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Keywords

Magnetic Susceptibility, Iceland, Natural Remanent Magnetization, Maximum Angular Deviation, Median Destructive Field

Disciplines

Environmental Sciences | Geology

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Holocene Sediment Magnetic Properties along a Transect from Ísafjardardjúp to Djúpáll, Northwest Iceland

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Introduction

The purpose of this paper is to examine changes in the magnetic properties of sediments from Ísafjardardjúp, a large fjord that dissects Vestfirðir, Northwest Iceland, and Djúpáll, the adjacent shelf trough (Fig. 1). Changes in magnetic properties represent changes in the concentration, grain size, and mineralogy of the magnetic minerals. Such changes reflect shifts in the processes that control sediment transport and deposition in glacial marine environments. We examine 10 sediment cores that record the last 12,000 cal yr. BP of sedimentation. During the Last Glacial Maximum (LGM), local ice caps and glaciers covered much of Vestfirðir (Andrews et al., 2002b; Geirsdóttir et al., 2002; Principato et al., 2006). Vestfirðir experienced deglaciation between 15,000 and 10,000 cal yr. BP, followed by regrowth of glaciers at ≤ 5000 –6000 cal yr. BP (Eythorsson, 1935; Caseldine, 1987; Principato, 2003). Terrestrial records commonly preserve only intermittent evidence of glacial expansion in the form of moraines. By contrast, near-shore marine depocenters retain a full record of sediment history that allow the reconstruction of continuous changes in sediment characteristics throughout the Holocene. Although this study is focused on identifying climate/glacial events during the Holocene, other processes affect the marine sediment magnetic records, including deposition of tephra, debris flows, and turbidites (Hein and Syvitski, 1992).

Background

Vestfirðir, the Northwest Peninsula of Iceland, is located at approximately 66°N (Fig. 1). It consists of a broad upland incised

by relatively shallow fjords, the largest of which is Ísafjardardjúp, which together with its tributary fjords has a surface area of 1150 km^2 and a drainage basin area of $\sim 2300 \text{ km}^2$. Drangajökull, the modern ice cap, is present on the eastern upland, and its glacial meltwaters are directed into Ísafjardardjúp and Jökulfirðir (Fig. 1). The bedrock consists of 13 Ma basalts with some thin sedimentary horizons (Einarsson, 1973; Kristjánsson et al., 1979). We expect *a priori* that sediments derived from erosion of the basalts will have high magnetic susceptibilities. Quantitative X-ray diffraction analysis of the sediments in Djúpáll indicated the presence of magnetite (0 to 1 %), maghemite (2 to 6%), and hematite ($<0.5\%$) (Chesley et al., 2004; Andrews and Eberl, 2007).

The glacial history of the area is based in part on data from the cores considered in this paper (Andrews et al., 2000; Geirsdóttir et al., 2002) and on terrestrial field work (John, 1975; Larusson, 1983; Principato et al., 2006). The extent of ice in the area during the LGM is uncertain, but there is evidence for ice extending onto the continental shelf (Geirsdóttir et al., 2002). Iceberg rafting of sediments from Iceland glaciers ceased along the north coast by 10,000 cal yr. BP (Castañeda, 2001; Castañeda et al., 2004). Questions remain regarding the presence or absence of the ice cap on the uplands during the Holocene thermal maximum (Kaufman et al., 2004) and the timing of glacier expansion during the Neoglaciation (Wastl et al., 2001).

Relative sea level variations associated with glacial fluctuations have significant impacts on sediment accumulation in fjords (Syvitski and Andrews, 1994). The marine limit on the Ísafjardardjúp coast varies from 14 to 50 m (Larusson, 1983; Principato, 2003). Sea level dropped below present after 10,000 cal yr. BP

FIGURE 1. Location of the field area and core sites around Vestfirðir, the Northwest Peninsula of Iceland. *Isa* marks the location of Ísafjardardjúp, and *J* shows the location of Jökulfirðir. *V* is the location of the Vatnsdalvatn site (Thompson and Turner, 1985). Core 1232 is from the JM96 cruise; cores 311, 315, 335, 336, 339, and 342 are from cruise B997; core KN-72 (KN-158-4-72GGC) is from the Knorr cruise; and 2266 is from the IMAGES MD99 cruise. Cores MD99-2265 and JM96-342 are from the same site. MD99-2269 occurs just east of the right-hand map boundary.

(Helgadóttir and Thors, 1991; Rundgren et al., 1997), and it may have risen slightly during the late Neoglacial (John, 1975; Principato, 2003). These sea level fluctuations impact sedimentation rates within the fjords (Quillmann, 2006). In Iceland, human occupancy and subsequent land erosion has also resulted in a detectable shift in magnetic properties in offshore sites (Jennings et al., 2001).

The relatively hospitable climate for this latitude (mean annual temperature of $\sim 3^{\circ}\text{C}$) is due to the offshore presence of warm Atlantic water entrained in the Irminger Current (Stefansson, 1962; Stefansson, 1969; Thors, 1974; Hopkins, 1991). The northern coast of Iceland also lies close to the colder and fresher Arctic/Polar waters of the East Iceland Current. In years when the East Iceland Current moves further south, extensive drift ice covers the shelf in this region (Koch, 1945; Ogilvie, 1996), and the drift ice potentially transports and deposits “exotic” sediment mineralogies to the outer to mid shelf (Andrews and Eberl, 2007). No hydrographic data are available from the glacially fed rivers that drain Drangajökull. The fjords discussed in this study lack a pronounced sill, allowing exchange with the Atlantic waters on the shelf. The tidal range is only ~ 3 m, resulting in limited tidal mixing.

Methods

Cores were collected on three cruises (Table 1). In 1996 (*Jan Mayen JM96*–) a 10-cm-diameter gravity corer was employed. In 1997 (*Bjarni Saemundsson B997*–) 7-cm-diameter piston cores were

collected, and in 1999 (*Marion Dufresne MD99*–) 10-cm-diameter giant piston cores were retrieved. The coring process can impact the quality of sediment section recovered, particularly in terms of paleomagnetic parameters due to sediment compaction or stretching (Hillaire-Marcel et al., 1999; Skinner and McCave, 2003). Sediment recovery from the inner part of Djúpáll was limited by a lack of sediment cover and the presence of erosional unconformities (Smith et al., 1999; Thors and Helgadóttir, 1999). Thus, core sites in Djúpáll (Fig. 1) are clustered toward the mid and outer shelf and were selected on the basis of 3.5 kHz acoustic data.

In a two-dimensional model of a fjord-to-shelf trough system, we expect a diminution of the magnetic concentration signal from the fjord heads, where glacial and fluvial sediments accumulate, to the mid and outer trough where the signal is diluted by the input of diamagnetic materials such as organic carbon and carbonate. In addition to this dilution, at distal sites, slower rates of sediment accumulation might favor increased bioturbation, which results in the attenuation of sediment magnetic or paleomagnetic events (Anderson, 2001) (Table 2). However, in our study area, the presence of shallow banks adjacent to Djúpáll, combined with storm activity affecting the region (Thors, 1974; Dawson et al., 2002, 2003), results in the disruption of a simple fjord-to-trough signal. This signal is further complicated by the temporally and spatially variable importation of drift ice that transports “exotic” minerals to the region (Andresen and Bjorck, 2005; Moros et al., 2006).

TABLE 1

Location, water depth, and core lengths of the sediment cores used in this study. Sediment accumulation rates (SAR) are shown, as well as the magnetic methods used on each core (Cryogenic vs. Bartington measurements).

Core#	Lat. ($^{\circ}\text{N}$)	Long. ($^{\circ}\text{W}$)	Water depth (m)	Core length (cm)	Measurements	SAR average (cm k.y.^{-1})
B997-339PC2	22.800	66.017	104	527	Cryogenic	59
MD99-2266	23.265	66.228	106	~ 3800	Cryogenic	476
B997-311PC	22.857	66.273	100	265	Bartington	29
B997-342	22.859	66.275	94	440	Cryogenic	58
B997-341	22.842	66.277	96	173	Bartington	81
JM96-1232	24.000	66.618	215	280	Cryogenic	45
B997-335	24.178	66.687	239	428	Cryogenic	53
B997-336	24.166	66.688	242	242	Cryogenic	51
B997-315	24.33	66.732	220	268	Bartington	42
B997-314	24.18	66.685	243	269	Bartington	N/A

TABLE 2

Inferred changes in magnetic concentrations (magnetic susceptibility [MS]), grain-size (anhysteretic remanence), and mineralogy (ARM ratios) associated with Vestfirðir marine sediment (volume units).

Magnetic concentration MS or mass MS	Magnetic grain-size k_{ARM}	Magnetic mineralogy ARM or IRM ratios
1. Decrease upcore because of decrease in sediment density.	1. Will increase due to an increase in glacial and glacio-fluvial transport, increase in storminess.	1. Climatic deterioration results in soil erosion and an increase in hematite (e.g. Jennings et al., 2001)
2. An increase will reflect increased glacial activity and/or run-off.	2. Changes in relative sea level.	
3. Increase might also be due to a decrease in diamagnetic minerals such as calcium carbonate (and vice versa).		

The cores range in length from ~4 to 40 m. As the basal dates are approximately the same, this indicates that sediment accumulation rates varied by an order of magnitude (Table 1). Whole core magnetic susceptibility (WCMS) was measured on all cores. We used Exploratory Data Analysis (Velleman and Hoaglin, 1981) to identify outliers in WCMS. These were then eliminated because they reflected the ends of the core sections. The cores were subsequently split and visually described. The archive half of the core was X-radiographed for detection of sediment structures. Samples were taken for sedimentological analyses at 5- or 10-cm intervals. Mass magnetic susceptibility (MMS) analyses on 10 cm³

cubes, using a Bartington MS2 instrument (Walden et al., 1999), were carried out using dried and packed sediment subsamples of the <2-mm size fraction. Additional sediment properties were determined in the INSTAAR Sedimentology Lab, including carbonate and organic carbon content using a Coulometer and grain size using a Malvern long-bed laser system (Andrews et al., 2002c).

Samples for magnetic measurements were extracted in 2 × 2 × 100-cm- or 150-cm-long u-channels from the archive sections; analyses of the u-channels were performed at the Paleomagnetism Laboratory at the University of California, Davis. Remanent

TABLE 3
Radiocarbon dates from the cores with u-channel magnetic data.

Core ID	Depth (cm)	Date (cal yr. BP)	± error	Lower limit	Median cal age	Upper limit
B997-339	1	1450	65	1054	991	927
	41	4530	55	4807	4731	4654
	81	6000	55	6466	6403	6339
	132	8415	65	8974	8909	8844
	358	9815	70	10796	10560	10323
	527	10450	85	11676	11425	11174
B997-342	11	1857	33	1344	1386.5	1429
	185	5408	40	5730	5785	5840
	440	9270	80	9807	10019	10230
MD99-2266	1.5	780	40	471	429	387
	73	1151	53	734	692.5	651
	163	1800	45	1376	1334	1292
	258	2503	36	2240	2224	2208
	689	5130	40	5550	5506	5462
	1063	6098	50	6582	6518.5	6455
	1267	6570	45	7146	7086	7026
	1868	7826	49	8337	8279	8221
	2762	8840	65	9549	9316	9083
	3129	9320	190	10275	10043	9811
	3762	9800	70	10787	10553	10318
	3795	9804	70	10789	10554	10319
JM96-1232	1	2805	60	2666	2565	2464
	101	5590	65	6052	5975.5	5899
	199	8360	80	8950	8860	8770
	279	9060	70	9823	9650	9477
B997-335	1	1965	60	1585	1513	1441
	1	2875	65	2735	2615.5	2496
	143	9240	200	10255	9944.5	9634
	379	10705	80	12300	11985	11670
	454	10860	160	12629	12190	11751
B997-336	1	1800	200	1569	1356.5	1144
	169	9490	70	10308	10094	9879
	300				10300	
	428	10350	80	11620	11380	11139

FIGURE 2. Box plots of whole core magnetic susceptibility from cores collected during the B997 cruise. Each box includes 50% of the observations; the line within each box represents the median value. The small circles represent statistical outliers, whereas the lines outside the box represent the normal limits of the distribution. (A) Cores within Ísafjardardjúp (see Fig. 1); (B) cores from Djúpáll.

magnetizations were obtained using a 2G Enterprises Model 755R long-core superconducting rock magnetometer (SRM) located in a magnetically shielded room (Verosub, 1999). Although measurements were conducted at 1-cm intervals, the data are somewhat smoothed (~ 4.5 cm) due to the response function of the magnetometer's pickup coils (Weeks et al., 1993). The magnetometer produces data in raw x, y, z magnetic moments, which are subsequently transformed to inclination and declination in degrees and intensity as $A\ m^{-1}$. The natural remanent magnetization (NRM) was measured and remeasured after six to nine alternating field (AF) demagnetization steps. The results of these demagnetization steps are defined in the following sections of the paper as $J(0)$, $J(20)$ where 20, for example, represents the NRM intensity after 20 mT peak AF demagnetization. Anhysteretic remanent magnetization (ARM) was imparted to the u-channels using a 100 mT AF field and 0.5 mT DC field. The ARM was also measured and remeasured after stepwise AF demagnetization. Isothermal remanent magnetization (IRM) was produced using a 1.0-T pulsed magnetic field. The IRM was measured and remeasured after AF demagnetization. Frequently the intensity of

the induced IRM was beyond the upper detection limit of the SRM system, hence the IRM data are not used. Volume susceptibility ($k \times 10^{-5}$ SI units) was measured on u-channels using a Bartington loop system. The patterns of variability between the WCMS and u-channel MS values are highly correlated ($r \geq 0.9$; Paillard et al., 1996), though the units show significant differences reflecting uneven calibration of the two systems. Therefore, discrete samples of a known volume were obtained, measured for MS using a $10\ cm^3$ Bartington sample system and weighted so that mass specific MS could be calculated. Coercivity (ease or difficulty to change magnetization) varies with magnetic mineralogy and magnetic grain size. Ratios constructed from AF demagnetization of the ARM, such as $ARM(J20)/ARM(J0)$, where (J) refers to the intensity of the magnetization after AF demagnetization, can be used as indicators of changes in magnetic mineralogy or grain size (Heider et al., 2001). High values indicate a higher coercivity, reflecting an ARM that is more resistant to AF demagnetization. Anhysteretic susceptibility (k_{ARM}) uses the intensity of the ARM normalized by the intensity of the biasing DC field. See Table 2 as to how some of the magnetic variables are interpreted.

The declination, inclination, and intensity data were processed for each demagnetization step in an Excel program "Macro-Uch-1.xls" (Mazaud, 2005). This program calculated the maximum angular deviation (MAD) based on a three-dimensional principal component analysis (Kirschvink, 1980), median destructive field (MDF), and characteristic remnant magnetization directions for each 1-cm interval in order to derive a component magnetization that under optimal circumstances may be interpreted as paleomagnetic secular variation (PSV).

TEMPORAL RESOLUTION

The u-channels were measured at 1-cm intervals, but the temporal resolution that this interval represents is a function of the sediment accumulation rate combined with the response functions of the magnetometer or Bartington MS core loop. The width at half-height of the response function of the u-channel magnetometer is ~ 4.5 cm. The whole core MS response function is around ± 5 cm and is especially evident at the ends of the core sections—these core-end data points are omitted. AMS ^{14}C dates were calibrated to calendar years using CALIB4.3 (Stuiver et al., 1998) with a ΔR of 0 (~ 400 yr ocean reservoir correction). All dates are reported in INSTAAR Date Lists (Smith and Licht, 2000; Dunhill et al., 2004) (Table 3). Core MD99-2266 is well dated (18 dates); cores JM96-1232 and B997-336, -339, and -341 have moderate dating control, whereas B997-311, -335, and -342 have very limited dating control. The age control for B997-314PC was obtained by comparing the WCMS data to B997-314GGC from the same location and using the three radiocarbon dates from the latter site (Smith and Licht, 2000). Dates from the core tops rarely give modern radiocarbon ages (Table 3) and are as old as 1000–2000 cal yr. BP, which reflects the loss of sediment during the retrieval of the core or nondeposition. A regional early Holocene isochron is provided by the Saksunarvatn tephra, which has a distinct magnetic signature (Andrews et al., 2002a) and an age of approximately 10,200 cal yr. BP (Gronvold et al., 1995), or about 9000 ^{14}C yr. BP (Birks et al., 1996; Hafliðason et al., 2000). KN-158-4-72GGC was retrieved in 1998 from the same site as B997-314 (Andresen, 2003; Andresen et al., 2005) and has 42 ^{14}C AMS dates in the last ca. 12,000 cal yr. BP. Sediment accumulation rates (SAR) were determined from statistical best fits of second- or third-order polynomial equations. Though polynomials may not be the best way to construct an age model (Telford et al., 2003; but

FIGURE 3. Plots showing the WCMS variations in B997 cores (Fig. 1) plotted along the axis of the fjord/trough system. Radio-carbon dates are shown as ^{14}C k.y. BP after a 400 yr. ocean-reservoir correction.

see Andrews et al., 1999) they do not force sedimentation rate changes to occur at dated intervals (Stoner et al., 2007). The high rate of sediment accumulation in MD99-2266 allows this core to capture more of the multi-decadal variability than is preserved in any other core in this study.

Results

WHOLE CORE MAGNETIC SUSCEPTIBILITY

Box plots show the magnitude and variability of whole core magnetic susceptibility (WCMS) for the B997 cores only (Fig. 2), because differences in core diameters and the diameter of the

Bartington scanning loops make quantitative inter-cruise comparisons difficult. WCMS is relatively high with values ranging between 100 and 2500×10^{-5} SI. Median values are somewhat higher in Djúpáll than Ísafjardardjúp suggesting that there is not a simple source-to-sink association. WCMS values in Djúpáll are high (Andrews et al., 2002c) despite the high carbonate values (>40%), which typically dilute WCMS (Table 2). WCMS is considered to reflect changes in magnetic concentration, but is also biased by extremely fine and/or large coarse silt to sand size magnetite grains (Maher, 1988).

In Figures 3 and 4 WCMS data are plotted versus depth and age, respectively. There is an overall decline in WCMS associated with the natural decrease in sediment density toward the surface.

FIGURE 4. (A) Plot of whole core magnetic susceptibility from sites B997-342, -339, and MD99-2266 within Ísafjardardjúp. Note the different scale for MD99-2266 (right-hand vertical axis). (B) Plot of whole core magnetic susceptibility from sites B997-314, -335, JM96-1232, and KN-158-4-72GGC (at B997-314) within Djúpáll (Fig. 1). (C) Residuals from a fourth-order polynomial fit to the whole core magnetic susceptibility data from B997-342 from Jökulfirðir (J, Fig. 1) and from JM96-1232. Letters a, b, c, and d indicate probable correlative events, and the temporal offsets give a measure of dating uncertainties.

However, there is a major increase in WCMS in the lower half of the cores probably associated with the final deglaciation of Vestfirðir ca. 10,000 cal yr. BP (Castañeda et al., 2004; Principato et al., 2006). In B997-314, -335, and -336 (Fig. 1) there is an increase in WCMS within the uppermost 20–50 cm suggesting an increase in transport and deposition of magnetic minerals or reduced dilution through a reduction in nonmagnetic biogenic components (i.e., carbonate). The WCMS data for B997-339, -342, and MD99-2266 (Figs. 1 and 4A) display a sharp peak in WCMS ca. 8400 cal yr. BP. In B997-339 this peak is associated with a turbidite. A single turbidity current might have ascended from the floor of Ísafjardardjúp into Jökulfirðir (Fig. 1), or alternatively, an earthquake might have triggered a regional series of mass movement events. These mass movement events may also correlate with the Storegga tsunami (Bondevik et al., 2003, 2005). Major disruptions in sediment history at this time are also observed in sediments from the North Iceland shelf (Kristjansdóttir, 1999).

The sharp drop in WCMS at ca. 10,200 cal yr. BP in MD99-2266 reflects the presence of Saksunarvatn tephra (see Andrews et al., 2002a), which also coincides with the final deglaciation of Vestfirðir (Geirsdóttir et al., 2002; Principato et al., 2006). Judging by the large amount of basaltic tephra in the basal sediments of B997-342, this core recovered sediments deposited shortly after the eruption. B997-342 is located only a few kilometers from one of the main outlet glaciers of Drangajökull, and the core site is well positioned to record glacially driven fluctuations in sediment characteristics (Fig. 1). The WCMS record from B997-342 is more variable than that from B997-339 further up-fjord, probably in response to changes in glacio-fluvial sediment inputs (Fig. 4A). The impact of the late Little Ice Age advances (ca. A.D. 1850) around Ísafjardardjúp (Eythorsson, 1935) is not documented in our archives because none of the cores recovered sediments that record the last 200–600 years.

The three fjord cores (B997-339, -342, and MD99-2266) show a progressive temporal decrease in WCMS to a broad low that is

FIGURE 5. Whole Core Mass Susceptibility (WCMS) vs. Mass Magnetic Susceptibility ($MMS \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) in (A) core B997-342 and (B) core JM96-1232.

reached sometime between 4000 and 6000 cal yr. BP (Fig. 4A). Core B997-342 has a series of small peaks that might represent glacially induced changes in the sediment supply from Drangajökull. The peak around 6500 cal yr. BP corresponds to a cold interval on the north Iceland shelf (Castañeda et al., 2004; Smith et al., 2005) and may suggest a coeval glacial response; they are not associated with debris flows in B997-342 whereas such are present in -339 (Quillmann, 2006).

The WCMS data from Djúpáll are plotted for four cores (Figs. 1 and 4B). All four cores show the characteristic steep decline in WCMS associated with the deposition of the Saksunarvatn tephra at 10,200 cal yr. BP (Andrews et al., 2002a). The duration of the low WCMS following the onset of tephra deposition is poorly dated in B997-335, and the length of time that the tephra affected the WCMS signal through reworking is best resolved in KN-158-4-72GGC where it approaches 500 years in duration (Andresen et al., 2005). Following the Saksunarvatn tephra, the WCMS data show some variability, which is probably associated with the processes involved in the construction of the sediment drift in Djúpáll (Geirsdóttir et al., 2002), including intervals of erosion on the trough margin. The

time-scale <10,000 cal yr. BP for B997-335 is only based on two dates (Table 3), which may explain its apparent difference from the other three sites. Plots of the residuals from a fourth-order polynomial fit of the WCMS values versus age from B997-342 (Jokulfirdir) and from JM96-1232 (Djúpáll) indicate potential correlative events between the fjords and the shelf (a, b in Fig. 4C). The temporal offset between the events in the two cores gives a measure of possible dating uncertainties; however, the similarities between the fjord and trough signals of WCMS suggest some sediment magnetic events resulted from a regional common overall process, although the causes are not yet clear.

MASS MAGNETIC SUSCEPTIBILITY

Measurements of mass magnetic susceptibility (MMS) avoid the smoothing and density change problems associated with WCMS. Discrete samples of a known volume that are dried, weighed, and measured allow dry sediment density to be factored into the magnetic measurement (Walden et al., 1999). On a core-by-core basis there is a strong correlation between WCMS and MMS (see Figs. 5A, 5B). In JM96-1232, the largest mismatch is in

FIGURE 6. (A) k_{ARM} for cores B997-339, -342, and MD99-2266 in Ísafjardardjúp (note right-hand y-axis scale for MD99-2266), compared with (B) k_{ARM} for cores in Djúpáll: JM96-1232, B997-335, and -336. The timing of the Saksunavratn tephra is also shown. Dashed lines represent possible coeval events.

the upper section of the core where the decrease in density does not capture the increase in magnetic susceptibility noted in the MMS data (Fig. 5B). The correlation coefficient of $r = 0.89$ indicates that 79% of the variance is held in common. The MMS versus WCMS data for B997-342 has a correlation coefficient of $r = 0.84$, and the largest differences occur toward the top of the core where the decrease in sediment density lowers the WCMS signal.

MMS and WCMS signals are lowered by diamagnetic minerals (Dearing, 1999; Stoner and Andrews, 1999) (Table 2). In JM96-1232, there is a strong inverse correlation between the carbonate content and MMS ($r = -0.88$). In B997-342, the correlation between these two variables is weaker ($r = -0.53$), but it remains statistically significant. In general, intervals of low MMS reflect periods of increased carbonate accumulation. In Djúpáll, examination of the coarse sand fraction indicates that increased carbonate is associated with the accumulation of the remains of mollusks, foraminifera, echinoderms, corals, and other biota. These periods of carbonate-rich sand accumulation may reflect intervals of enhanced bottom current transport (Andresen et al., 2005).

ANHYSETERETIC SUSCEPTIBILITY (k_{ARM})

A 1-cm interval measure of changes in the concentration of magnetic minerals is provided by anhysteretic susceptibility (k_{ARM}) (Walden et al., 1999). Although essentially a concentration parameter, k_{ARM} has significant grain-size dependence (increasing with decreasing grain size), and is, therefore, commonly used with magnetic susceptibility (increases with increasing grain size) to

develop grain-size dependent ratios. The correlations between u-channel MS and k_{ARM} in cores B997-339 and -342 are high, with values of $r = 0.88$ and 0.91 , respectively. Such correlations suggest that the dominant minerals are magnetite and maghemite and, further, that the magnetic grain size of the sediments is relatively homogeneous, because the two parameters are grain-size dependent in the opposite sense (Maher, 1988).

In the cores from the fjords, the Holocene variations in k_{ARM} mimic most features of the WCMS records (Figs. 4A and 6A). The k_{ARM} values for MD99-2266, the most distal fjord site, are much lower than the k_{ARM} values from cores within the fjord, partly a reflection of the coarse (magnetic) grain size in -2266. In the fjord cores, high k_{ARM} values prevail during the late deglacial interval, and an abrupt decrease in k_{ARM} is coeval with the occurrence of the Saksunavratn tephra and final deglaciation of the area (Geirsdóttir et al., 2002; Principato et al., 2006). There is little variability in the k_{ARM} record in B997-339 after the turbidite event at ca. 8000 cal yr. BP. By contrast, there are pronounced k_{ARM} oscillations in B997-342, located a few kilometers from one of the outlet glaciers of Drangajökull (Fig. 1), including a sharp peak dated at ca. 9800 cal yr. BP (but note the poor dating control, Table 3) implying a more variable input of sediments from the glaciated basins. The slight offsets in events in Figures 6A versus 4A probably represent small differences in the recording of depths between the measurements of WCMS versus measurements on the u-channels.

In Djúpáll, the u-channel data from B997-336 show two high magnetic concentration events at 8500 and 2900 cal yr. BP (Fig. 6B). Comparisons of the k_{ARM} records from the fjord sites

FIGURE 7. (A) ARM (J20)/ARM (J0) ratios in cores B997-342, -339, and MD99-2266 from Ísafjardardjúp. (B) Data from Djúpáll; and (C) the correlation of $k_{ARM}/\text{susceptibility}$ and ARM (J20)/ARM (J0) in core B997-342 with a correlation value of $r = 0.66$.

(Fig. 6A) with -336 from Djúpáll (Fig. 1) show a series of coeval variations marked by arrows (Fig. 6B).

CHANGES IN MAGNETIC GRAIN SIZE AND MINERALOGY

A variety of ratios are used to extract information on magnetic grain size and magnetic mineralogy (Thompson and Oldfield, 1986; Hall and King, 1989; King and Channell, 1991; Walden et al., 1999; Heider et al., 2001; Evans and Heller, 2003). For example, the ratio ARM (J20)/ARM (J0) is correlated with grain size from core MD99-2269 located on the north Iceland shelf (Andrews et al., 2003). The ratio of $k_{ARM}/\text{magnetic susceptibility}$ is also used as an indicator of magnetic grain size (King and Channell, 1991).

The ARM (J20)/ARM (J0) data from the cores within Ísafjardardjúp (Fig. 7A) show a change coeval with the deposition of the Saksunartvatn tephra. In B997-339 and MD99-2266 the ratio is very high in the early Holocene. The ratio decreases during the middle and late Holocene with the major transition from high to low values occurring between 8000 and 9000 cal yr. BP. This decrease indicates a trend toward more easily demagnetized sediments, associated with an increase in magnetic grain size and an increase in the sand fraction.

FIGURE 8. ARM (J20/0) vs. phi mean for cores B997-335, -339, -342, and MD99-2266. The inclined lines are the best-fit regression lines for each core showing that, as the sediments get coarser, on average the ratio decreases. The boxes include most of the data for the four cores, but some extend beyond the box limits (e.g. data for B997-339).

The down-core variations in the ratios ARM (J20)/ARM (J0) and ARM (J40)/ARM (J20) reflect changing coercivity fractions (i.e., components of the magnetic grain-size assemblage). Plots of the two ratios (not shown—these differences in ARM ratios will be the subject of future investigation) indicate distinct difference between the sediments on the shelf versus those within the fjord system. In B997-335 and -336 plots of ARM (J20)/ARM (J0) parallel each other, indicating similar grain-size changes, whereas in the fjord sites (MD99-2266, B997-339, and -342) the ratios are frequently trending in opposite directions after ca. 5000 cal yr. BP, indicating variations in the input of coarsest and finer magnetic grain-size assemblages.

Grain size was measured on B997-335, -339, -342, and MD99-2266 at 5- or 10-cm intervals using a laser-sizing system (Andrews et al., 2002c). There are modest inverse correlations (r values between -0.7 and -0.22) between phi mean grain size and ARM (J20)/ARM (J0) (Fig. 8). These correlations indicate, as would be expected, that the larger average grain sizes are less resistant to demagnetization. The ARM ratios for the three fjord sites show a smaller drop in intensity after 20 mT AF demagnetization than at the distal basin where MD99-2266 was retrieved, indicating a coarser magnetic grain size. The sediments on average are coarser in Djúpáll (B997-339 to -335; Fig. 1). Overall the Djúpáll sediments are either silty sands or sandy silts and coarser than the sediments within Ísafjardardjúp (Fig. 8) because Djúpáll is affected by sediment reworking and transport associated with strong wind and tidal currents (Olafsdóttir, 2004; Andresen et al., 2005).

In Djúpáll (Fig. 1), the early Holocene ARM (J20)/ARM (J0) ratios are high, possibly associated with inputs of fine-grained “glacial flour,” but then decrease gradually and rise in the last 3000 to 4000 cal yr. BP (Fig. 7B). The sharp rise in ARM(J20)/ARM(J0) in B997-335 after the deposition of the Saksunartvatn tephra shows that the tephra is quite resistant to demagnetization. Backfield IRM measurements on discrete samples had previously indicated that the Saksunartvatn tephra is resistant to demagnetization (Andrews et al., 2002a). However, we cannot explain why the signal is less distinct in nearby core -336, which also contains the Saksunartvatn tephra.

FIGURE 9. Characteristic remanent magnetization declination, inclination, and maximum angular deviation data (MAD) for core MD99-2266 (Mahout, 2005).

PALEOMAGNETIC INCLINATION

The geocentric axial dipole inclination for northwest Iceland is approximately 77.5°N (Tarling, 1983). Paleomagnetic declination and inclination data for a lake on the southern shore of Vestfirðir (Fig. 1, V) were presented by Thompson and Turner (1985). Stoner et al. (2007) present high-resolution paleomagnetic data from the exceptionally well-dated core MD99-2269 (Kristjansdóttir, 1999, 2005) (Fig. 1).

AF demagnetization reveals a stable, single component magnetization directed toward the origin. Ninety percent of the median destructive field (MDF) from all sites had values <20 mT compared with 25 to 30 mT in MD99-2269 (Stoner et al., 2007). Our data, combined with the strong remanent intensities and high susceptibilities, are consistent with relatively coarse-grained magnetite or titanomagnetite being the remanence carrier, as expected from glacial and fluvial erosion of the Tertiary basalts. Characteristic remanent magnetization (ChRM) directions were calculated by principal component analysis using measurements made after 6 to 9 AF demagnetization steps at peak fields between 10 and 60 mT (Kirschvink, 1980). Ninety percent of ChRM inclination angles were >60° and 50% were >75°. The maximum angular deviations (MAD) of the ChRM had a mean of 6° ± 4.5° with 82% of the values <10°. These are relatively high for recent sediments and probably reflect the moderate sand content. Many of the high MAD values were obtained from measurements made on the youngest sediments, which were commonly soupy and probably disturbed during coring and shipping. Eighty percent of the MAD values from MD99-2266 are <10° and 50% are <5° (Figs. 9 and 10). In Figure 10, we plot the ChRM inclinations and show the percentages of MAD values <5° and <10°, the latter being the standard cutoff. The quality of the MAD values suggests that the data from the other sites are often superior to that in -2266 with 69% to 92% of MAD values <5° (Fig. 10). We compare our high-resolution paleomagnetic data from core -2266 (Fig. 9) to paleomagnetic inclination estimates from MD99-2269 from north Iceland (66.641°N, 20.863°W) (Stoner et al. 2007), from Olafsdóttir et al. (2005), and from Thompson and Turner (1985).

The data from MD99-2266 show inclination values of nearly 90° close to 8000 cal yr. BP, which could reflect a possible proximal pole position. This is followed by a pronounced interval of lower inclinations until ca. 6000 cal yr. BP. The values

<2000 cal yr. BP are not shown because of sediment disturbance. B997-342 also has PCA inclinations near 90° close to 8000 cal yr. BP followed by an interval of lower inclination (Fig. 10). These inclination features, very steep inclinations at ca. 8000 cal yr. BP followed by several thousand years of shallow inclinations, are consistent with inclination data from Icelandic marine (MD99-2265, near B997-342; Fig. 1) and lake (not shown) cores (Olafsdóttir et al., 2005). The data from Vatndalsvatn on Vestfirðir (Fig. 1, V) (Thompson and Turner, 1985) also show a low inclination feature around 4.5 m depth in core VDVS2 associated with a calibrated date of 7400 ± 100 cal yr. BP. However, the chronology of the record is such that it is difficult to make detailed comparisons.

An overlay of MD99-2269 inclination data (Stoner et al., 2007) and -2266 inclination data have a correlation of $r = 0.4$ (Fig. 11A). Over the last 11,000 cal yr. BP the rate of sediment accumulation at these sites is such that 1 cm of sediment represents, on average, 5 and 3 years, respectively. Smoothed inclination data from -2269 are presented in Stoner et al. (2007), and a median smoother of length 20 was used for the -2266 data (Fig. 11B). For -2266 the correlation between the raw data and the smoothed series was $r = 0.85$, which is a measure of the loss of information attributed to smoothing. With adjustments so that the end points of each record had the same dates (600 and 10,800 cal yr. BP), the AnalySeries program indicated that the agreement between the records increased to $r = 0.4$ with 12 tie-points (Fig. 11A) (Paillard et al., 1996). Higher correlations are possible if a more complete alignment was attempted (e.g., Stoner et al., 2007). To extract the simplest signal for both records we used the “smooth” and “weighted” functions (weight = 15%) in Kalaidograph™ to derive the underlying changes in inclination. These changes are well correlated with $r = 0.81$ (Fig. 11B), which reflects the long-period high-amplitude changes that characterize both records prior to approximately 6000 cal yr. BP.

Discussion and Conclusions

We have presented data on sediment magnetic and paleomagnetic parameters at years to multidecadal resolution. Our evaluation of these data focuses on three questions: (1) Can we detect a simple source-to-sink change in parameters between the

FIGURE 10. Characteristic inclination data from the u-channel cores (Table 1, Fig. 1) using the Mahout (2005) program which follows. For each core the percentage of samples with maximum angular deviations $<5^\circ$ (upper-most) and $<10^\circ$ (lower) are listed.

FIGURE 11. (A) Comparison of the characteristic inclination data from Stoner et al (2007) on MD99-2269 (Fig. 1) and MD99-2266 from Ísafjardardjúp. (B) Comparison between MD99-2269 and MD99-2266 on the smoothed characteristic inclination data. The values for correlation, r , in Figure 11A and 11B are based on the AnalySeries program (Paillard et al., 1996).

fjord cores and those from the shelf trough (Fig. 1, Table 2)? (2) What are the major features of the Holocene sediment magnetic records? and (3) Are there essential points of similarity (i.e. events) between the records?

(1) Simple source-to-sink changes are not detected. The expected changes in sediment magnetic characteristics from the fjords to the trough are not apparent. The sediments do not fine seaward (Fig. 8), and the magnetic data are not clearly demarcated into two distinct sets (e.g. Figs. 3–8). One reason for this is that a simple two-dimensional transport model neglects the three-dimensional reality that includes strong tidal and storm activity on the shallow banks that surround Djúpáll (Thors, 1974; Andresen et al., 2005).

(2) The sediment magnetic records illustrate at least three major Holocene events. The sediment magnetic properties indicate high magnetic mineral concentrations and fine-grained sediments during the onset of the Holocene, when the local glaciers and ice caps on Vestfirðir were retreating from their LGM (Geirsdóttir et al., 2002; Principato et al., 2006). However, the Saksunarvatn tephra represents a distinct low MMS and k_{ARM} signal (Figs. 4, 6, 7). A second correlative event includes the high MS signal ca. 8400 cal yr. BP associated with a debris flow or turbidite in B997-339, and this signal is also clear in B997-342 and MD99-2266 (Fig. 4). The distribution of this signal within the Ísafjardardjúp and Jökulfirðir fjord systems suggests that an earthquake or other processes caused extensive mass movements during this time. There are no sharp changes in the magnetic records that reflect the onset of Neoglaciation, but the peaks in magnetic concentrations after 4000 cal yr. BP and an associated increase in the ARM (J20)/ARM (J0) ratio (Fig. 7), are correlative with Neoglaciation. Several cores show an increase in magnetic mineral concentrations over the last 3000 cal yr., which may reflect an increased transport of suspended sediments during Neoglaciation. Andresen et al. (2005) also pointed to evidence from core KN-158-4-72GGC (Fig. 1) for a deterioration of climate at about this time. The

oldest dated Neoglacial moraines in Ísafjardardjúp are between 2500 and 3000 cal yr. BP (Principato, 2003).

(3) There are points of similarity between the paleomagnetic inclinations from the 10 sediment core records. The paleomagnetic inclination data (Figs. 9, 10, 11) capture high-resolution paleomagnetic secular variations across northwest Iceland. Our data, combined with other u-channel data from both marine sites (Stoner et al., 2007) and lake sediments (Olafsdóttir et al., 2005) will allow the computation of a master paleomagnetic secular variation curve for the region of northern Iceland.

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