Magnetic properties of eight particle size ranges from nine locations in Iceland and 26 locations in southern Greenland reveal the importance of source variation for our understanding of paleomagnetic and environmental magnetic records in the marine environment. These terrestrial samples show varying degrees of particle size dependence with all samples showing that the silt fraction possesses greater concentrations of ferrimagnetic minerals than either clay or sand. Fine pseudo-single domain (PSD) size magnetic grains dominate the magnetic assemblage of all Icelandic fractions. In contrast, Greenlandic samples possess greater variation in magnetic grain size; only fine silt and clay are as magnetically fine as the Icelandic PSD grains, while Greenlandic silts and sands are dominated by coarser PSD and multi-domain grains. These observations from potential marine sediment sources suggest that the silt size fraction is a likely driver for much of the concentration-dependent parameters derived from bulk magnetic records and that the magnetic grain size of the silt fraction can be used to discriminate between Icelandic and Greenlandic sources. Using these results to examine magnetic grain size records from marine sediment cores collected across the northern North Atlantic suggests that source, not just transport-controlled physical grain-size, has a significant impact on determining the magnetic grain size at a particular location. Homogeneity of magnetic grain size in Icelandic sediments at least partially explains the consistent quality of paleomagnetic records derived from cores surrounding Iceland and their ability to buffer large environmental changes.

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measurement aggregates the contributions from all the different clastic size fractions and source lithologies into a single measurement that can either smooth or amplify source and/or sorting information in a way that can make interpretation of the bulk magnetic record potentially problematic. Similarly, bulk measurements make it difficult to ascertain why some paleomagnetic records work better than others. We know that the best paleomagnetic records are derived from sediments possessing a restricted magnetic grain-size range (e.g., King et al., 1983; Tauxe, 1993); however, we rarely understand where or how these grains are sourced, making it difficult to predict where high quality records are likely to be obtained.

How magnetic properties from different source regions vary with particle-size, how particle-size fractions vary through sedimentary processes (weathering, erosion, transportation, and deposition), and how this influences the sediment magnetic record at different locations across the NNA has rarely been considered when interpreting bulk environmental and paleomagnetic records. An evaluation of these influences and an understanding of their potential effects on the bulk sediment record of the NNA is therefore critical for any comprehensive evaluation. Here we present grain-size specific magnetic data from terrestrial glaciated terranes of Iceland and southern Greenland (Fig. 1). We then use these data to differentiate between these source regions, and begin to discuss the implications that both source and particle size variation may have for the interpretation magnetic records from different locations around the NNA.

2. Materials and methods

A large proportion of the lithogenic sediment in the NNA results from glacial erosion of Iceland and Greenland (Ruddiman, 1977; Laine, 1980; Larsen et al., 1994; Prins et al., 2002). The geology of Iceland (and east-central Greenland) is dominated by Neogene and Paleogene flood basalts (Jakobsson, 1972; Pedersen et al., 1997). The Precambrian rocks in southern Greenland can be further divided into three geological terranes (Fig. 1); the Ketilidian Mobile Belt (KMB) is primarily juvenile Proterozoic crust consisting of voluminous granitic intrusions, while the Archean Block (AB) and the Nagssugtoqidian Mobile Belt (NMB) are crystalline Archean basement rocks that remained undeformed or were metamorphosed during the Proterozoic, respectively (Fig. 1; Kalsbeek and Taylor, 1985; Korstgård et al., 1987; Escher and Pulvertaft, 1995). Throughout the text we use the term “Greenlandic” in reference to sediment sourced only from these three southern Greenlandic terranes. To characterize these NNA terrestrial sediment sources we collected sediment from streams draining actively glaciated watersheds of Iceland and the three southern Greenlandic terranes (Fig. 1). Bulk magnetic properties were first measured prior to grain-size separation. Sand was isolated through sieving at 63 μm. Half of the <63 μm fraction was settled according to Stokes’s Law to attain bulk silt (3–63 μm) and clay (<3 μm) fractions. The remainder of the <63 μm fraction was sieved and settled to create four silt fractions: 45–63 μm, 32–45 μm, 20–32 μm, 10–20 μm and a fine silt/clay fraction <10 μm which is at the boundary defining cohesive/non-cohesive sediment transport (e.g., McCave et al., 1995; McCave and Hall, 2006). All bulk and fractionated samples were immobilized in plastic 8 cc discrete sample boxes prior to measurement of magnetic susceptibility and magnetic remanence; 200 mg gelatin caps were used for hysteresis measurements. Mass normalized magnetic susceptibility (MS) was measured at 0.47 kHz on a Bartington MS2B. Mass-normalized anhysteretic remanent magnetization (ARM) was imparted at 100 mT in a 0.05 mT d.c. biasing field and mass-normalized isothermal remanent magnetization (IRM) was acquired at 100, 300, and a 1000 mT saturation IRM field (SIRM). ARM and IRM were measured on a 2G Enterprises cryogenic magnetometer along with MS in the Paleo-and-Environmental Magnetism Laboratory at Oregon State University. Hysteresis parameters (Ms, Mr, Hc, and Hcr) were acquired in a saturating field of 1000 mT on a Princeton MicroMag.

![Fig. 1. Location of terrestrial stream sediment samples collected from the Paleogene Volcanics (PV) of Iceland (black squares), and the Ketilidian Mobile Belt (KMB; orange squares), the Archean Block (AB; red squares) and the Nagssugtoqidian Mobile Belt (NMB; purple squares) terranes of southern Greenland. The location of the Greenland Ice cores sites (GRIP, GISP2, and NGRIP; yellow squares) are also shown for reference. Core locations (circles) are color coded as per their spatial groupings in Fig. 5. The path of major bottom water currents as components of North Atlantic Deep Water (NADW) is also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)
VSM at the Pacific Northwest Paleomagnetic Laboratory at Western Washington University.

MS, ARM and IRM are primarily related to the concentration of ferrimagnetic grains. Ratios of these parameters can provide information on magnetic mineralogy and magnetic grain size. Magnetic grain-size is related to the mean magnetic domain state measured through the magnetic response to applied fields (e.g., Dunlop, 2002a, 2002b), whereas clastic grain-size is based on the physical particle size. Hysteresis parameters were corrected for paramagnetic contributions before construction of Day plots (Day et al., 1977) to accurately distinguish between single domain (SD), pseudo-single domain (PSD) and multi domain (MD) ferrimagnetic grain sizes (see Stoner et al. (1996), Stoner and St-Onge (2007) or Table 1 in the online supplementary material for further explanation of these terms).

3. Results

Magnetites and/or titanomagnetites have been shown to dominate the magnetic fraction of sediments in the NNA (e.g., Stoner et al., 1995a, 1995b; Lehman et al., 1996; Channell and Lehman, 1997; Kissel et al., 1997; Kissel, 2005). Our terrestrial sediments are consistent with that interpretation. Bulk MS is $> 0.2 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$. > 90% of SIRM is acquired in a field of 300 mT, and all hysteresis loops display saturation in fields $< 200 \text{ mT}$, indicating that ferrimagnetic phases govern the bulk magnetic mineral assemblage (Thompson, 1986; Channell et al., 1997; Dearing, 1999). These samples all fall on magnetite mixing lines (Dunlop, 2002a, 2002b) within a Day plot (Day et al., 1977) plot consistent with (titanom)agnetite as the major remanence carrier. In general, bulk Greenlandic samples have slightly lower

Fig. 2. (a) Histograms of bulk $\chi_{ARM}/\chi$ of terrestrial sediment samples from Iceland and the three terranes of southern Greenland. (b) Mean magnetic susceptibility with one standard deviation about the mean for each of the six particle size fractions from Iceland and the three terranes of southern Greenland. Note for each terrane the similarity in the four silt fractions (10–20 μm, 20–32 μm, 32–45 μm, and 45–63 μm) and their higher values compared to the fine silt/clay fraction (< 10 μm) for all terranes and the sand fraction (> 63 μm) in the Greenlandic terranes.
coercivity, acquiring a greater portion of their SIRM by 100 mT than bulk Icelandic samples. Icelandic samples have higher $\chi_{ARM}/\chi$ ratios than the Greenlandic samples (Fig. 2a), suggesting that higher Icelandic bulk coercivity may be related to finer magnetic grain sizes. All Greenlandic and Icelandic samples show strong particle size dependence of magnetic susceptibility (Fig. 2b). Greenlandic silts (10–63 μm) possess two to three times the MS of the > 63 μm fraction and greater than five times the mean MS of the < 10 μm fraction. The particle size dependence of Icelandic samples is lower yet distinct, with the MS of the < 10 μm fraction two to three times weaker than the > 10 μm fraction. For each of the four terranes, the four silt fractions possess similar MS, suggesting lower inter-fraction variation within the silt fraction; much of the variance in MS is between sand, silt, and fine silt/clay. Hysteresis loops of representative sand, silt, and clay fractions for the four terranes are shown in Fig. 3. Like MS, $M_s$ is higher in the silt fraction, indicating a greater concentration of ferrimagnetic minerals. All Icelandic fractions have similar shaped, relatively wide hysteresis loops indicating contributions of relatively fine magnetic grains. In contrast in Greenland, only clays display this behavior; silts and sands from these terranes have much narrower loops, consistent with coarser

Fig. 3. Representative Hysteresis loops of clay (< 3 μm), silt (3–63 μm) and sand (> 63 μm) fractions from the four different terranes. Magnetic acquisition is dominated by paramagnetic contributions above 500 mT. Note the common magnetization values within terranes but different values between terranes with variations in $M_s$ similar to MS. Hysteresis loops display ferrimagnetic behavior with wider loops characteristic of fine ferrimagnetic grain sizes in all Icelandic samples and the clay fractions of Greenlandic samples.
magnetic grains. Day plots (Day et al., 1977) of the six particle-size fractions from representative samples are shown in Fig. 4a, and a range of clay (< 3 μm), silt (3–63 μm) and sand (> 63 μm) fractions from different Iceland and Greenland samples are shown in Fig. 4b. As suggested from Fig. 3, Icelandic samples show little grain-size dependence between size fractions; clays, fine silts/clays, silts, and sands all cluster within the fine PSD range (Fig. 4a and b), possessing a higher proportion of SD grains (Dunlop and Carter-Stiglitz, 2006). In contrast, Greenlandic silts and sands possess a higher proportion of MD size grains and plot within the coarser PSD/MD and MD grain size range; only Greenlandic clays possess fine Icelandic-sized PSD magnetites. Icelandic PSD grains also have slightly higher ratios of $H_{cr}/H_{c}$ than Greenlandic PSD samples, possibly indicating either greater concentrations of oxidized magnetite and processes of maghematization (e.g., Özdemir et al., 1993; Stoner et al., 1995a; Smirnov and Tarduno, 2000) or the presence of small concentrations of superparamagnetic (SP) grains (e.g., Dunlop, 2002b). Subtle, yet distinct variation exists between Greenlandic silt fractions. M5 is highest in NMB sediments followed by KMB with AB samples the weakest magnetically (Fig. 2). The high-MS NMB silt samples are magnetically a little coarser than the KMB or AB samples, with the NMB silts plotting to the bottom right of the Day plot (Fig. 4c).

In summary, differences exist in magnetic concentration and magnetic grain size both between different terranes, and between different size fractions within a given terrane. When mass normalized, the silt fraction carries a large proportion of the magnetic signal from all terranes (Fig. 2b) and can be expected to dominate the properties of bulk marine records derived from them. In Greenlandic sediments this fraction has a coarser

**Fig. 4.** Magnetic hysteresis parameters $M_{r}/M_{s}$ and $H_{cr}/H_{c}$ with magnetic grain size SD (single domain), PSD (pseudo-single domain) and MD (multi-domain) zonations after Day et al. (1977) for (a) representative fine silt/clay (< 10 μm), four silt (10–20 μm, 20–32 μm, 32–45 μm, and 45–63 μm) and sand fractions (> 63 μm) from terrestrial Icelandic and Greenlandian terranes; (b) clay (< 3 μm), silt (3–63 μm) and sand (> 63 μm) fractions from Iceland and Greenland; and (c) silts (3–63 μm) from Iceland (black crosses) and the three terranes of southern Greenland (orange triangles, KMB; red diamonds, AB; purple circles, NMB). The observed trend from fine SD to coarse MD magnetite is consistent with magnetic grain-size variations and with the empirical and theoretical defined magnetite mixing line (after Dunlop and Carter-Stiglitz (2006)). Note that only the clay and fine silt/clay sized particles from Greenland are as magnetically fine as Icelandic material of any size. Differences between the magnetic grain size of silt and sand size fractions from Greenland and Iceland can be used to distinguish between these sources. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
magnetic grain size than Icelandic sediments (Fig. 4a and b), with the latter being restricted to relatively homogeneous fine PSD magnetic grain sizes across all particle-size fractions.

4. Discussion

Our stream sediment data (Figs. 2–4) suggest that variations in sediment contributions from different terranes, and the particle sizes eroded from those terranes, have the potential to substantially influence the bulk magnetic properties of marine sedimentary sequences in the NNA. It is critical to understand why and how these variations potentially affect the bulk magnetic record because paleomagnetic records demand, and environmental magnetic records have almost exclusively been derived from, measurement of undisturbed bulk sediments.

Because ferrimagnetic minerals dominate all fractions, MS is primarily sensitive to the concentration of ferrimagnetic grains. In all samples, silts have higher MS than sand or clay. Lower concentrations of ferrimagnetic minerals in the finest clastic fraction may result from a relative resistance to sub-micron weathering and/or chemical weathering, resulting in the generation of paramagnetic clay minerals (e.g., Nesbitt and Wilson, 1992; Stefansson and Gislason, 2001). Relatively few discrete ferrimagnetic grains grow to sand size or larger. Thus the ferrimagnetic component in the sand fraction may exist as discrete ferrimagnetic inclusions or interwoven fabrics within non-magnetic host grains (e.g., Hounslow and Morton, 2004; Feinberg et al., 2005), which dilute and lower the overall MS. Silt fractions have the highest magnetic concentration and therefore appear to be the optimal physical size for discrete, unaltered ferrimagnetic particles and/or poly-crystalline clasts dominantly composed of ferrimagnetic grains. The similarity between Icelandic silts and their clay and sand fractions probably results from a more homogeneous basaltic parent geology compared to the more complex mineralogy of Greenland’s Precambrian terranes, where geochemical processes and cooling rates can be important factors in determining mineralogy, physical crystal-size and magnetic domain state (Thompson and Oldfield, 1986; Radhakrishnamurty, 1990; Zhou et al., 1997; Butler, 1992). In rapidly cooled basalts, growth of MD grains may be restricted (Radhakrishnamurty et al., 1977, 1978; Radhakrishnamurty, 1990), and they commonly contain a greater proportion of fine-grained magnetites (in the SP/SD/PSD grain size range) than slowly cooled intrusive rocks (Pick and Tauxe, 1993, 1994; Kent and Gee, 1994; Gee and Kent, 1999; Zhou et al., 2000). In contrast, igneous intrusions and metamorphosed gneisses in southern Greenland cooled over a longer time period and at much slower rates (e.g., 1–7°C Ma$^{-1}$ for the NMB; Willigers et al., 2001, 2002; Sidgren et al., 2006), potentially permitting growth of different size magnetic domains up to and including larger MD size crystals. Subsequent weathering and sorting of this more heterogeneous mineralogy can cause partitioning of magnetic minerals into different clastic size fractions. The dominantly basaltic and simpler composition of Icelandic samples results in greater homogeneity in magnetic concentration and grain size across all clastic fractions (Figs. 2–4). The more complex Greenland geology and associated variety in magnetic grain size appears to track the clastic distribution, with finer PSD grains and/or a higher proportion of SD grains residing in the finest fraction and coarser PSD–MD grains dominant in silts and sands (Fig. 4a and b).

4.1. Magnetic minerals in the northern North Atlantic

Deep sea sediments can have a long, complex and varied history. Ice rafting can provide sand-sized grains to these environments during glacial periods but otherwise many deep sea records, and those outside of the ice-rafted debris belt (e.g., Ruddiman, 1977) are dominated by relatively fine silts and clays (e.g., Stow and Holbrook, 1984; Revel et al., 1996; Kissel et al., 1999, 2009; Snowball and Moros, 2003; Channell and Raymo, 2003; Praetorius et al., 2008). As most magnetic records are acquired through measurement of bulk sediments, they are an aggregated and averaged assessment of all the magnetic particles in all clastic fractions, reflecting contributions from different sources and/or changes in sediment transport or deposition. Our data highlight the importance of understanding subtle variations in source and clastic size composition when interpreting bulk magnetic records.

For example, a compilation of magnetic grain size data from 18 bulk NNA records spanning from the Norwegian Sea to the Bermuda Rise (Fig. 1) are spatially grouped and compared to Greenlandic and Icelandic silt fractions in Fig. 5. These records are constructed of mixtures of different source end-members that vary spatially across the NNA. While PSD grains dominate the average magnetic grain size of these records, distinct spatial groupings are apparent. Iceland proximal cores possess the finest bulk magnetic records. More distal records, which may be increasingly influenced by other terrestrial sources like Greenland, Norway and North America, fall further along the PSD–MD mixing line, indicating greater concentrations of coarser magnetic grains (e.g., Dunlop, 2002a; Dunlop and Carter-Stiglitz, 2006). This may suggest that like Greenland, sediments from Norway and...
North America possess significant grain-size dependence in their magnetic properties and that fine magnetic homogeneity across all sized fractions is somewhat unique to Iceland within the NNA. Fine magnetic grain sizes from bulk records around Iceland have been previously inferred (e.g., Watkins and Maher, 2003; Kissel et al., 2009); however with our data, we demonstrate that this reflects an intrinsic property of the sediment source regardless of sediment grain-size.

4.2. Implications for paleomagnetic and environmental magnetic data

Many high quality paleosecular variation (PSV) and relative paleointensity (RPI) records have been obtained from the NNA, and in particular from sediment drifts in the vicinity of Iceland (e.g., Channell and Lehman, 1997; Channell et al., 1997, 2002, 2004; Laj et al., 2002). These sediments are generally characterized by consistently well-resolved magnetic vectors (Maximum Angular Deviation (MAD) values generally <2°) and homogenous, relatively fine magnetic grain sizes. Coupled with relatively high sedimentation rates, these NNA records have driven much of our understanding of RPI and PSV, and have become important components in stacked paleomagnetic records (e.g., Laj et al., 2000; Valet et al., 2005; Channell et al., 2009; Ziegler et al., 2011). Interactions with bottom water currents that source and sort basaltic fragments are generally thought to be responsible for the homogenous PSD character of these drift records (e.g., Kissel, 2005; Kissel et al., 2009). However, homogeneously fine magnetic grains in Iceland-proximal records are often maintained through periods when bottom current strength is highly variable (e.g., Channell et al., 1997; Praetorius et al., 2008) and over glacial–interglacial cycles when the magnetic grain size of other drifts coarsens (e.g., Channell and Raymo, 2003; Evans et al., 2007). Seemingly unique in the NNA, the magnetic grain size of Icelandic sediments is independent of physical grain-size; records derived from these sources receive PSD grains despite the clastic fraction supplied, deposited, or sorted. This buffering of the magnetic grain size record against environmental change places greater importance on the source of the material rather than subsequent current related sourcing in the generation of these high quality records. The consistent quality of Iceland-proximal records had not been specifically examined, hindering our ability to predict locations that are likely to provide continuous high-quality paleomagnetic records.

With our new data it seems that the fine PSD character of Iceland-derived sediments likely minimizes the influence of varying sedimentary processes, which in other regions could result in the sourcing and deposition of coarser, sub-optimal magnetic grain sizes for developing quality paleomagnetic records.

Excluding dia genetic and authigenic effects, variations in magnetic parameters in the NNA are often interpreted as variation in the sourcing of material (e.g., Robinson, 1986; Stoner et al., 1995a; Grousset et al., 1993; Watkins and Maher, 2003). Our data show that differences in bulk records can also potentially be driven by variation in clastic grain size from the same source, particularly when those sources possess strong particle-size dependence. Thus for interpretation, it is important to recognize and evaluate how these different contributions vary and can affect a record. Figs. 2–4 suggest that the silt size fraction is a likely driver for much of the magnetic parameters derived from bulk magnetic records, with the important implication that the magnetic grain size of the silt fraction can be used to discriminate between Icelandic and Greenlandic sources.

These inferences may be able to help explain some complex magnetic records from the NNA like, for example, the strong linkage between MS and the Greenland Ice core (e.g., GISP2, GRIP, NGRIP) oxygen isotope record (e.g., Rasmussen et al., 1996, 1997; Kissel et al., 1999). As greater current speed is often associated with a coarser fraction of sortable silt (e.g., McCave et al., 1995; Bianchi and McCave, 1999; Praetorius et al., 2008) and as the silt fraction possesses 2–5 x the MS of the clay fraction (Fig. 2), changes in the physical grain size of oceanic records may have significant effects on bulk magnetic properties. While magnetic grain size remains relatively constant in Icelandic proximal records (Ballini et al., 2006; Kissel et al., 2009) changes in clastic grain size and their attendant effect on MS may result in the coupling and strong sensitivity of marine MS records with current speed and Greenland ice-core records. Where magnetic grain size changes significantly, our data suggest that this may reflect a change in the sediment source. Increased distance from Icelandic sources results in a coarser average magnetic grain size (Fig. 5), suggesting that local sourcing is a basin wide process affecting the magnetic composition of all cores. In areas influenced by many sources, like the Snorri and Eirik drifts (e.g., Innocente et al., 1997; Fagel et al., 2004) and the Reykjanes Ridge (e.g., Prins et al., 2002), the interpretation of magnetic grain-size and magnetic concentration as reflecting circulation may be more complicated than can be assessed with bulk magnetic measurements alone. This is particularly true over glacial to interglacial timescales where large changes in sediment source and flux are linked to the waxing and waning of continental ice sheets (e.g., Stoner et al., 1995b; Carlson et al., 2008; Colville et al., 2011). Because both source and/or particle size variation can drive the bulk magnetic properties of ocean sediments, it can be difficult to document the degree to which the bulk magnetic signal is affected by either process. However, we have shown potential for isolation and unraveling of these competing signals through grain-size-specific magnetic measurements.

5. Conclusions

Magnetic properties of potential NNA sediment sources from Iceland and Greenland are strongly dependent on sediment particle size. Icelandic sediments, whether they are sand, silt or clay, show little variation in magnetic grain-size, plotting in a restricted region on Day plots. In contrast, magnetic grain-sizes of Greenlandic sediments vary with physical grain-size; only Greenlandic clay has Icelandic-like fine magnetic grains, while silts and sands possess coarser PSD and MD grain sizes. Higher MS of the silt fraction makes it potentially an important driver of bulk concentration dependent parameters in sediments derived from Greenland and Iceland, with magnetic grain size variations of the silt-size component capable of discriminating between these two sources. These remanence and hysteresis measurements provide new insights for interpreting paleomagnetic records, specifically related to the quality of paleo-geomagnetic records obtained from specific locations and the consistent quality of records through changing sedimentary and environmental regimes. For environmental magnetic records, these results highlight the importance of particle-size dependence, and how the knowledge of this dependence improves the discrimination afforded by magnetic measurements.

Supplementary data

All data are available from the World Data Center for Paleoclimatology (http://www.ncdc.noaa.gov/paleo/paleo.html).

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