in the sedimentary records of the North Icelandic shelf [15,19].

The response of oceanic conditions to NAO variability on a longer timescale is, however, not yet fully understood. This is partly because the NAO reconstructions only extend 500–600 years back in time [20,21]. Nevertheless, records of West Greenland ice accumulation [22], tree-ring widths from the circum-North Atlantic [23], lake sediments in Northwest Iceland [24] and marine sediments from the North Atlantic [25–28] amongst others indicate that the NAO exhibits periodic episodes of stability at decadal and possibly centennial timescales. Since the coupling between the northern North Atlantic and global climate suggests that these stable modes of the NAO should affect global climate patterns, longer records of the NAO activity are needed to assess the viability of model predictions.

Detailed magnetic study of shelf sediments from the MD99-2275 core on the mid-outer shelf area of North Iceland presented here, resolves these centennial to millennial scales of climate variability. Previous studies of a series of high-resolution datasets from the North Iceland margin have identified measurable changes in oceanography and sea–ice interaction during the last 15 cal kyr, and considerable variability during the late Holocene [25,26,29–36], including the Little Ice Age (LIA) [27,35,36]. Sediments have proven to be reliable recorders of the past geomagnetic field, and it is well known that the rock magnetic properties of sediment cores, particularly magnetic susceptibility, can be correlated with past climatic and oceanographic changes (e.g. [37,38]). Magnetic parameters can reflect either changes in the sources and transport of sediments, thus reflecting the deep water current dynamics linked with climatic variability [39], or chemical and biological processes during diagenesis which also control the iron mineralogy in the sediments [40,41]. A study of the magnetic properties for the last 12 cal kyr of core MD99-2269 from the North Iceland margin [26] has allowed establishment of a link between grain size, magnetic mineral concentration and solar forcing, which is interpreted as being controlled by oceanographic and atmospheric changes related to changes in relative advection of Atlantic and Polar waters along the Iceland margin. However, the water mass history of the North Iceland margin and its relation to global Holocene climatic variability remain to be fully understood.

High-resolution magnetic results for the last 10 cal kyr in core MD99-2275 from the North Icelandic margin confirm the long-term sensitivity of this area to changes in environmental conditions. The study area has the advantage of being close to Icelandic volcanoes, which have produced numerous wide-spread instantaneous air-fall deposits of rhyolitic, andesitic, and basaltic composition during the Holocene [42–45], allowing the establishment of a well-constrained

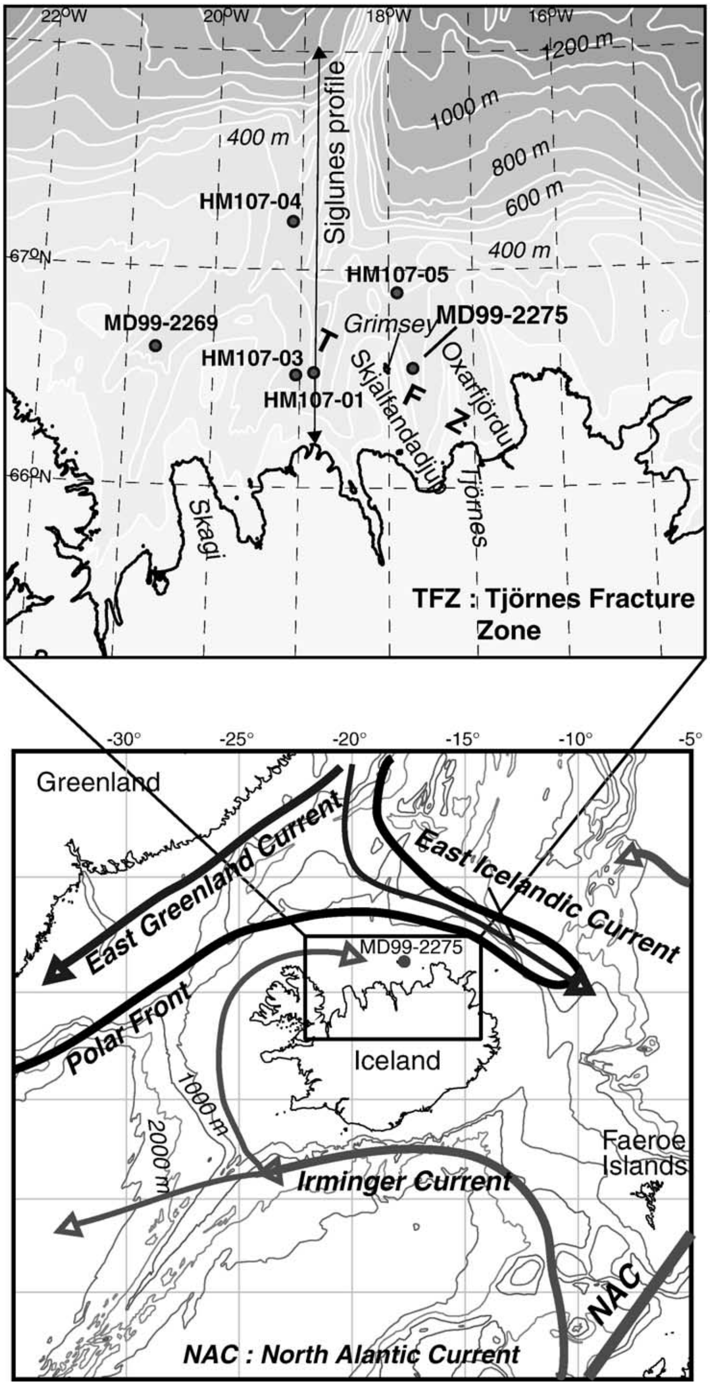

Fig. 1. (Bottom) Present-day ocean surface circulation in the northern North Atlantic region around Iceland. (Top): Location map with the study area north of Iceland. Piston cores MD99-2275 and MD99-2269 from the IMAGES V cruise in 1999 (R.V. Marion Dufresne) and gravity cores HM107-05, HM107-04, HM107-03 and HM107-01 from the 1995 BIOCE cruise (R.V. Haakon Mosby) locations are also shown. The Siglunes profile corresponds to an oceanographic section along which temperature and salinity data were measured [33,35].

age model for the last 12 cal kyr [33,46,47]. With this chronology as a background, the purpose of this paper is to provide new insights on observed variability in sediment magnetic characteristics as a proxy for sediment transport and depositional processes during the Holocene.

2. Oceanographic setting

The margin of North Iceland is a key area for the study of changes in paleoceanography of the North Atlantic (Fig. 1). The North Iceland shelf seabed is strongly affected by surface circulation in the area [30], and the conjugate influences of the relatively warm, high salinity surface Irminger Current (IC) and both the cold, low salinity East Greenland Current (EGC) and East Icelandic Current (EIC) make it an oceanographically sensitive boundary region [28]. This boundary region between relatively warm and cold surface water masses defines the oceanic Polar Front, which at present lies close to the North Icelandic shelf.

Over the last 50 years, the North Iceland margin has recorded drastic changes in temperature and salinity associated with the relative dominance of warm Atlantic water versus cold Arctic or Polar waters. In the late 1960s, the Great Salinity Anomaly (GSA) involved a sharp decrease in both temperature and salinity at hydrographic stations in Hunafloi and along the Siglunes transect [48]. The GSA resulted from an excursion of freshwater (sea–ice) from the Arctic Ocean, even though the causes remain to be defined [49,50]. A later salinity anomaly in the 1980s, sourced in the northwestern Atlantic has also been reported [51]. These freshwater perturbations affected convection in the Labrador Sea and caused reduction in the formation of North Atlantic Deep Water [51,52]. Changes in the formation of this water mass have been shown to propagate rapidly through the North Atlantic [53]. The strength of the North Atlantic Current, and hence of the IC, is usually related to deep water formation in the Nordic Seas and is expected to get stronger during periods of active deep water formation. During periods of freshening north of Iceland, strong inputs of the EGC and EIC are associated with weakening of the IC [33]. Periods with strong EIC are characterized by increased sea–ice, cold winters and short summers. Thus, decadal to centennial changes in the relative strength of the ocean currents can have dramatic consequences for the climate in Iceland, which is oceanic in character [54].

On the northern shelf of Iceland, the strongest current velocities are generally observed at the surface close to the shelf edge, decreasing landward and below 50 m depth, and considerable mixing of water masses takes place. The IC influences the sea floor of the inner part of the North Icelandic shelf, while the deepest realms, reaching water depths of over 600 m, are occupied by Arctic Intermediate waters (AIW), which is formed by convection in the Iceland and Greenland seas (i.e. [29,30,34,55,56]). To the north of Iceland, the surface water masses are replaced at ~400–500 m by the Norwegian Sea Deep Water (NSDW), which fills the deep-sea basins down to the sea floor. This water mass forms cold southward overflows, the closest of which to the North Icelandic shelf crosses the Iceland–Faroe Ridge at depths of less than 500 m. Based on the modern temperature and salinity data of the Siglunes transect (Fig. 1), Knudsen and Eiríksson [33] state that due to the topography of the shelf, deep water masses may be expected to encroach into topographic lows and basins during periods of active deep water formation in the Nordic Seas.

3. Core setting and age model

CALYPSO piston core MD99-2275 (66°33.06′N, 17°41.59′W; 440 m water depth) was recovered during the 1999 IMAGES V cruise of the *R/V Marion Dufresne* from the North Icelandic shelf close to Grimsey Island (Fig. 1). The coring site is situated in the tectonically active Tjörnes Fracture Zone (TFZ), which is characterized by a series of north–south trending troughs and ridges [57], thus featuring numerous active basins in a mud-dominated shelf environment. Site MD99-2275 lies in the Skjalfandadjup trough, which is about 50 km offshore. It was cored on relatively level topography in order to minimize risks of catastrophic depositional or erosional events and to avoid turbidity current channels fed by the North Icelandic fjord deltas [33]. The sediments of the ~25 m record studied here are mainly composed of dark silty clays.

Available high-resolution seismic profiling (3.75 kHz sub-bottom profiler) indicates that the whole sequence penetrated by core MD99-2275 is conformable and undisturbed by tectonic events [58]. The water depth of over 400 m is well below the reach of erosional forces by storm waves [59]. Measurements of anisotropy of magnetic susceptibility (AMS) performed over the top 8 m of the core reveal systematically oblate fabrics (P factor ranging from 1.01 to 1.05) with the minimum axis perpendicular to the deposition plane. This indicates a sedimentary deposition in a calm environment with no further perturbation. Core stretching is also not evidenced by these measurements. In addition, thirty-five radiocarbon dates are available between tephra layers throughout the Holocene ([47] and unpublished data) and they reveal no disturbances nor major deviations from linear sedimentation rates. However, reservoir age variability in the research area has

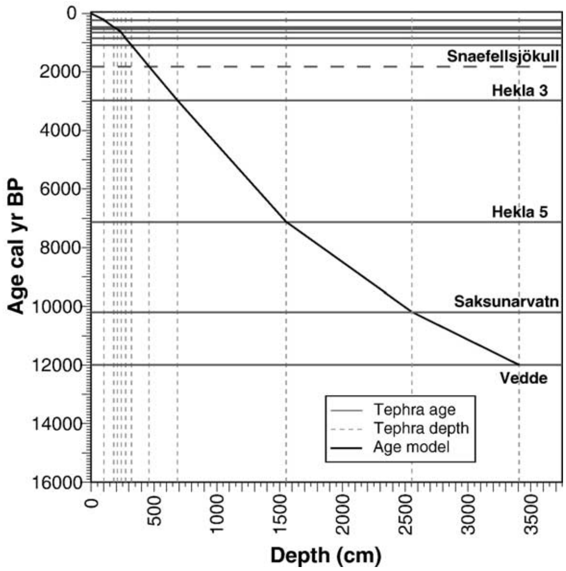

Fig. 2. Age-depth model for core MD99-2275 based on the tephrochronology established for the Holocene by Larsen et al. [46] and Eiríksson et al. [47].

been demonstrated and therefore a tephrochronological age model was preferred for this core [47].

The tephrochronological age model for core MD99-2275 (Fig. 2) has been established following Larsen et al. [46], Knudsen and Eiríksson [33] and Eiríksson et al. [47] by linear interpolation between well-constrained ages of eleven tephras. This age model is considered as very reliable for the last 1100 years while, for the earlier part of the record, tephra markers provide reliable dates at 2980, 4200, 7125, 10200 and 12000 cal. yr BP. Between these points, the age model uncertainties may amount to tens to hundred years, although available radiocarbon dates do not indicate major deviations. The Holocene tephrochronology of Iceland is well documented and distribution maps for all major rhyolitic and most of the major basaltic air fall tephras, as well as their approximate age, are known in detail (e.g. [42–46,60,61]). Consequently, the occurrence of major unknown or undetected tephra deposits in core MD99-2275, which has been checked visually at 1 cm intervals, is considered unlikely. The ages of the tephra markers are based on historical records from Iceland for the last 900 yr, correlation with Greenland Ice for the Settlement layer (AD 872), and on radiocarbon dates of terrestrial material for the older tephras [46,47,61]. These independent in situ dates provide a reliable basis for high-resolution analysis of climatic variations in this record. All ages reported in this paper are calibrated years (before AD 1950). Based on this age model, the sediment accumulation rate of core MD99-2275 amounts to between ~2 and 5 mm/yr, being close to 5 mm/yr at the top and base of the record, but mainly close to 2 mm/yr from c. 9.5 to 0.5 cal. kyr BP.

4. Magnetic results

Various measurements and ratios of sediment magnetic parameters can be used to describe magnetic mineral concentrations, mineralogy and grain size [37,38,62]. Below, we present magnetic property analyses of the uppermost ~25 m of core MD99-2275.

The core was sampled continuously with 1.5 m u-channels [63,64] and measurements of the natural remanent magnetization (NRM), anhysteretic remanent magnetization (ARM), and isothermal remanent magnetization (IRM) were made at 2 cm intervals using a pass-through, high-resolution cryogenic magnetometer with DC-SQUIDs that is housed in a shielded room at the LSCE. Demagnetization of the u-channels was

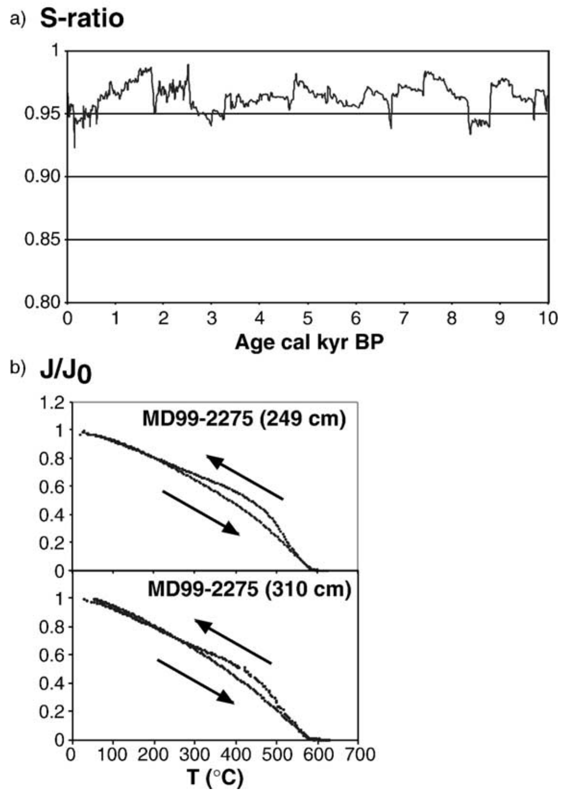

Fig. 3. (a) S-ratio ($IRM_{0.3\ mT}/IRM_{1T}$) for core MD99-2275 versus age in calendar years before 1950. All the values are close to unity, which is consistent with magnetite as the main magnetic carrier. (b) Example of high-field thermomagnetic curves showing a single Curie point at around 580 °C, which is also representative of low-Ti magnetite as the main component of the magnetic fraction.

performed with stepwise in-line alternating field (AF) treatment in 10 to 15 steps. ARM was imparted along the axis of the u-channel using a 100 mT AF and a 50 μT DC bias field. IRM was imparted along the *Z* axis of the u-channel with a field of 1 T using a solenoid pulse magnetizer. Low-field magnetic susceptibility (κ) was measured at 2 cm intervals with a Bartington Instruments coil. The measurement resolution of both the cryogenic magnetometer and the small diameter Bartington coil is about 4.5 cm. Therefore, for core MD99-2275, the sampling resolution is one independent data point every ~10–20 years depending on sedimentation rate. An alternating gradient magnetometer (AGM 2900) was used for hysteresis analysis of small amounts of sediment taken at 2 to 10 cm intervals. A few magnetic extractions were conducted for

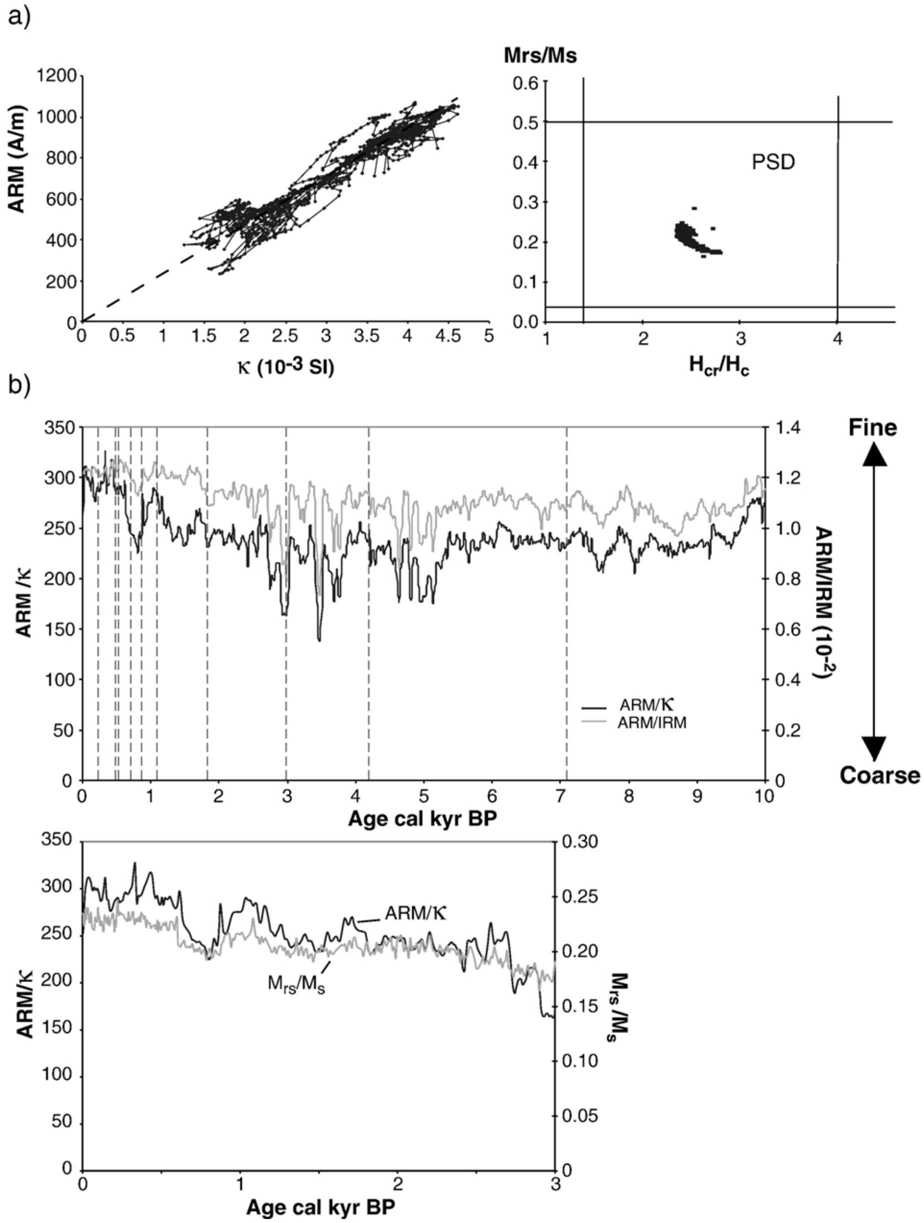

Fig. 4. Grain size of magnetite. (a) ARM versus κ plot (left) and 'Day' plot (right). (b) ARM/κ and ARM/IRM curves versus age and enhanced view of the ARM/κ and M_{rs}/M_s curves between 0 and 3 cal kyr BP. Within the limited magnetic grain size range, variations are identified. Increased variability and a tendency to decreasing grain size are observed for the ~5.5 cal kyr BP to present interval. The occurences of the tephra layers are indicated with dashed lines.

sediments from the uppermost 5 m of the core for thermomagnetic analysis.

In general, the core has strong magnetizations illustrating a high magnetic mineral content of these basaltic derived sediments. The *S*-ratio ($IRM_{-0.3T}/IRM_{1T}$) remains remarkably constant and varies between 0.94 and 1 (Fig. 3a), which is indicative of the predominance of low-coercivity grains. The average value of the median destructive field of the NRM is about 25 mT, and the coercivity of remanence varies between 35 and 44 mT. The few thermomagnetic curves obtained for the uppermost 5 m of the core, with their almost reversible behavior, indicate the presence of a single magnetic phase with a Curie Temperature of 580 °C, which is typical of low-Ti magnetite (Fig. 3b). The small irreversibility could be interpreted as limited neo-formation of magnetite or loss of Ti upon heating. All of these parameters are consistent with low-Ti magnetite as the main ferromagnetic carrier (s.1.). We note that the basaltic province of Iceland is one of the most significant sources of magnetite for the North Atlantic and probably also for the southern Norwegian Sea [65].

ARM values versus low field susceptibility κ data are commonly plotted to infer changes in magnetite grain sizes (Fig. 4a, left). In our record, they are distributed along a line that passes through the origin of the ARM vs. κ plot, indicating rather uniform magnetic grain sizes and a weak paramagnetic contribution to κ. All samples fall within the pseudo single domain (PSD) grain size range [66] (Fig. 4a, right), with M_{rs}/M_s ratios ranging from 0.16 to 0.28 and H_{cr}/H_c ratios ranging from 2.34 to 2.79. Within this rather limited grain size range, we observe some scatter around the mean slope on the ARM vs κ diagram and a small trend on the Day diagram. To visualize these small changes with time, we report variations of the ARM/κ and ARM/IRM ratios (Fig. 4b, upper) and show a comparison with the M_{rs}/M_s ratio for the most recent time interval (Fig. 4b, lower). On long-term scales, we note that the magnetic grain size seems relatively constant before ~5.5 cal kyr BP, while a more unstable pattern is observed from ~5.5 cal kyr BP to present, which is superimposed on a slight decreasing trend in magnetite grain size.

The bulk magnetic parameters κ, ARM and IRM have similar patterns for long-term trends and short-term features (Fig. 5). The similarity of the three bulk magnetic parameters combined with the data above confirms that the observed variations are essentially controlled by changes in concentration of magnetite rather than by dominant changes in magnetic mineralogy and/or magnetic grain size. On the long-term, a sharp increase in magnetite concentration is recorded in the 10 to 9.5 cal kyr BP interval (even though a longer record would be necessary to constrain this feature better). It is followed by a rather progressive decrease from 9.5 cal kyr BP to the present. Short-term features are observed mainly between 5.5 cal kyr BP and the present and are illustrated by abrupt decreases in mag-

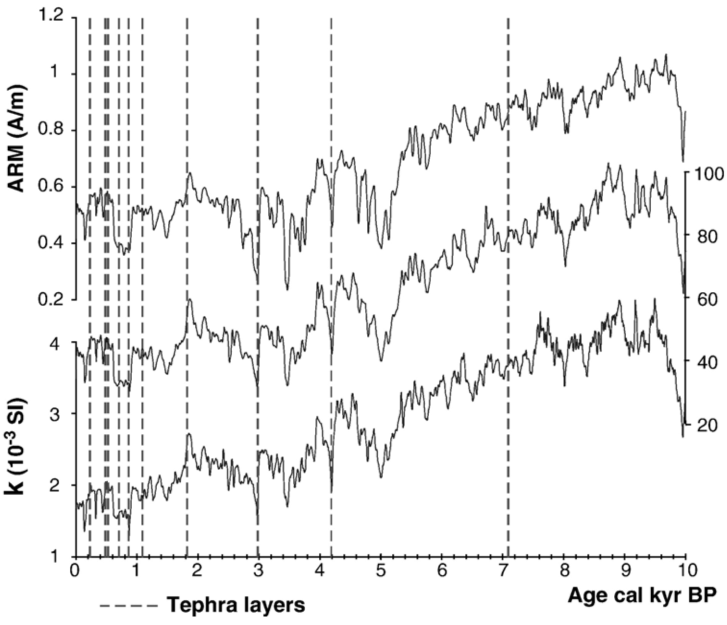

Fig. 5. Bulk magnetic parameters: low-field magnetic susceptibility κ, ARM and IRM versus age indicating that the main changes in the magnetic parameters reflect changes in magnetite concentration. The occurrences of the tephra layers are indicated with dashed lines.

netite concentration and slightly coarser magnetite grains (Figs. 4 and 5). These features are observed in the time intervals 5.20–4.90, 3.77–3.41, 3.01–2.70 and 0.93–0.62 cal kyr BP. For older ages, where the age model is less well constrained, the more subdued character of the record renders the characterization of inferred events more difficult. However, although less prominent than the younger ones, significant drops in the magnetite content are also observed at 7.7–7.5 and 8.2–8.0 cal kyr BP.

Whether these changes can partly be related to dilution by carbonate cannot accurately be assessed since carbonate content has not yet been analyzed at the same resolution as the magnetic properties in core MD99-2275. However, we know that the carbonate content in the region is generally low, mainly around or below 10% (from measurements in nearby cores HM107-03 and HM107-05 [29,33]) and core MD99-2275 is no exception with values ranging between 4% and 5% during and immediately before the MWP, and with a gradual decrease to a minimum of 2% during the LIA [67]. It is, thus, unlikely that carbonate content plays a dominant role in dilution of the magnetic fraction. Moreover, each identified change in magnetite concentration is associated with a change in magnetic grain size, which is a parameter that is independent of dilution processes. On the other hand, two of the short-term features also include large rhyolitic tephra markers (Fig. 5), the Hekla 3 (2980 cal yr BP) and Hekla AD 1104 (850 cal yr BP) layers, which might locally enhance these features, because rhyolite glass does not contain appreciable amounts of magnetite. A magnetite concentration minimum is also observed at the level of the Hekla 4 (4200 cal yr BP) rhyolitic tephra marker, but not at the Hekla 5 layer (7125 cal yr BP). Based on these considerations, and on the duration of the short-term features identified, the low likelihood of missing tephra (see above) and the fact that the occurrence of the tephra markers does not notably affect the grain size record (see Fig. 4b, Hekla 4, for example), which always accompanies the short-term features, it seems unlikely that these latter features on the magnetite concentration record owe their origin only to the presence of tephra.

Changes in the amount of PSD magnetite (s.l.) thus dominate the short and long-term variations observed in the bulk magnetic parameters of core MD99-2275. Because the magnetic record is dominated by magnetite and because the effects of diagenesis are minimal, the magnetic record can be interpreted as a primary depositional signal (rather than authigenic) that is controlled by provenance and/or sediment dynamics. In terms of long-term trends, it seems that the dynamics of the detrital input to this site changed at around 5.5 cal kyr BP. The magnetic input, which had a rather uniform grain size between 10 and 5.5 cal kyr BP, underwent rapid and abrupt changes during the younger period. These short-term events are characterized by a lower magnetite content associated with slightly coarser magnetic grains than in the neighboring intervals.

5. Interpretation and discussion

Different mechanisms may be invoked for the transport of magnetic particles to the site of deposition, the principal mechanisms being wind, melting of icebergs or seabed currents. As far as melting events are concerned, we first observed the absence of a clear relationship between variations in magnetite concentration and the presence of ice rafting events in the North Atlantic [3] at about 8.1, 5.9, 4.3, 2.8 and 1.4 cal kyr (Fig. 6). In addition, the grain size of the magnetic particles, which should be larger on average during IRD events, also seems highly uncorrelated. Thus, no obvious contribution of magnetic IRD is observed in our record.

The effect of wind versus seabed currents is more difficult to assess. Interpretation of Holocene sea surface temperature (SST) records from surface currents of the North Atlantic [28] have demonstrated that the North Icelandic shelf is an oceanographically unstable frontal zone between the EIC, EGC and IC that is sensitive to climate changes (see also the records in [26,29–36]). These records [28] also seem to imply long-term NAO signatures, which were more positive from the Early Holocene to 4 cal kyr BP with a gradual transition toward a negative NAO signature after 4 cal kyr BP. On the other hand, a record of the last 10 kyr BP from Icelandic eolian soil deposits [9] reveals several windy and cold episodes, associated with evidence for cold and windy climate in central Greenland and diminution of deep-water formation (NADW) in the North Atlantic, which is not consistent with a persistent negative phase of the AO–NAO. These apparently conflicting datasets first demonstrate the strong long-term atmosphere-ocean coupling for the Holocene in this region, but they also reflect the fact that even the present-day links between the atmosphere and hydrographic variations in the Greenland and Iceland Seas and the THC are not clear [55]. Neither is there a clear long-term association between major salinity anomalies of North Iceland and the phases of the NAO [15,16]. However, the best known of these events, the ‘Great Salinity Anomaly’ of the 1960s

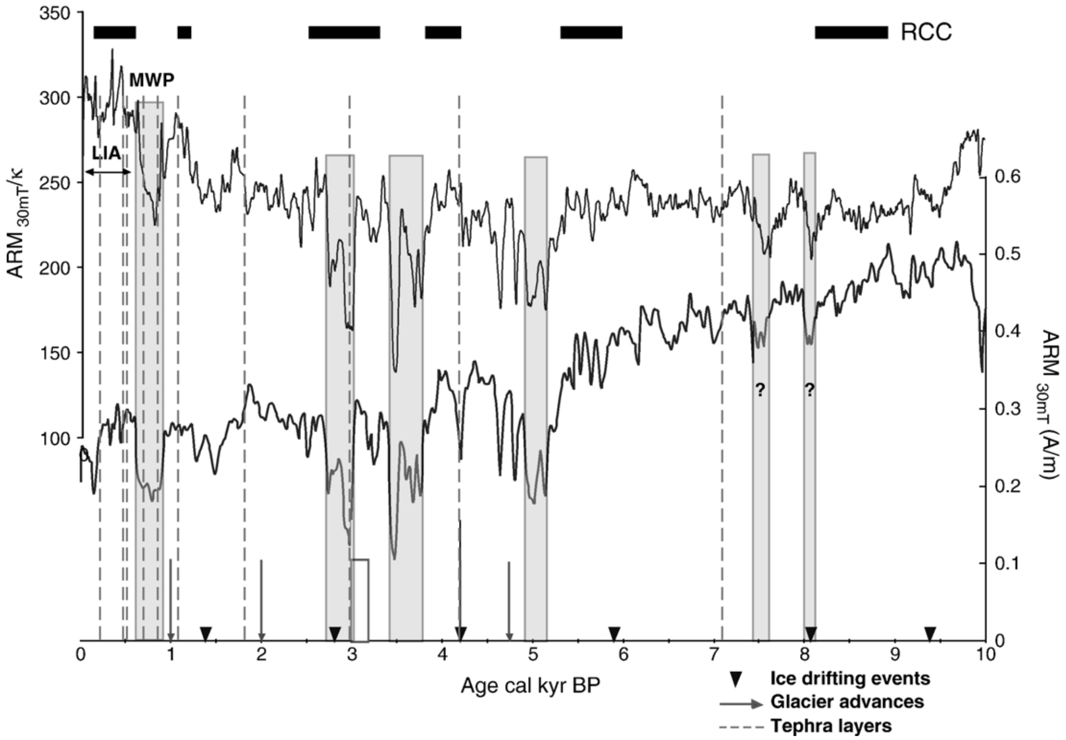

Fig. 6. ARM and ARM/κ versus age (cal kyr BP (before 1950)) curves. Intervals of main variability, potentially associated with renewed activity of the paleo-Irminger Current, are shown as shaded bars. Ice drifting events in the North Atlantic [3] and glacier advances in Iceland [8] are indicated (the box on the bottom axis corresponds to a postulated 200-year period of glacier advances [8]). LIA: Little Ice Age, MWP: Medieval Warm Period (see text). Periods of colder or more unstable Holocene climates (RCC) by Mayewski et al. [1] are also shown as black boxes at the top of the figure.

[48,55], coincided with a strong negative NAO winter index. A negative state of the NAO index, sustained over a decade or longer, leads to predominantly northerly winds east of Greenland caused by high pressure over Greenland. This enhances the flow of the East Greenland and East Icelandic Currents and leads to a southward movement of the sea–ice limit toward or onto the North Icelandic shelf (see also [69]). The Great Salinity Anomaly was a period of freshening and cooling of surface waters north of Iceland and prolonged sea–ice cover on the North Icelandic shelf. Conversely, in a sustained positive NAO index, storminess is increased and the wind directions across Iceland are characterized by a strong Iceland Low and predominantly southerly and southeasterly winds, carrying relatively warm air to the Greenland and Iceland Seas and pushing the sea–ice limit northward, probably by a combination of thermodynamic processes and wind stress.

Prolonged intervals with a tendency to a preferred negative NAO index can be predicted to cause reduced current velocities on the North Iceland shelf seabed and increased deposition of sediment released from melting sea–ice and icebergs. This additional sediment source would be predicted to dilute the magnetic mineral content of the shelf sediment during intervals of increased sea–ice. The linkage of these oceanographic changes to atmospheric conditions associated with a negative NAO index has been suggested by Hurrel et al. [15], involving a high pressure field over Greenland and enhanced northerly winds to the east of the high. Conversely, dominantly southeasterly winds across Iceland would strengthen the IC. The magnetite concentration would then be predicted to increase again to reflect the predominance of provenance from Iceland.

Therefore, the changes in the magnetic parameters measured here most probably result from the combination of the different but related effects of sea-bed activity and wind. In particular, they could reflect changes in the flux of Atlantic versus Arctic/Polar waters and associated current activity, which in turn are related to the strength and location of the Iceland Low and Greenland High pressure systems, as these control the wind curl stress off North Iceland [55]. Due to the proximity of the oceanographically unstable front, we tentatively hypothesize that the most plausible explanation of short-term oscillations in core MD99-2275 is that they mainly reflect variations in current dynamics in this region of the North Iceland shelf (as for core MD99-2269, see [32]). If true, then changes in the magnetite concentration and associated small variations in magnetic grain size would reflect changes in the velocity of bottom currents during deposition of the sediment drift, which would have induced variations in the efficiency of the bottom current to transport magnetite-rich sediments to the site. Based on this hypothesis, we first examine the meaning of the clearly expressed intervals of low magnetite concentration associated with slightly coarser magnetic grain sizes.

The time interval 0.93–0.62 cal kyr BP corresponds temporally to the Medieval Warm Period (MWP). A strong climate manifestation of this event is clearly expressed in previous studies of North Iceland shelf sediments, primarily from foraminiferal, diatom and stable isotope studies of core MD99-2275 and the nearby cores HM107-01 and HM107-03 [35,36]. These authors report a time period between 1.2 and 0.7 cal kyr BP (for core MD99-2275), which includes the MWP, that is characterized by relatively high bottom and surface temperature due to increased influence of the IC. Historical records report that around the time of settlement (AD 870), Iceland experienced a relatively warm interval, while cooler conditions were noted around AD 1200–1300 [56]. Low magnetite concentration and relatively coarse magnetic grain sizes, as expressed in our record from AD ~1020 to 1330 are therefore thought to be associated with renewed activity of the warm, saline IC.

The subsequent period, which corresponds in time to the Little Ice Age (LIA), is characterized by more abundant and finer magnetic grains. The termination of this period is not clearly expressed, but it could be at around 0.15 cal kyr BP where a significant drop in the magnetite concentration is observed. The most recent values are still lower than in the 0.62–0.15 cal kyr BP interval. According to historical sources, the Icelandic climate cooled further in the LIA from AD ~1400 to 1900 [54]. Even though this cooling was variable and punctuated by mild intervals, warm conditions were not reached again before the end of the 19th century. Foraminiferal and isotopic results from the same core [35] indicate a general drop in temperature, both in surface waters and at the sea floor, after ~0.7–0.65 cal kyr BP. This marks the transition to increased influence of the cold, low salinity waters of the East Icelandic Current. This shift corresponds in time to the beginning of our period of higher magnetite concentration and finer grain size. The finer grain size is considered consistent with the data of Knudsen et al. [35] that indicate sluggish bottom currents resulting from a reduced IC influence north of Iceland. High sedimentation rates appear to have been maintained, however, probably due to increased ice rafting and biological productivity associated with the presence of the Polar Front. A subsequent shift at around 0.4–0.3 kyr BP to renewed influence of dense, high salinity Atlantic waters at the sea floor [70] is not clearly expressed in our magnetic record. The older reported historical climatic variability (i.e. the Dark Ages Cold Period and the Roman Warm Period) was also not clearly triggered in our record. However, relatively higher SST at ~1.6 cal kyr BP and cooler waters at around 1.3 cal kyr BP, as recorded by the diatom distribution in core HM107-03 [57], are in broad agreement with the pattern of the magnetic variations before the MWP.

Using the MWP as an analog, observed short-term intervals of decreased magnetite content and slightly coarser grain size (i.e. 5.2–4.9, 3.77–3.41 and 3.01–2.7 cal kyr BP, perhaps as well as 8.2–8.0 and 7.7–7.5 cal kyr BP), would be expected to reflect periods of relative warming or at least more enhanced IC influence, that were potentially related to periods of enhanced NADW formation (see [33]). Some of these events are weakly correlated with a high-resolution oxygen isotope record in a speleothem from Southwest Ireland [5]. This record suggests cooling events at 8.2, 7.73, 5.21, 4.2 cal kyr BP, each followed by a warming event. The events expressed in our record at 8.2–8.0, 7.7–7.5, 5.2–4.9 and 3.77–3.41 cal kyr BP roughly coincide with these warming events, but a clear relationship cannot be established. Recent data from eolian soil deposits from southern Iceland [9] also reveal the presence of cold and windy periods with peaks at 8.2, 7.4, 5.5, 4.3, 3.3, 1.6 and 0.6–0.1 kyr. Winds climaxed in Iceland at 5.5 kyr [9], a period that correlates with evidence of a minimum in NADW formation. Again, even if a clear relationship cannot be established, it is striking and encouraging that all of these cold and windy events fall outside the boundaries of our so-called ‘warmer’ periods or periods with increased influence of the IC. Our record is also coherent with the global Holocene climate variability discussed by Mayewski et al. [1] (see Fig. 6). However, we should note here that cooling events do not seem to have a marked signature in the magnetic record, which is apparently more sensitive to enhanced influences of the warm saline IC. This renders correlations more difficult since triggering of ‘cold’ events is discussed more in the literature. For example, the 8.2 kyr BP cooling event, which is generally regarded as the most significant Holocene cooling episode and was associated with a major influx of freshwater in Hudson Bay [71], is not explicitly expressed in the magnetic record, although it has a clear expression in sediments of the Norwegian Sea [72] and its effects were felt widely in the North Atlantic region (e.g. [11,73]). Considering the age model uncertainties for this part of the record, however, the slight increase in magnetization associated with finer magnetic grain-sizes just before 8.2–8.0 cal. kyr BP (Fig. 6) might correspond to the 8.2 cal. kyr BP cooling event. No clear relationship could also be found with the glacier advances from Iceland [8] (Fig. 6). These observations suggest that incursions of the IC have a pronounced influence on short-term changes in the dynamics of detrital input at the core site, which is otherwise dominated by cold currents. These short-term changes are especially expressed in the interval from 5.5 cal kyr to the present.

A multi-proxy analysis of two cores from the North Icelandic shelf (Fig. 1), HM107-04 and HM107-05 [29,74], indicates a faunal change immediately before deposition of the 10.2 kyr BP Saksunarvatn tephra which is linked to an influx of relatively warm, saline and nutrient-rich water that was related to a strengthening of the paleo-Irminger Current. This change trigger the beginning of the Holocene Climatic Optimum identified between 10.2 and 6–7 cal kyr BP in this area [29,74]. It corresponds in our record to an increase in magnetite concentration that is accompanied by an increase in grain size until ~9 cal kyr BP, and is followed by a period with a constant magnetite grain size and a quasi-monotonous decrease in magnetite concentration (Fig. 6). After ~6 cal kyr BP, continued dominance of relatively warm, saline water remained at the site of core HM107-05, but with gradually cooling and fluctuating conditions. The sortable silt fraction is generally lower and fluctuates strongly after ~6 cal kyr BP. This is interpreted to be a result of gradually more sluggish currents and increased influence of the EIC [30]. These changes presumably also influenced the MD99-2275 record, which exhibits clearly increased variability after 6 cal kyr BP.

Based on a δ^{13}C record from epifaunal benthic foraminifera at ODP site 980 (55° N, 15° W, depth 2179 m) on the Feni Drift, Oppo et al. [75] reported reductions in the NADW contribution at 9.3, 8, 5, and 2.8 kyr ago. They also identified a trend of decreasing NADW contribution that began at about 6.5 kyr with a minimum at around 5 kyr BP. The long-term decrease in NADW contribution could be expressed in our record by the decreasing trend in the magnetite content, although the detailed records do not match well. This trend could also express a change in current dynamics at around 5.5 cal kyr BP, with a tendency to finer magnetite grain size toward the present (Fig. 4b) potentially reflecting a decreasing influence of the IC associated with a cooling trend.

The MD99-2275 record therefore seems to be influenced by two different oceanographic regimes: a long-term trend of decreasing input of magnetic minerals to the core site with a marked change in oceanographic dynamics at around 5.5 cal kyr and short-term fluctuations that are more clearly expressed in the last 5.5 cal kyr and that are considered to be related to incursions of the warm high salinity IC. One explanation for the long-term trend might be that at around 5.5 cal yr BP a change took place in the regional oceanography, which resulted in sediment load coming from a different petrological region with more non-magnetic grains with respect to the previous period that was dominated by the magnetite-rich Icelandic provenance. This would not necessarily affect the strength of the IC, but the water column on the North Icelandic shelf would then become more stratified. In the North Iceland shelf sedimentary record, a relationship between heavy sea–ice intervals based on documentary evidence and increased sand sized quartz in the sediments dated to these intervals has been demonstrated [35]. Quartz is an extremely rare mineral in the bedrock of Iceland and must have provenance outside Iceland. Benthic foraminifera, stable isotopes and IRD fluxes recorded in two east Greenland shelf cores (JM96-1206/1-GC and JM96-1207/1-GC; [76]) also indicate a shift toward colder, low salinity 'polar' conditions after 5 cal kyr BP. A surface water cooling, indicated by ice rafted debris, starting at ~6 cal kyr BP and termed the neoglacial cooling, is also evidenced in the Denmark Strait [3]. The mechanism driving the short-term oscillations observed from 5.5 cal kyr BP to present is more difficult to explain. These oscillations seem to be linked to incursions of Atlantic water carried by the IC that caused the events of reduced magnetite concentration and slightly coarser magnetite grain-size. A possible explanation could be that rapid incursions of this current could have enhanced the bottom flow and washed the fine particles elsewhere.

Giraudeau et al. [34] studied coccoliths and benthic foraminifera at a more westward locality on the North Icelandic shelf for the last 10 cal kyr (core MD99-2269; Fig. 1), and used modern oceanographic and atmospheric data as analogues to explain the long-term Holocene evolution of surface and bottom hydrology. They argued that the early Holocene up to 7 cal kyr BP was a time of enhanced atmospheric circulation over the Nordic Seas, with surface water warming off North Iceland linked to reduced influence of the EIC, but with limited inflow of Irminger water around NW Iceland.

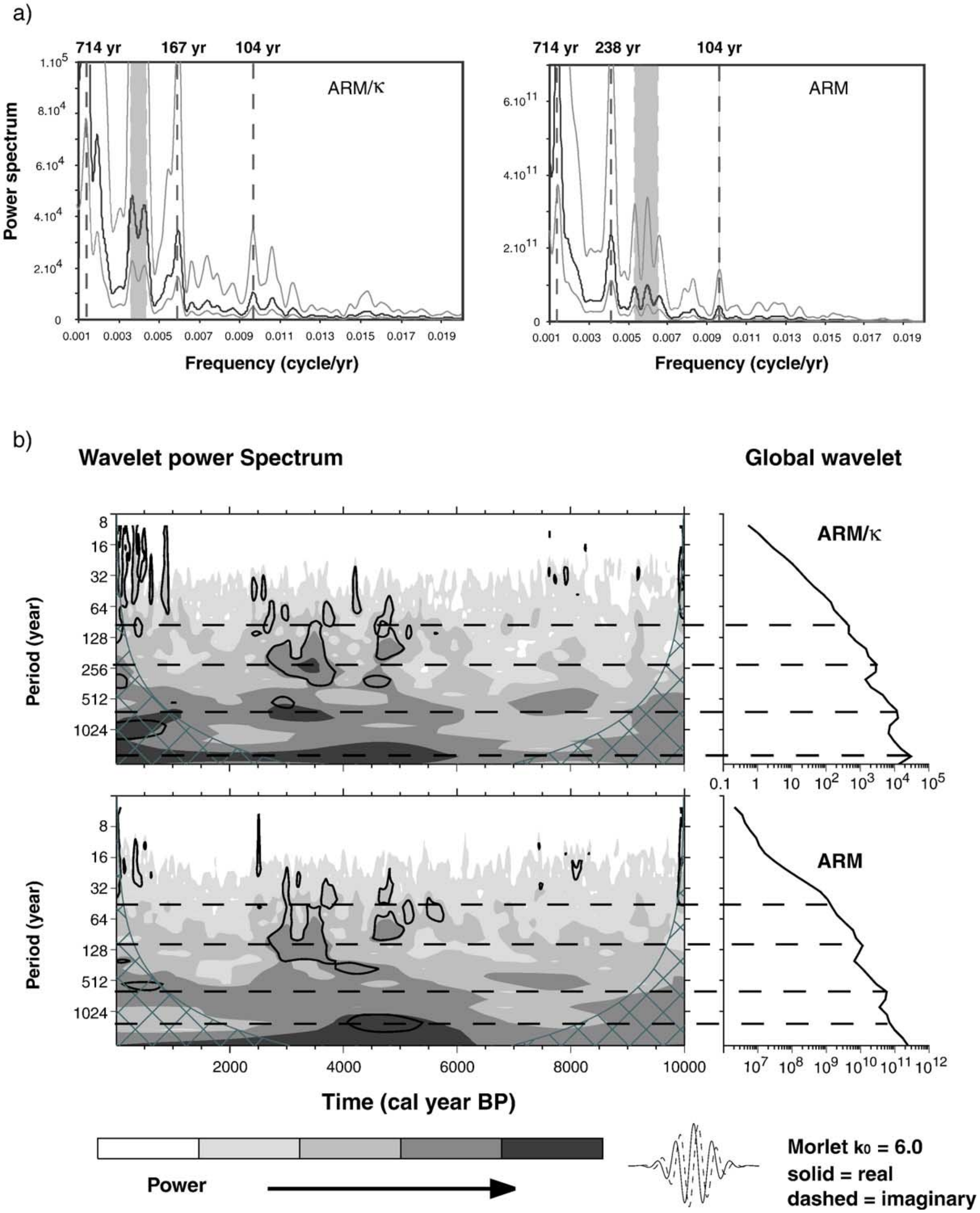

Fig. 7. (a) Simple Blackman–Tukey periodograms for the ARM/κ and ARM_{30mT} parameters. Key periodicities are identified and indicated by bold numbers and the 95% confidence envelop is shown as gray lines in the periodograms. (b): a Morlet wavelet analysis of ARM/κ and ARM_{30mT} time series. Bold contours and dotted gray lines indicate 95% confidence limits. Note that spectral peaks in the Blackman–Tukey analysis are again detected using this wavelet analysis, however, they are much enhanced in the 0–6 cal kyr BP period.

These conditions were followed by cooling from 6.5 to 3.5 cal kyr BP, associated with reduced atmospheric and gyre circulation in the Iceland sea and a strong Atlantic signature of intermediate waters over the North Iceland shelf in relation to enhanced flow of Irminger waters. In this oceanographic setting, reduced concentrations of magnetite would always be associated with enhanced activity of the IC and enhanced carbonate content. However, we note that the timing of these postulated changes does apparently not coincide with the changes observed in the magnetic record of the present study.

An investigation of cyclicity in the magnetic record of core MD99-2275 was also performed using a simple Blackman–Tukey spectral analysis. This analysis was performed on κ and ARM records, and on the ratios ARM/IRM and ARM/k. In Fig. 7, we present the analyses for ARM and ARM/κ. Comparison of spectral analysis for different magnetic parameters indicates statistically significant periodicities at ~714, 238, 167 and 104 yr. We choose only the peaks that were the most significant at the 95% confidence interval and were more intense than a background red noise.

Also shown in Fig. 7 is a wavelet analysis, which indicates the non-stationary frequencies by decomposing them in time and space [77]. The wavelet used here provides relatively poor time resolution, but high frequency resolution so that cycles in the data can be identified with a narrower spectral band. This analysis was performed using the ION program (http://ion.researchsystems.com/cgi-bin/ion-p?page=wavelet.ion). The results of this spectral analysis emphasize again the change of regime at around 6 cal kyr BP, with much of the well-expressed cyclicity being principally reflected in the 0–6 cal kyr BP time interval. Most of the periodicities described above are also identified by this analysis, and, even though their expression is enhanced after 6 cal kyr BP, they are apparent in the rest of the record, especially the ~714, ~238 and ~104 yr periods. We are less confident in the multi-decadal variability, which is not isolated by the Blackman–Tukey spectral analysis, and we do not discuss it further.

Some of the identified peaks from both spectral analyses have also been found in other records from Iceland and adjacent areas. Doner [24] reported periods of 100 to 130 yr in a geochemical record from two lakes in Northwest Iceland, with the 100 yr cycle being the most persistent. This author hypothesized that the signal is linked to erosion related to higher precipitation and/or freeze–thaw activity. High erosion can be expected when the NAO winter index is positive, with strong westerlies and northeast trade wind and anomalously strong Iceland Low increasing cyclogenesis in the region (see also [16]). Alternatively, salinity anomalies such as the GSAs are known to create many of the same climate effects as the NAO in the northern North Atlantic and could be an alternative mechanism for erosion cycles. The overall forcing behind the GSAs and the NAO has been linked to the Arctic Oscillation. Therefore, this marine record combined with lake records further strengthens the need to take into account this 100 yr cycle in models of global climate changes.

The study of MD99-2269, also from the north Icelandic shelf [32], equally reveals various centennial-scale cyclicities, including a period at 170 yr, which is also present in our record. Moreover, the 240 and 715 yr periods, which are robust in our record, approach the 230 and 885 yr cyclicities of Sarnthein et al. [78] and the 210–230 and 800–900 yr cyclicities of Bond et al. [4], which were interpreted to represent solar variability. Therefore, the observations presented here should constitute a valuable extended target for dynamical model approaches to understand forced climate variability and instability during the Holocene.

6. Conclusion

The high-resolution record of magnetic properties from the MD99-2275 core since 10 cal kyr BP (before 1950) has allowed us to identify some important features of Holocene climatic variability at high northern latitudes. Increased oceanic instability, which was likely linked to climatic variability, is observed from around 6 cal kyr BP, with enhanced short-term oscillations in the more recent period. The MWP is well expressed in the magnetic record (0.67–0.93 cal kyr BP; AD ~1020 to 1330) by reduced concentration of magnetic minerals and slightly coarser magnetic grain size, which are probably linked to increased activity of the Irminger Current. Several similar periods at 5.2–4.9, 3.77–3.41 and 3.01–2.7 cal kyr BP, and maybe also 8.2–8.0 and 7.7–7.5 cal kyr BP are presumably also related to changes in the relative strength of the Irminger Current and the East Icelandic Current. North Atlantic ice rafting events and glacier advances on Iceland cannot be correlated with the observed variations. The 8.2 cal kyr BP cooling event [79] is not clearly expressed in our record either. Clearly, more proxies and comparisons are needed to achieve a better understanding of the background for the observed variations. A strong cyclicity, which is particularly enhanced in the last 6 kyr, is observed with periods of ~715, 240, 170 and 100 yr. These periods might be associated with longer-term effects of the North Atlantic Oscillation (NAO). Our results emphasize the need for further investigation of high-resolution records of the Holocene to assess climatic instability in this period and its impact on global climate model predictions.

Acknowledgements

We thank the Institut Paul Emile Victor (IPEV) for the IMAGES coring operation aboard the *Marion Dufresne* as well as the captain and crew. We also acknowledge the help of J. L. Turon, Chief scientist during this leg. A. Mazaud developed the software used for acquisition of magnetic data at LSCE. Our thanks also to J. Giraudeau and C. Lauer–Leredde for useful comments and discussions. Constructive reviews by S. Brachfeld, A. Roberts, E. Rohling and an anonymous reviewer significantly improved the quality of the original manuscript. This work is part of the PACLIVA EU project EVK2-2002-00143. The laboratory analyses were funded by the CEA-CNRS and Sonia Rousse acknowledges a Post-doc grant from the CEA. This is LSCE contribution n° 2354.

References

[1] P.A. Mayewski, E.J. Rohling, J.C. Stager, W. Karlén, K.A. Maasch, L.D. Meeker, E.A. Meyerson, F. Gasse, S. van Kreveld, K. Holmgren, J. Lee-Thorp, G. Rosqvist, F. Rack, M. Staubwasser, R.R. Schneider, E.J. Steig, Holocene climate variability, Quat. Res. 62 (2004) 243–255.

[2] D. Dahl-Jensen, K. Mosegaard, N. Gundestrup, G.D. Clow, S.J. Johnsen, A.W. Hansen, N. Balling, Past temperature directly from the Greenland Ice sheet, Science 282 (1998) 268–271.

[3] G.C. Bond, W. Showers, M. Cheseby, R. Lotti, P. Almasi, P. deMenocal, P. Priore, H. Cullen, I. Hajdas, G. Bonani, A pervasive millennial scale cycle in North Atlantic Holocene and glacial climates, Science 278 (1997) 1257–1266.

[4] G. Bond, B. Kromer, J. Beer, R. Muscheler, M.N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, G. Bonani, Persistent solar influence on North Atlantic climate during the Holocene, Science 294 (2001) 2130–2136.

[5] F. McDermott, D.P. Mattey, C. Hawkesworth, Centennial-scale Holocene climate variability revealed by a high-resolution speleothem δ^{18}O from SW Ireland, Science 294 (2001) 1328–1331.

[6] G.H. Denton, W. Karlén, Holocene climatic variations—their pattern and possible cause, Quat. Res. 3 (1973) 155–205.

[7] H.J. Gudmundsson, A review of Holocene environmental history of Iceland, Quat. Sci. Rev. 16 (1997) 81–92.

[8] J. Stötter, M. Wastl, C. Caseldine, T. Häberle, Holocene paleoclimatic reconstruction in northern Iceland: approaches and results, Quat. Sci. Rev. 18 (1999) 457–474.

[9] M.G. Jackson, N. Oskarsson, R.G. Trønnes, J.F. McManus, D.W. Oppo, K. Grönvold, S.R. Hart, J.P. Sachs, Holocene loess deposition in Iceland: evidence for millennial-scale atmosphere-ocean coupling in the North Atlantic, Geology 33 (2005) 509–512.

[10] S.R. O'Brien, P.A. Mayewski, L.D. Meeker, D.A. Meese, M.S. Twickler, S.I. Whitlow, Complexity of Holocene climate as reconstructed from Greenland ice core, Science 270 (1995) 1962–1964.

[11] U. Von-Grafenstein, H. Erlenkeuser, J. Müller, J. Jouzel, S. Johnsen, The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland, Clim. Dyn. 14 (1998) 73–81.

[12] D. Oppo, Millenial climate oscillations, Science 278 (1997) 1244–1246.

[13] H.A. Viles, A.S. Goudie, Interannual, decadal and multidecadal scale climatic variability and geomorphology, Earth Sci. Rev. 61 (2003) 105–131.

[14] J. Marshall, Y. Kushnir, D. Battisti, P. Chang, A. Czaja, R. Dickson, J. Hurrell, M. McCartney, R. Saravanan, M. Visbeck, North Atlantic climate variability: phenomena impacts and mechanisms, Int. J. Climatol. 21 (2001) 1863–1898.

[15] J.W. Hurrel, Y. Kushnir, G. Ottersen, M. Visbeck, An Overview of the North Atlantic Oscillation, in: J.W. Hurrel, Y. Kushnir, G. Ottersen, M. Visbeck (Eds.), The North Atlantic Oscillation: Climatic Significance and Environmental Impact, AGU Geophys. Monogr., vol. 134, American Geophysical Union, Washington DC, 2003, pp. 1–35.

[16] J.W. Hurrell, Decadal trends in the North Atlantic Oscillation: regional temperature and precipitation, Science 269 (1995) 676–679.

[17] J.W. Hurrell, Influence of variations in extratropical wintertime teleconnections on the Northern Hemisphere temperature, Geophys. Res. Lett. 23 (1996) 665–668.

[18] H. van-Loon, J.C. Rogers, The seesaw in winter temperature between Greenland and northern Europe. Part I: general description, Mon. Weather Rev. 106 (1978) 296–310.

[19] M. Visbeck, E.P. Chassignet, R.G. Curry, T.L. Delworth, R.R. Dickson, G. Krahmann, The Ocean's response to the North Atlantic Oscillation variability, in: J.W. Hurell, Y. Kushnir, G. Ottersen, M. Visbeck (Eds.), The North Atlantic Oscillation: Climatic Significance and Environmental Impact, AGU Geophys. Monogr., vol. 134, American Geophysical Union, Washington DC, 2003, pp. 113–145.

[20] J. Luterbacher, E. Xoplaki, D. Dietrich, P.D. Jones, T.D. Davies, D. Porties, J.F.G. les-Rouco, H.V. Storch, D. Gyalistras, C. Casty, H. Wanner, Extending North Atlantic Oscillation reconstruction back to 1500, Atmos. Sci. Lett. (2002), doi:10.1006/asle.2001.0044.

[21] E.R. Cook, R.D. D'Arrigo, M.E. Mann, A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation since AD 1400, J. Clim. 15 (2002) 1754–1765.

[22] C. Appenzeller, T.F. Stocker, M. Anklin, North Atlantic oscillation dynamics recorded in Greenland ice cores, Science 282 (1998) 446–449.

[23] E.R. Cook, R.D. D'Arrigo, K.R. Briffa, A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe, Holocene 8 (1998) 9–17.

[24] L. Doner, Late-Holocene paleoenvironments of northwest Iceland from lake sediment, Palaeogeogr. Palaeoclimatol. Palaeoecol. 193 (2003) 535–560.

[25] J.T. Andrews, C. Caseldine, N.J. Weiner, J. Hatton, Late Holocene (ca. 4 ka) marine and terrestrial environmental change in Reykjarfjordur, North Iceland: climate and/or settlement, J. Quat. Sci. 16 (2001) 133–143.

[26] J.T. Andrews, J. Hardardottir, G.B. Kristjansdottir, K. Grönvold, J.S. Stoner, A high-resolution Holocene sediment record from

Húnaflóaáll, N Iceland margin: century to millennial-scale variability since the Vedde tephra, Holocene 13 (2003) 625–638.
[27] A. Jennings, S. Hagen, J. Hardardottir, R. Stein, A.E.J. Ogilvie, I. Jonsdottir, Oceanographic change and terrestrial human impact in a post AD 1400 sediments record from the southwest Iceland Shelf, Clim. Change 48 (2001) 83–100.
[28] C. Andersen, N. Koç, A. Jennings, J.T. Andrews, Nonuniform response of the major surface currents in the Nordic Seas to insolation forcing: implications for the Holocene climate variability, Paleoceanography 19 (2004) A2003, doi:10.1029/2002PA00873.
[29] J. Eirıksson, K.L. Knudsen, H. Haflidason, P. Henriksen, Late-glacial and Holocene paleoceanography of the North Icelandic shelf, J. Quat. Sci. 15 (2000) 23–42.
[30] J. Eirıksson, K.L. Knudsen, H. Haflidason, J. Heinemeier, Chronology of late Holocene climatic events in the northern North Atlantic based on AMS ^{14}C dates and tephra markers from the volcano Hekla, Iceland, J. Quat. Sci. 15 (2000) 573–580.
[31] J.T. Andrews, G. Helgadottir, A. Geirsdottir, A.E. Jennings, Multicentury scale record of carbonate (hydrographic?) variability on the Northern Iceland margin over the last 5000 years, Quat. Res. 56 (2001) 199–206.
[32] J.T. Andrews, J. Hardardottir, J.S. Stoner, M.R. Mann, G.B. Kristjansdottir, N. Koc, Decadal to millennial scale variability in North Iceland shelf sediments over the last 12000 yr: a long-term North Atlantic oceanographic variability and solar forcing, Earth Planet. Sci. Lett. 210 (2003) 453–465.
[33] K.-L. Knudsen, J. Eirıksson, Application of tephrochronology to the timing and correlation of palaeoceanographic events recorded in Holocene and late Glacial shelf sediments off North Iceland, Mar. Geol. 191 (2002) 165–188.
[34] J. Giraudeau, A.E. Jennings, J.T. Andrews, Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Seas over the last 10,000 cal year: a view from the North Iceland shelf, Quat. Sci. Rev. 23 (2004) 2127–2139.
[35] K.-L. Knudsen, J. Eirıksson, E. Jansen, H. Jiang, F. Rytter, E.R. Gudmundsdóttir, Paleoceanographic changes off North Iceland through the last 1200 years: foraminifera, stable isotopes, diatoms and ice rafted debris, Quat. Sci. Rev. 23 (2004) 2231–2246.
[36] H. Jiang, J. Eirıksson, M. Shultz, K.-L. Knudsen, M.-S. Seidenkrantz, Evidence for solar forcing of sea-surface temperature on the North Icelandic shelf during the late Holocene, Geology 33 (2005) 73–76.
[37] B.A. Maher, R. Thompson, Quaternary Climates, Environment and Magnetism, Cambridge Univ. Press, Cambridge, 1998, 284 pp.
[38] K.L. Verosub, A.P. Roberts, Environmental magnetism: past present and future, J. Geophys. Res. 100 (1995) 2175–2192.
[39] C. Kissel, C. Laj, L. Labeyrie, T. Dokken, A. Voelker, D. Blamart, Rapid climatic variations during marine isotopic stage 3: magnetic analysis of sediments from Nordic Seas and North Atlantic, Earth Planet. Sci. Lett. 171 (1999) 489–502.
[40] M.J. Dekkers, Environmental magnetism: an introduction, Geol. Mijnb. 76 (1997) 163–182.
[41] J.C. Larrasoaña, A.P. Roberts, J.S. Stoner, C. Richter, R. Wehausen, A new proxy for bottom-water ventilation in the eastern Mediterranean based on diagenetically controlled magnetic properties of sapropel-bearing sediments, Palaeogeogr. Palaeoclimatol. Palaeoecol. 190 (2003) 221–242.
[42] G. Larsen, S. Thorarinsson, H-4 and other acid Hekla tephra layers, Jökull 27 (1977) 28–46.
[43] O. Sigmarsson, M. Concomines, S. Fourcade, A detailed Th, Sr, and O isotope study of Hekla: differentiation processes in an Icelandic volcano, Contrib. Mineral. Petrol. 112 (1992) 20–34.
[44] C. Lacasse, H. Sigurdsson, H. Johannesson, M. Paterne, S. Carey, Source of Ash Zone 1 in the North Atlantic, Bull. Volcanol. 57 (1995) 18–32.
[45] C. Lacasse, C.D. Garbe-Schönberg, Explosive silicic volcanism in Iceland and Jan Mayen area during the last 6 Ma: sources and timing of major eruptions, J. Volcanol. Geotherm. Res. 107 (2001) 113–147.
[46] G. Larsen, J. Eirıksson, K.L. Knudsen, J. Heinemeier, Correlation of late Holocene terrestrial and marine tephra markers, North Iceland: implication for reservoir age changes, Polar Res. 21 (2002) 283–290.
[47] J. Eirıksson, G. Larsen, K.-L. Knudsen, J. Heinemeier, L.A. Sımonarson, Marine reservoir age variability and water mass distribution in the Iceland Sea, Quat. Sci. Rev. 23 (2004) 2247–2268.
[48] R.R. Dickson, J. Meincke, S. Malmberg, A. Lee, The 'great salinity anomaly' in the northern North Atlantic 1968–1972, Prog. Oceanogr. 20 (1988) 103–151.
[49] M.C. Serreze, J.A. Maslanik, R.G. Barry, T.L. Demaria, Winter atmospheric circulation in the Arctic Basin and possible relationships to the Great Salinity Anomaly in the Northern North Atlantic, Geophys. Res. Lett. 19 (1992) 293–296.
[50] L.A. Mysak, S.B. Power, Sea-ice anomalies in the western Arctic and Greenland-Iceland Sea and their relation to an inter-decadal climate cycle, Climatol. Bull. 26 (1992) 147–176.
[51] I.M. Belkin, S. Levitus, J. Antonov, S.-A. Malmberg, 'Great salinity anomalies' in the North Atlantic, Prog. Oceanogr. 41 (1998) 1–68.
[52] B. Dickson, From the Labrador Sea to global change, Nature 386 (1997) 649–650.
[53] A. Sy, M. Rhein, J.R.N. Lazier, K.P. Koltermann, J. Meincke, A. Putzka, M. Bersch, Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean, Nature 386 (1997) 675–679.
[54] A.E.J. Ogilvie, T. Jonsson, Little Ice Age research: a perspective from Iceland, Clim. Change 48 (2001) 9–52.
[55] S.-A. Malmberg, S. Jonsson, Timing of deep convection in the Greenland and Iceland Seas, J. Mar. Sci. 54 (1997) 300–309.
[56] F. Rytter, K.-L. Knudsen, M.-S. Seidenkrantz, J. Eirıksson, Modern distribution of benthic foraminifera on the North Iceland shelf and slope, J. Foraminiferal Res. 32 (2002) 217–244.
[57] O.G. Flovenz, K. Gunnarsson, Seismic structure in Iceland and surrounding area, Tectonophysics 189 (1991) 1–17.
[58] L. Labeyrie, E. Jansen, E. Cortijo, and shipboard participants, Ginna cruise, MD114-IMAGES V, Scientific Report, IPEV Ed. (2003), 850 pp.
[59] M. Leeder, Sedimentology and sedimentary basins, From Turbulence to Tectonics, Blackwell Science Ltd, Oxford, 1999, 592 pp.
[60] G. Larsen, A.J. Dugmore, A.J. Newton, Geochemistry of historical-age silicic tephras in Iceland, Holocene 9 (1999) 463–471.
[61] H. Haflidason, J. Eirıksson, S. Van Kreveld, The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review, J. Quat. Sci. 15 (2000) 3–22.
[62] D.J. Dunlop, Ö. Özdemir, Rock Magnetism: Fundamentals and Frontiers, Cambridge University Press, Cambridge, 1997, 573 pp.

[63] L. Tauxe, J.L. LaBrecque, R. Dobson, M. Fuller, J. Dematteo, "U"-channels: a new technique for paleomagnetic analysis of hydraulic piston cores, Eos Trans. AGU 64 (1983) 219.
[64] R. Weeks, C. Laj, L. Endignoux, M. Fuller, A. Roberts, R. Manganne, E. Blanchard, W. Goree, Improvements in long-core measurement techniques: applications in palaeomagnetism and palaeoceanography, Geophys. J. Int. 114 (1993) 651–662.
[65] M. Parra, P. Delmont, J.C. Dumont, A. Ferragne, J.C. Pons, Mineralogy and origin of the Tertiary inter basaltic clays from the Faeroe Islands, Northern Atlantic, Clay Miner. 22 (1987) 63–82.
[66] R. Day, M. Fuller, V.A. Schmidt, Hysteresis properties of titanomagnetite: grain size and compositional dependance, Phys. Earth Planet. Inter. 13 (1977) 260–267.
[67] J. Eiríksson, H.B. Bartels-Jónsdóttir, A. Cage, E.R. Gudmundsdóttir, D. Klitgaard-Kristensen, F. Marret, T. Rodrigues, F. Abrantes, W.E.N. Austin, H. Jiang, K.-L. Knudsen, H.P. Sejrup, Variability of the North Atlantic Current during the last 2000 years based on shelf bottom water and sea surface temperatures along an open ocean shallow marine transect in western Europe, The Holocene (submitted for publication).
[69] R.A. Woodgate, E. Fahrbach, G. Rohardt, Structure and transports of the East Greenland Current at 75° N from moored current meters, J. Geophys. Res. 188 (1999) 165–188.
[70] H. Jiang, M.-S. Seidenkrantz, K.-L. Knudsen, J. Eirıksson, Late-Holocene summer sea-surface temperature based on a diatom record from the North Icelandic shelf, Holocene 12 (2002) 49–58.
[71] D.C. Barber, A. Dyke, C. Hillaire-Marcel, A.E. Jennings, J.T. Andrews, M.W. Kerwin, G. Bilodeau, R. McNeely, J. Southon, M.D. Morehead, J.-M. Gagnon, Forcing of the cold event of 8200 years ago by catastrophic drainage of the Laurentide lakes, Nature 400 (1999) 344–348.
[72] B. Risebrobakken, E. Jansen, C. Andersson, E. Mjelde, K. Hevroy, A high-resolution study of Holocene paleoclimatic and paleoceanographic change in the Nordic Seas, Paleoceanography 107 (2003) 509–519.
[73] J.U.L. Baldini, F. McDermott, I.J. Fairchild, Structure of the 8200-year event revealed by a speleothem trace record, Science 296 (2002) 2203–2206.
[74] K.-L. Knudsen, H. Jiang, E. Jansen, J. Eirıksson, J. Heinemeier, M.-S. Seidenkrantz, Environmental changes off North Iceland during the deglaciation and the Holocene: foraminifera, diatoms and stable isotopes, Mar. Micropaleontol. 50 (2004) 273–305.
[75] D.W. Oppo, J.F. McManus, J.L. Cullen, Deepwater variability in the Holocene epoch, Nature 422 (2003) 277–278.
[76] A. Jennings, K.-L. Knudsen, M. Hald, C.V. Hansen, J.T. Andrews, A mid-Holocene shift in arctic sea–ice variability on the East Greenland shelf, Holocene 12 (2002) 49–58.
[77] T. Torrence, G.P. Compo, A practical guide to wavelet analysis, Bull. Am. Meteorol. Soc. 79 (1998) 61–78.
[78] M. Sarnthein, S. Van Kreveld, H. Erlenkeuser, P.M. Grootes, M. Kucera, U. Pflaumann, M. Schulz, Centennial-to-millennial-scale periodicities of Holocene climate and sediment injections off the western Barents shelf, 75° N, Boreas 32 (2003) 447–461.
[79] E.J. Rohling, H. Pälike, Centennial-sclae climate deterioration with a superimposed cold snap around 8200 years ago, Nature 434 (2005) 975–979.