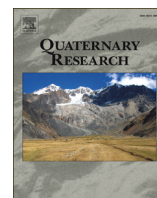




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Provenance and deposition of glacial Lake Missoula lacustrine and flood sediments determined from rock magnetic properties

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ABSTRACT

Repeated outburst flooding from glacial Lake Missoula, Montana, affected large areas of Washington during Marine Oxygen Isotope Stage 2 (29–14 ka). We present the first high-resolution rock magnetic results from two sites that are critical to interpreting these outburst floods and that provide evidence of sediment provenance: glacial Lake Missoula, the source of the floods; and glacial Lake Columbia, where floodwaters interrupted sedimentation. Magnetic carriers in glacial Lake Missoula varves are dominated by hematite, whereas those in outburst flood sediments and glacial Lake Columbia sediments are mainly magnetite and titanomagnetite. Stratigraphic variation of magnetic parameters is consistent with changes in lithology. Importantly, magnetic properties highlight depositional processes in the flood sediments that are not evident in the field. In glacial Lake Columbia, hematite is present in fine silt and clay deposited near the end of each flood as fine sediment settled out of the water column. This signal is only present at the end of the floods because the hematite is concentrated in the finer-grained sediment transported from the floor of glacial Lake Missoula, the only possible source of hematite, ~240 km away.

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Introduction

During the last, or Fraser glaciation (Marine Oxygen Isotope Stage 2, 29–14 ka), the Purcell Trench lobe of the Cordilleran ice sheet advanced south into Idaho and dammed Clark Fork River, impounding glacial Lake Missoula in the intermontane basins of western Montana (Fig. 1; Pardee, 1910, 1942). At approximately the same time, the Okanogan lobe, farther west, dammed Columbia River, creating glacial Lake Columbia in northeast Washington (Fig. 1; Bretz, 1932; Waitt and Thorson, 1983; Atwater, 1984, 1986). For several thousand years, between approximately 17.2 and 11.6 ¹⁴C ka BP (Clague et al., 1980; Kuehn et al., 2009), glacial Lake Missoula repeatedly filled and emptied catastrophically (Chambers, 1971; Baker, 1973; Chambers, 1984; Waitt, 1984, 1985). Floodwaters entered glacial Lake Columbia, where deposits of approximately 89 separate floods are interbedded with glacial Lake Columbia sediments (Atwater, 1986). Floodwaters also spilled across basalts of the Columbia Plateau, creating the distinctive topography of the Channeled Scablands of eastern Washington and depositing giant flood bars and current dunes, as well as fine-grained, rhythmically bedded, slackwater sediments in central Washington (Fig. 1; Bretz, 1925, 1928; Bretz et al., 1956; Baker, 1973; Bjornstad, 1980; Waitt,

1980; Bunker, 1982; Waitt, 1985; Waitt et al., 2009). The floods continued down Columbia Valley and backed up into Willamette Valley in Oregon, where they deposited a sequence of fine-grained slackwater sediments (Fig. 1; Allison, 1978; Waitt, 1980, 1985; O'Connor et al., 2001). Each time, all of the floodwaters reached the Pacific Ocean at the mouth of Columbia River within a few weeks (Baker, 1973; Craig, 1987; O'Connor and Baker, 1992; Denlinger and O'Connell, 2010).

The number of times that glacial Lake Missoula drained catastrophically during the last glaciation was a source of controversy for decades. Estimates of the number of floods range from one to nearly 100. Debate focussed largely on the rhythmically bedded slackwater deposits in the Walla Walla and Yakima valleys of Washington (Fig. 1), where individual beds were attributed to either single floods (Waitt, 1980, 1985) or to hydraulic surging during a single or a few floods (Bretz et al., 1956; Bretz, 1969; Baker, 1973, 1978; Carson et al., 1978; Patton et al., 1979; Bjornstad, 1980; Bunker, 1982; Baker and Bunker, 1985; Smith, 1993; Shaw et al., 1999). Work on the paleomagnetic secular variation record of the slackwater sediments and flood sediments in glacial Lake Columbia (Lovett, 1984; Kietzman, 1985; Steele, 1991; Clague et al., 2003) has shown that the sequence of rhythmic beds must record dozens of individual floods separated by decades. Interflood varve counts in glacial Lake Columbia attest to similar timing between flood events (Atwater, 1986). There is still debate, however, as to whether all of these floods were sourced from glacial Lake Missoula or whether there was another source, such as glacial Lake Columbia or a water body beneath the

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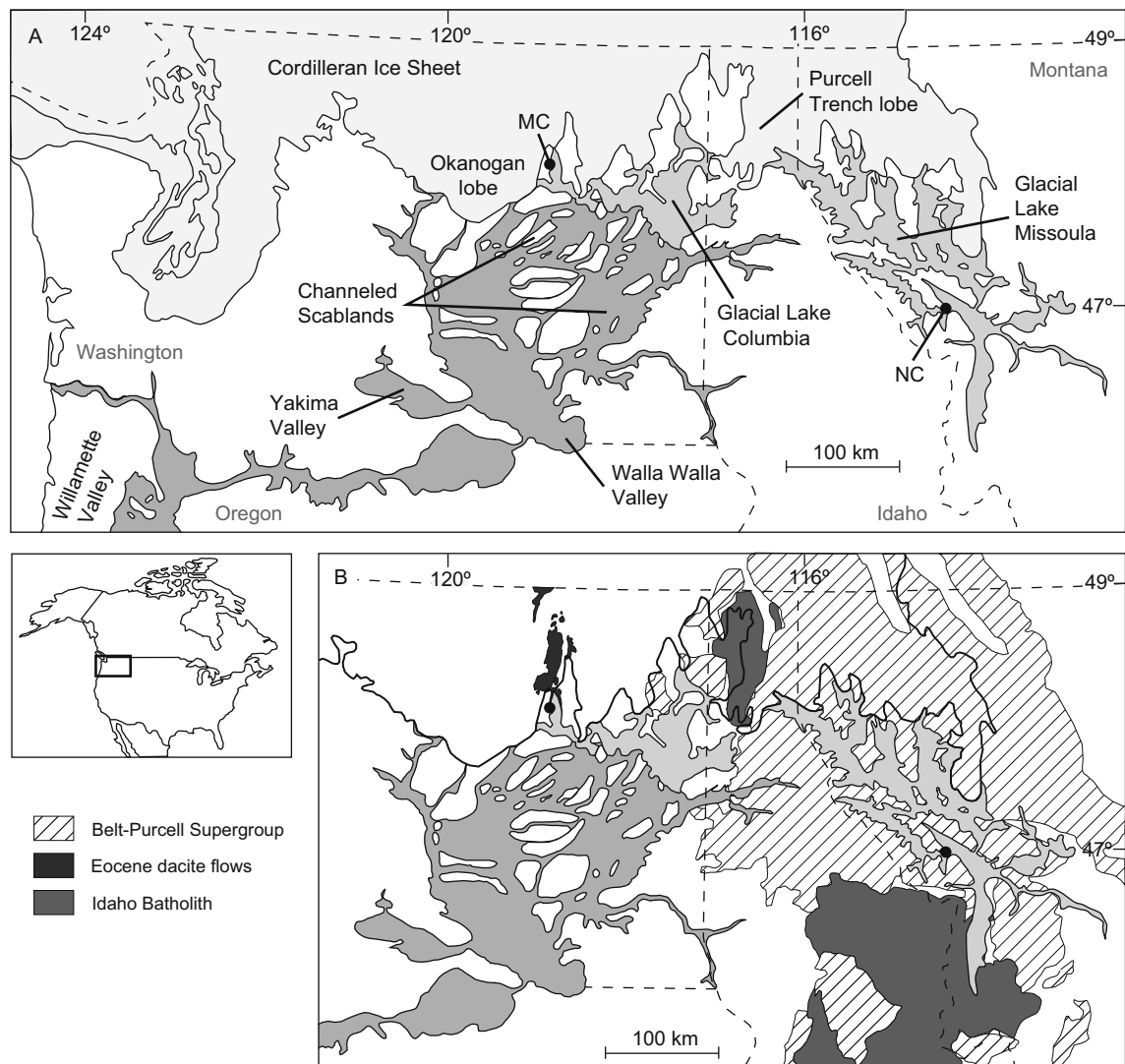


Figure 1. (A) Study area showing locations of sites mentioned in the text. MC: Manila Creek; NC: Ninemile Creek. Dark gray areas were swept by floodwaters from glacial Lake Missoula. Figure adapted from Waitt (1985), Atwater (1986), and Levish (1997). (B) Generalized, relevant geology of the study area (adapted from Stoffel, 1990; Vuke et al., 2007; Lewis et al., 2012).

Cordilleran ice sheet (Bretz et al., 1956; Bretz, 1969; Baker and Bunker, 1985; Shaw et al., 1999; Gaylord et al., 2005, 2007; Lesemann and Brennand, 2009).

Many researchers have conducted sedimentological studies on glacial Lake Missoula lacustrine sediments and on the flood sediments and landforms produced by outburst floods from the lake (Chambers, 1971; Baker, 1973; Bjornstad, 1980; Waitt, 1980; Bunker, 1982; Chambers, 1984; Waitt, 1984, 1985; Smith, 1993; Levish, 1997; Smith, 2006; Hanson et al., 2012). This study is the first to examine these sediments from a rock magnetic perspective. Magnetic properties characterize the mineralogy, concentration, and magnetic domain state of the iron oxide and sulfide minerals found in the sediments, providing a sensitive tool for investigating sediment transport and deposition, as well as provenance. In this paper, we present a rock magnetic record of lacustrine sediments deposited in glacial Lake Missoula, and interbedded flood and lacustrine sediments deposited in glacial Lake Columbia. The purpose of this study is two-fold: first to determine the magnetic characteristics of the sediments and relate them to different sedimentary environments and sedimentary processes; and second to determine different potential provenances of sediment in glacial Lake Columbia in order to resolve the controversy surrounding the source of flood deposits in Washington and Oregon.

Study areas

Ninemile Creek, glacial Lake Missoula (47°01'N, 114°23'W)

The Ninemile Creek section (Fig. 1), a roadcut along Interstate Highway 90 in western Montana that was originally described by Chambers (1971, 1984), is the unofficial type section for fine-grained glacial Lake Missoula lacustrine sediments. Thirty-four units,¹ ranging in thickness from 0.22 to 3.30 m and commonly thinning up-section, are exposed at this site. Each unit records a separate glacial Lake Missoula ponding event and has two sub-units (Fig. 2A). The lower sub-unit is characterized by a sharp, erosional lower contact and rippled and laminated fine sand and silt (Fig. 2A). This sub-unit was likely deposited by turbidity currents in relatively shallow water as glacial Lake Missoula began to fill (Chambers, 1971, 1984; Hanson et al., 2012). It grades upward into a sub-unit of silt and clay varves, which are annual sediment layers

¹ In this paper, we define "unit" as: (1) an ensemble of lithofacies recording a single lake phase from filling through maximum stage to drainage (e.g., glacial Lake Missoula); or (2) an ensemble of lithofacies recording a single glacial Lake Missoula flood event, including flood-deposited sediments and interbedded glaciolacustrine sediments deposited between successive floods (e.g., glacial Lake Columbia).

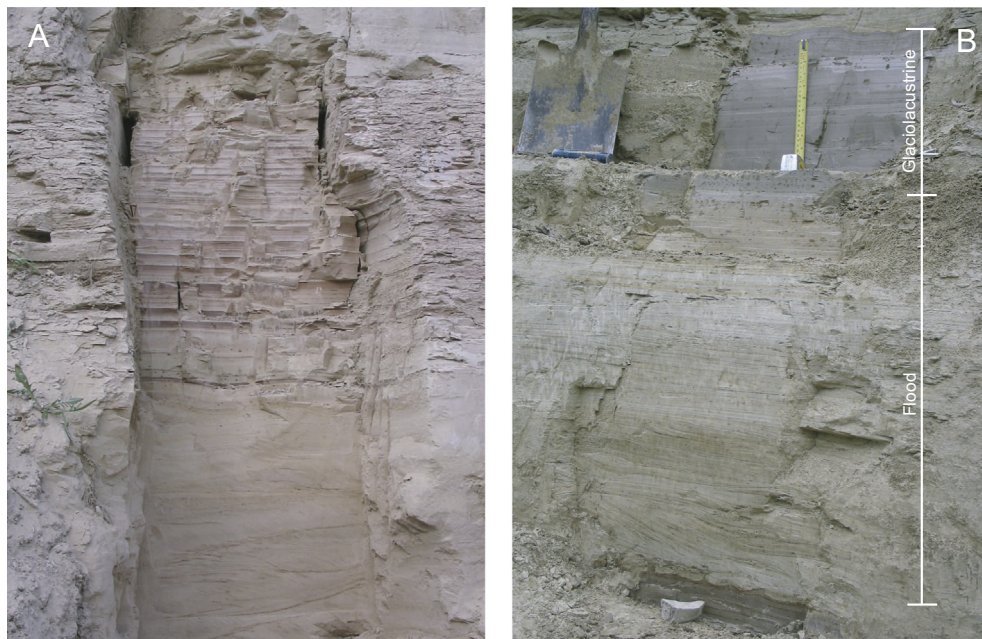


Figure 2. Photographs of units at each study site. (A) A single unit at Ninemile Creek that is about 3.3 m thick. The lower part of the unit consists of rippled and laminated fine sand and silt. This sediment grades upward into silt and clay varves. (B) One flood and one glaciolacustrine unit at Manila Creek. The lower flood sediment is characterized by a loaded lower contact and planar and inclined silt and clay laminations. The flood sediments grade up into glaciolacustrine, laminated clayey silt. The tape is about 30 cm long.

comprising a bed of relatively coarse (silt) sediment deposited by summer currents overlain by a bed of finer sediment (clay) that settles out of suspension during winter (Fig. 2A). Varves range from 0.3 to 20 cm thick, and the thickness of individual varves commonly decreases upward within the sub-unit, reflecting a progressive increase in the depth of the lake. The number of observed varves per unit ranges from 2 to 44 and averages 19. The total number of varves counted at Ninemile Creek is 583. Taking into consideration probable erosion of sediment during lake draining events and unrecorded lake refilling time, the entire exposure may record approximately 1500 yr (Hanson et al., 2012).

Manila Creek, glacial Lake Columbia (48°00'N, 118°42'W)

Atwater (1986, 1987) originally described glacial Lake Columbia sediments at Manila Creek (Fig. 1). At this site, glacial Lake Columbia sediments alternate with beds deposited by glacial Lake Missoula floodwaters (Fig. 2B). Up to 89 flood cycles have been reported here (Atwater, 1986, 1987), 46 of which were accessible for this study. Flood beds are 0.05 to 0.91 m thick and commonly thin up-section. They are characterized by erosional or loaded lower contacts; planar, inclined, or convoluted laminations of fine sand, silt, and clay; rippled fine sand and silt; and soft-sediment deformation structures indicative of rapid deposition (Fig. 2B). Flood units grade up into glacial Lake Columbia bedded and laminated very fine silt and clay (Fig. 2B). The glaciolacustrine units range from 0.04 to 1.69 m thick and, like the flood units, thin up-section. We were unable to consistently identify varves, but the 46 units record between 700 and 2600 yr (Atwater, 1986; Hanson, 2013).

Methods

Sampling

We collected 106 samples for detailed rock magnetic analysis – 44 samples from over three successive units at Ninemile Creek, 49 samples through just over two units in the lower part of the Manila Creek exposure, and 13 samples for thermomagnetic susceptibility measurements. We collected samples at 3–4 cm intervals. Between 9 and 16

plastic cylinders (2.5 cm diameter, 2.2 cm length) were inserted horizontally into vertically cleaned faces of each flood or glaciolacustrine unit, oriented using a Brunton compass, and removed for paleomagnetic analysis. We collected 288 additional samples at Manila Creek through the lower 25 units for magnetic remanence and magnetic susceptibility measurements only.

Magnetic remanence and susceptibility

We made all magnetic measurements at the Paleomagnetism and Petrophysics Laboratory at the Geological Survey of Canada. Paleomagnetic measurements were made on an AGICO JR5A spinner magnetometer. We measured loexposure-w-field volume magnetic susceptibility (K) of all samples with a Sapphire SI2B Susceptibility Meter.

Thermomagnetic susceptibility

The temperature dependence of magnetic susceptibility ($\chi_0 - T$) indicates magnetic and mineralogical changes during heating and thus can be used to identify magnetic minerals (Dunlop and Özdemir, 1997; Hrouda, 2003). We measured temperature dependence of low-field mass-specific magnetic susceptibility (χ_0) of 14 samples using a Bartington MS2WFP – six from Ninemile Creek and eight from Manila Creek (Table 1). Measurements were taken continuously as samples were heated from approximately room temperature to 700°C and then cooled to 100°C. We performed each run over a period of approximately 1 h on samples weighing between 1.26 and 2.59 g. The average heating and cooling rates were, respectively, approximately 15°C per minute and 40°C per minute. We determined the Curie temperature (T_c), which is the temperature at which a ferromagnetic material loses its ferromagnetic properties and becomes paramagnetic, by extrapolating the tangent line at the inflection point of the thermomagnetic curve to the x-axis (Lattard et al., 2006).

Magnetic hysteresis-loop parameters

We measured magnetic hysteresis-loop parameters of 93 samples at room temperature using a J-meter coercivity spectrometer (Enkin et al.,

Table 1
Curie temperatures and inferred magnetic mineralogy of samples analyzed for thermomagnetic susceptibility.

Sample code	T_c (°C)	Dominant magnetic mineral	Site ^a	Symbol ^b	D_{50} (μm)	Depositional environment
LKG134	555	Titano-magnetite	NC	□	14.0	Initial lake filling
LKG139A	660	Hematite	NC	◇	2.5	Varves
LKG139B	657	Hematite	NC	◇	2.2	Varves
LKG140	662	Hematite	NC	◇	2.4	Varves
LKG141	565	Titano-magnetite	NC	□	16.6	Initial lake filling
LKG145	660	Hematite	NC	◇	2.1	varves
LKF077	561	Titano-magnetite	MC	▽	30.9	Flood
LKF085	598	Magnetite	MC	△	3.9	Glaciolacustrine
LKF090	558	Titano-magnetite	MC	▽	10.0	Flood
MAH048	640	Hematite	MC	△	2.4	Top of glaciolacustrine
WMH003	551	Titano-magnetite	MC	▽	12.4	Flood
WMH007	600	Magnetite	MC	△	3.9	Glaciolacustrine
WMH010	557	Titano-magnetite	MC	▽	22.4	Flood
WMH015	603	Magnetite	MC	△	5.5	Glaciolacustrine

^a MC = Manila Creek; NC = Ninemile Creek.

^b Symbols relate to Figures 4–7.

2007) with a maximum applied field of 500 mT. We obtained saturation magnetization (J_s), saturation remanence (J_{RS}), coercive force (H_C), and coercivity of remanence (H_{CR}) after subtracting the paramagnetic susceptibility (K_p) contribution identified from the slope at fields >400 mT.

Grain-size analysis

We performed grain-size analysis on all samples for which hysteresis parameters were determined using a Malvern Mastersizer 2000 laser granulometer, which can measure particles ranging from 0.02 to

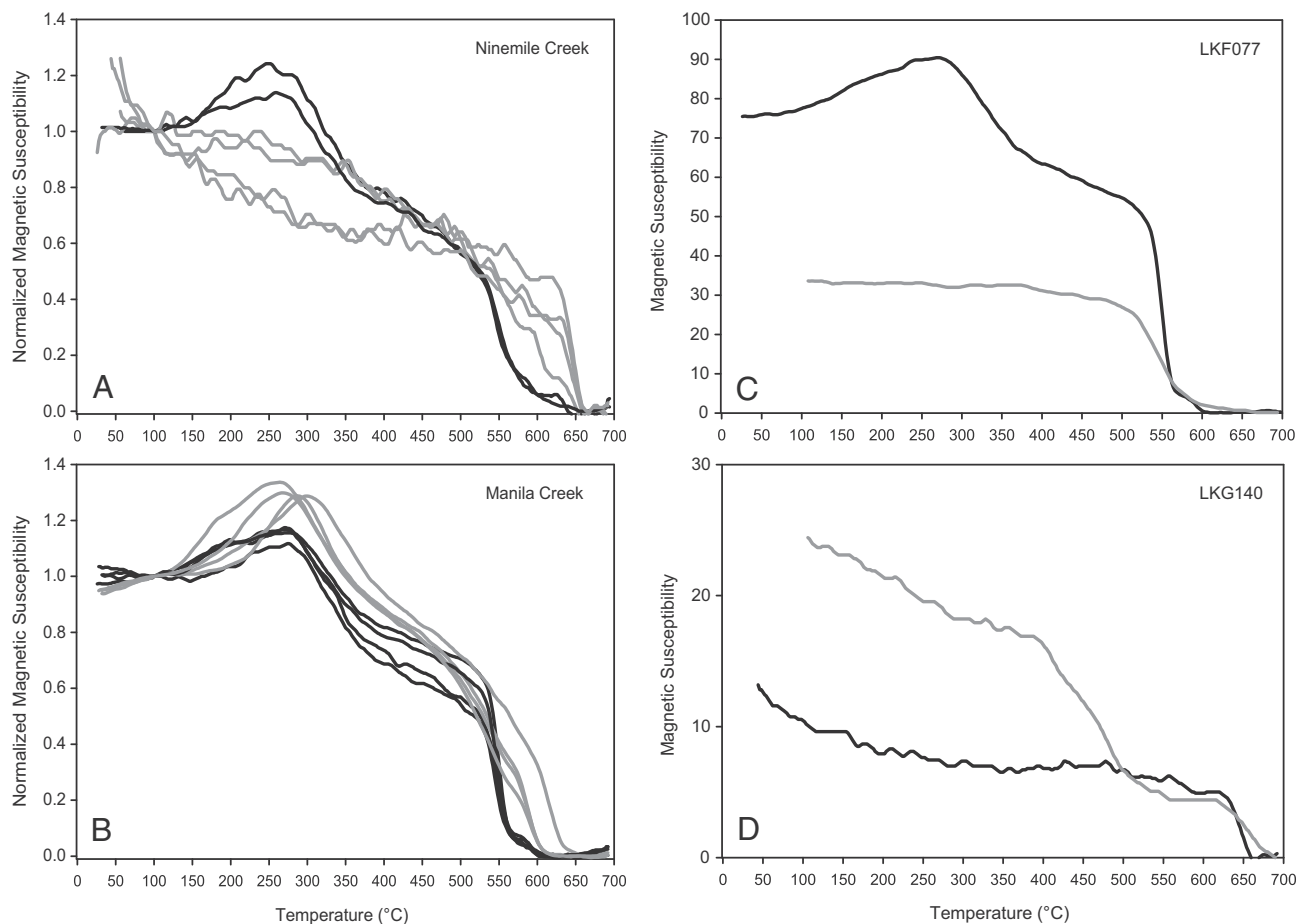


Figure 3. (A) and (B) Thermomagnetic curves from Ninemile Creek and Manila Creek, respectively. Curves of coarser-grained samples (turbidity currents at Ninemile Creek and flood units at Manila Creek) are black; curves of finer grained samples (glaciolacustrine units) are gray. To account for instrument drift, a small correction was applied to set the magnetic susceptibility to zero at high temperatures. We normalized susceptibility values to the susceptibility at 52°C, which is the highest starting temperature of any sample. (C) and (D) Examples of heating and cooling thermomagnetic curves from Manila Creek and Ninemile Creek, respectively. Black lines are heating curves; gray lines are cooling curves. To account for instrument drift, a small correction was applied to set the magnetic susceptibility to zero at high temperatures.

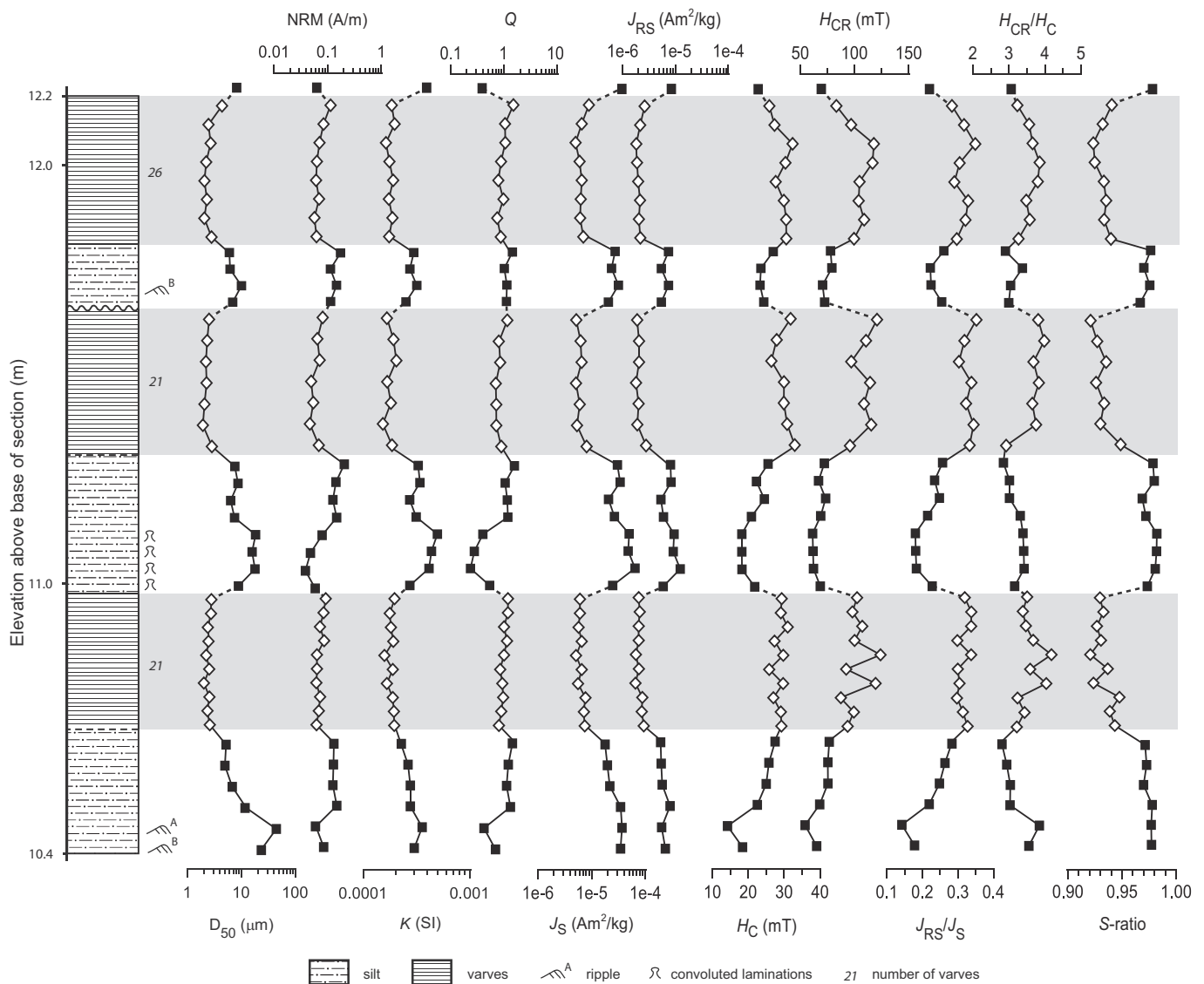


Figure 4. Magnetic results from samples collected through three glaciolacustrine units at Ninemile Creek. The stratigraphic column at the left shows major sedimentological units. Diamond symbols and gray banding are clay varved sediments; square symbols are silty sediments deposited by turbidity currents. Parameters displayed are median grain size (D_{50}), natural remanent magnetization (NRM), magnetic susceptibility (K), Koenigsberger ratio (Q), saturation magnetization (J_S), saturation remanence (J_{RS}), coercive force (H_C), coercivity of remanence (H_{CR}), and the S -ratio.

2000 μm . Our standard operating protocol is based on the work of Sperazza et al. (2004) and involved multiple trial runs of both a fine silt sample ($D_{50} = 9.7 \mu\text{m}$) and a clay-sized sample ($D_{50} = 2.9 \mu\text{m}$) from Ninemile Creek. We obtained subsamples of less than 2 g of sediment from the paleomagnetic cylinders for grain-size analysis. We soaked subsamples in 10 mL of a 0.55% sodium hexametaphosphate solution for approximately 16 h to disperse the grains. The subsamples were then mechanically stirred and sediment was drawn off with a pipette for analysis. The Udden–Wentworth scale (Wentworth, 1922) was used for textural classification. We note that laser granulometers tend to underestimate the clay fraction of samples because of the platy shape of clay minerals (Hao et al., 2008).

Results

The Koenigsberger ratio (Q) is the ratio of natural remanent magnetization to induced magnetization and is used to indicate the efficiency of magnetic acquisition. In sediments, a value above one indicates that the magnetic grains are individually stable (single-domain) and highly aligned, indicating that they were deposited in a low-energy

environment (Carter-Stiglitz et al., 2006). The Koenigsberger ratios for our samples are high for sediments; 91% of the samples have a Q value of greater than one. The Koenigsberger ratio and all other measured values discussed are plotted in Figures 3–6² and are listed in Table 1 and the Supplementary Table.

Thermomagnetic susceptibility

Thermomagnetic susceptibility heating curves are displayed in Figures 3A and B, grouped according to site. Table 1 shows the T_C of samples and inferred magnetic mineralogy. The thermomagnetic heating curves are of two types. At both sites, the heating curves that indicate the presence of magnetite or titanomagnetite have similar shapes.

² Note that sample MAH066, at the top of the first complete glaciolacustrine unit at Manila Creek (highlighted in gray in Fig. 5), is an anomalous sample that, in most cases (e.g., K and some hysteresis parameters) does not follow the trend of the other samples. An explanation for this anomaly is beyond the scope of this paper, thus this sample is plotted in Fig. 5 but is excluded when discussing parameter trends.

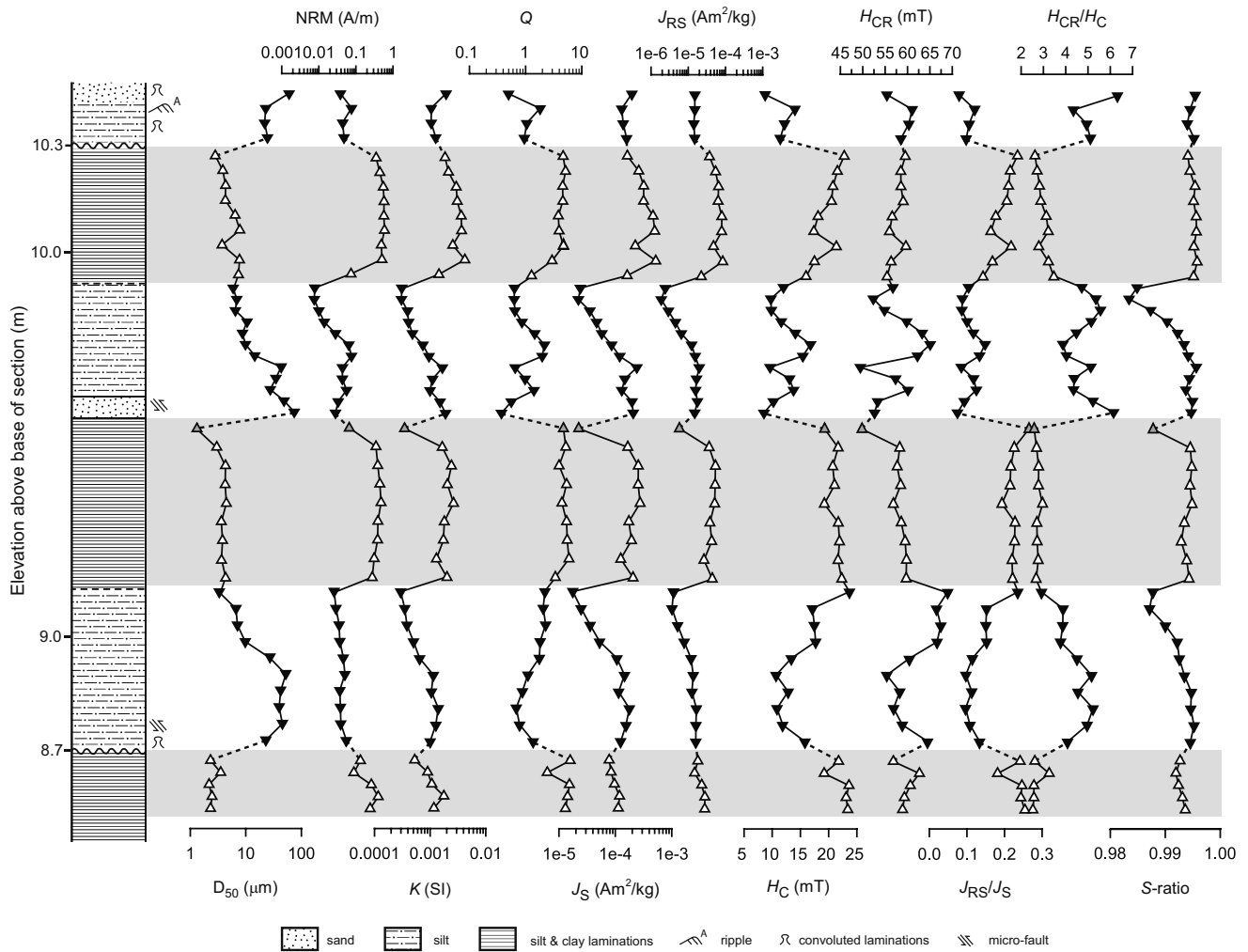


Figure 5. Results from samples collected through two units at Manila Creek. The stratigraphic column at the left shows major sedimentological units. Clay glaciolacustrine sediments are highlighted with gray banding and open triangles; closed upside-down triangles are flood sediments. Parameters displayed are median grain size (D_{50}), natural remanent magnetization (NRM), magnetic susceptibility (K), Koenigsberger ratio (Q), saturation magnetization (J_S), saturation remanence (J_{RS}), coercive force (H_C), coercivity of remanence (H_{CR}), and the S-ratio. One sample, highlighted in gray, is anomalous; see footnote 2 for details.

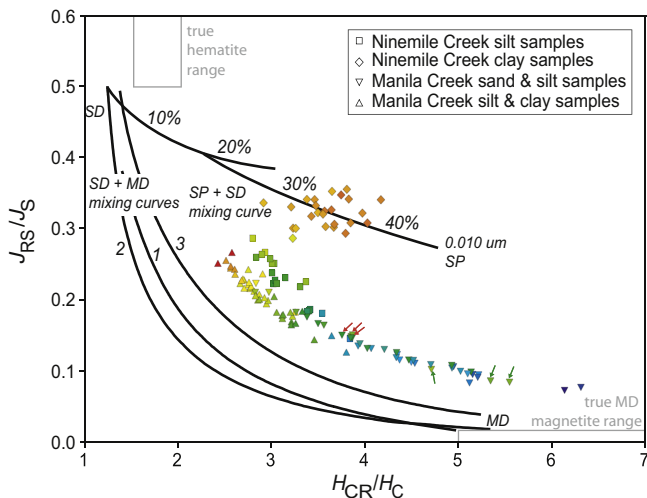


Figure 6. Hysteresis ratios for the two datasets shown on a Day plot. SD + MD and SP + SD mixing lines are from Dunlop (2002a). MD: multi-domain; SD: single domain; SP: superparamagnetic. The colors show a change in median grain size from 1.2 μm (red) to 78 μm (dark blue). The arrows indicate the top three samples in the two Manila Creek flood units (red = lower unit; green = upper unit). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

These curves are characterized by a steady increase of ~20% in susceptibility up to between 250°C and 350°C, followed by a gradual, and then more sudden, decrease toward the Curie temperature between 550°C and 600°C. The peak between 250°C and 350°C is commonly seen in samples that contain organic matter and is thought to indicate conversion of ferrimagnetic maghemite to weakly magnetic hematite (Stacey and Banerjee, 1974). However, there has been no pedogenesis or significant weathering at the sample sites, thus we would not expect maghemite in these samples. The second type of heating curve displays a generally steady decrease in susceptibility toward the Curie temperature well above 600°C and is characteristic of hematite-bearing samples. The thermomagnetic curves from Ninemile Creek (Fig. 3A) are noisier than the Manila Creek curves (Fig. 3B) because they have lower magnetic susceptibility, nearer the sensitivity limit of the equipment.

Cooling curves also are of two forms, examples of which are shown in Figures 3C and D. Cooling curves derived from samples dominated by magnetite and titanomagnetite (Fig. 3C) have distinctly lower susceptibilities than the associated heating curves, due to oxidation of magnetite to hematite. The cooling curves of the hematite-bearing samples (Fig. 3D) have higher susceptibilities than the heating curves, indicating that some hematite was reduced to magnetite during the heating process (Hrouda et al., 2002, 2003; Hrouda, 2003).

Room-temperature magnetic susceptibility

Volumetric magnetic susceptibility (K) depends on the concentration, mineralogy, and grain size of the magnetic fraction of the sample. Susceptibility is used as a measure of the concentration of ferrimagnetic minerals such as magnetite and titanomagnetite (Stacey and Banerjee, 1974; Opdyke and Channell, 1996). The contributions of diamagnetic, antiferromagnetic, and paramagnetic minerals to susceptibility are negligible because their susceptibilities are 10–100 times lower than those of magnetite and titanium-magnetite (Blanchet et al., 2007). If, however, the concentration of ferrimagnetic material is low, K depends on antiferromagnetic material such as hematite (Opdyke and Channell, 1996).

The following observations are of note: (1) at Ninemile Creek (Fig. 4), higher susceptibility values in the silts than the clay varves are consistent with $\chi_0 - T$ measurements, which indicate the presence of titanomagnetite in the silts and hematite in the clays; (2) at Manila Creek (Fig. 5), susceptibility decreases toward the top of each flood unit, which is consistent with the upward decrease in grain size as dense magnetite grains are preferentially transported with larger grains of common minerals. It is striking, however, that K increases abruptly from the top of each flood unit into the base of the overlying finer glaciolacustrine unit considering that the dominant magnetic mineral in both units is either titanomagnetite or magnetite and that grain size decreases upward. Additionally, K does not change significantly across the erosional contact at the base of the flood unit where grain size markedly increases.

Hysteresis properties

Hysteresis measurements provide information about the type, concentration, and domain state of magnetic minerals. We note that the samples were subjected to a maximum field of 500 mT, and so values of saturation magnetization (J_S), saturation remanence (J_{RS}), coercive force (H_C), and coercivity of remanence (H_{CR}) will be underestimated for samples dominated by hematite (i.e., varved clay sediment at Ninemile Creek), which requires a field of up to 3 T to saturate.

Saturation magnetization (J_S) and saturation remanence (J_{RS}) depend primarily on magnetic mineral content, but the ratio J_{RS}/J_S is mostly dependent on domain state. Both J_S and J_{RS} strongly or very strongly correlate to K if magnetite or titanomagnetite is the dominant magnetic mineral. At Manila Creek, J_S and J_{RS} follow the same unexpected trend of K from the flood sediments to the glaciolacustrine sediments.

Coercive force (H_C) and coercivity of remanence (H_{CR}) are key parameters in discriminating ferromagnetic and antiferromagnetic minerals. They increase in the presence of higher-coercivity, more stable minerals such as hematite (e.g., clay varves at Ninemile Creek, Fig. 4; Maher and Thompson, 1999; Blanchet et al., 2007). Coercivity of remanence is also a measure of domain state for a given magnetic mineral, with higher values indicating smaller, more stable magnetic grains (Maher and Thompson, 1999; Blanchet et al., 2007). At Manila Creek (Fig. 5), the range of values within the flood units is considerable; in the first flood, higher coercivity minerals are common toward the end; and in the second flood, they are more common in the middle. Overall, H_C and H_{CR} are negatively correlated to grain size.

Figure 6 is a Day plot showing the ratios J_{RS}/J_S and H_{CR}/H_C , which are used to determine domain states or magnetic grain sizes (Day et al., 1977). The Day plot was designed for use only for samples that contain magnetite, but we plot all of our samples in Figure 6. All samples are above the theoretical mixing curves for single domain (SD) and multi-domain (MD) grains (Fig. 6; Dunlop, 2002a). Most samples plot near the pseudo-single domain (PSD) range, well below the superparamagnetic and single domain (SP + SD) mixing curve. The Ninemile Creek varved clay samples cluster around the magnetite

SP + SD mixing curve, but only because the hematite was not saturated and thus the two ratios are anomalous. H_C is low for the hematite samples, resulting in high H_{CR}/H_C ratios; and the highest coercivity grains are not saturated, leading to low J_{RS}/J_S values. If hematite were truly saturated, it would plot higher than 0.5 on the y-axis of the Day plot and between 1.5 and 2 on the x-axis (Fig. 6; Dunlop, 2002b). Similarly, the presence of some hematite in the titanomagnetite in the Ninemile Creek silts displaces these samples toward the magnetite SP + SD mixing curves.

S-ratio

The S-ratio (Stober and Thompson, 1979) provides a measure of the proportion of low-coercivity ferromagnetic grains to high-coercivity grains. Because the maximum field of the coercivity spectrometer is 500 mT, the S-ratio used here is $(J_{RS}^{500\text{ mT}} - J_{RS}^{400\text{ mT}}) / J_{RS}^{500\text{ mT}}$. This ratio approaches unity as the proportion of low-coercivity magnetic grains, such as magnetite, increases. A lower value indicates the presence of a higher coercivity magnetic mineral, such as hematite, that is not saturated at the lower value (400 mT) but is closer to saturation at the higher value (500 mT). Hematite will not be fully saturated in this experiment, because it requires an applied field of more than 3 T for complete saturation. Titanomagnetite, on the other hand, is always saturated in fields below 300 mT. Thus we use the ratio to distinguish the relative amounts of magnetite and hematite at the different sites. Because the saturation magnetization of hematite is about 1/200 that of magnetite (Dunlop and Özdemir, 1997) and the hematite is not saturated at our maximum applied field, an S-ratio below 0.99 means there is more than twice as much hematite as magnetite in the sample.

S-ratios are low, dipping down to 0.90. Ninemile Creek has the lowest S-ratio values (mean = 0.95), indicating the presence of about 10 times greater concentration of hematite than magnetite in the sediment (Fig. 4). More hematite is present in the upper clay sub-units than in the lower silt sub-units, which is consistent with the $\chi_0 - T$ results. Most S-ratio values at Manila Creek (Fig. 5) are higher than those at Ninemile Creek (mean = 0.99), indicating that a low-coercivity magnetic mineral, such as magnetite or titanomagnetite, is dominant. There is, however, considerable variation within the Manila Creek results. The S-ratio values are constant across the erosional boundary at the base of a flood unit, but decrease at the end of a flood unit, a pattern similar to those shown by NRM, K , J_S , and J_{RS} values. Thus, the proportion of hematite increases toward the end of the floods.

Discussion

Rock magnetic measurements are easy to obtain, and we show that they can complement detailed sedimentological data, such as grain-size distributions and sedimentary structures. Magnetic methods focus on a small but sensitive sub-population of the sediment load: the iron oxides and sulfides. These minerals provide unique information on sediment provenance and transport mechanisms that are not necessarily discernable from field evidence. Table 2 summarizes the key magnetic properties of each depositional environment that are discussed below.

Magnetic properties and depositional environment

High Koenigsberger ratios ($Q > 1$) attest to high alignment of stable magnetic grains deposited in relatively low-energy settings. High ratios are characteristic of all Ninemile Creek samples, except those that record the early stage of lake filling when turbidity currents were present and sedimentation was more rapid (Fig. 4). At Manila Creek, the lake sediment samples are almost as well aligned, whereas the flood sediment samples have lower Q values. These lower values are to be

Table 2
Summary of the key magnetic properties for each depositional environment.

Location	Sedimentary environment	Key magnetic properties
Glacial Lake Missoula (Ninemile Creek)	□ ^a Initial lake filling – laminated and rippled fine sand and silt	<ul style="list-style-type: none"> Magnetic domain: difficult to determine; trending toward PSD $\chi_0 - T$, H_C, H_{CR}, and S-ratio: titanomagnetite is the dominant magnetic mineral; hematite, if present, is masked by the titanomagnetite Titano-magnetite comes from the surrounding Belt-Purcell Supergroup or the Idaho Batholith to the south K decreases up-unit Grain size (mean = 11.6 μm) decreases up-unit Magnetic domain: in SP + SD range but this is due to hematite that was not fully saturated $\chi_0 - T$, H_C, H_{CR}, and S-ratio: hematite is the dominant magnetic mineral Hematite comes from Belt-Purcell Supergroup in the surrounding area K is consistent up-unit
	◇ Deepened lake – silt and clay varves	<ul style="list-style-type: none"> Grain size (mean = 2.5 μm) is consistent up-unit Magnetic domain: PSD trending toward MD $\chi_0 - T$: titanomagnetite is the dominant magnetic mineral Titano-magnetite was eroded from the Idaho Batholith and sediment in eastern glacial Lake Columbia by the floodwaters K decreases up unit Grain size (mean = 27.3 μm) decreases up-unit Grain size decreases gradually but K, J_S, J_{RS}, and S-ratio increase abruptly from flood to glaciolacustrine sediments S-ratio shows that a higher-coercivity mineral (hematite) is present at the top of each flood unit Hematite is dominant in the fine-grained sediment deposited as fine grains settle out of the water column after the high-energy floodwaters have passed Glacial Lake Missoula is the only possible source of this hematite Magnetic domain: PSD $\chi_0 - T$: magnetite is the dominant magnetite mineral Magnetite sourced from volcanics north of site K is consistent up-unit Grain size (mean = 4.2 μm) is consistent up-unit
Glacial Lake Columbia (Manila Creek)	▽ Flood – bedded and rippled sand, silt and clay	
	▽ Transition to glaciolacustrine sediment – laminated or massive silt and clay	
	△ Deepened lake – laminated silt and clay	

^a Symbols relate to Figures 4–7.

expected in sediment characterized by ripples and soft-sediment deformation structures, which are indicative of very rapid sedimentation.

At Manila Creek, there are clear transitions in depositional environments resulting from the repeated influx of floodwaters to the site. Grain size, for example, markedly increases at contacts between glaciolacustrine sediments and overlying flood sediments as do the ratios J_{RS}/J_S and H_{CR}/H_C (Fig. 5). On the other hand, changes in some magnetic properties are not as evident at this contact; the small changes in Q , J_S , J_{RS} , H_C , H_{CR} reflect the fact that the glaciolacustrine sediment is dominated by magnetite and the flood sediment is dominated

by titanomagnetite. In contrast, many of the magnetic properties (e.g., NRM, K , J_S , J_{RS} , and S-ratio) change abruptly across the gradational sediment boundaries marking the ends of floods and resumption of normal glaciolacustrine sedimentation. This change is discussed in more detail below.

Magnetic susceptibility is strongly related to sediment grain size at each site and within each depositional environment (Figs. 4 and 5). Figure 7 shows that the two properties vary almost proportionally, indicating that the process that transported the larger grain sizes also transported more of the denser magnetite grains. Each of the four groups displays its own proportional relationship, but there is no common relation between magnetic susceptibility and grain size at all sites. This result indicates that proportions of ferromagnetic minerals differ among the four groups, probably because of differences in sediment provenance.

Similarly, the distributions of J_{RS}/J_S and H_{CR}/H_C (Fig. 6) indicate that trends in magnetic domain state and grain size are similar within each lithologic unit but distinct between units (Figs. 4–6), again highlighting the different sedimentary environments. Samples from each lithologic unit display homogeneity and most tend to cluster along a hyperbola, except for the Ninemile Creek clay samples. There is a clear separation of the two lithologies at Ninemile Creek and only a small amount of overlap of the flood and glaciolacustrine samples at Manila Creek. The overlap in the latter case may be explained by the gradual change from the flood environment to the glaciolacustrine environment. The upper three samples in each flood unit from Manila Creek are highlighted in Fig. 6. The three samples from the lower flood unit clearly overlap with the glaciolacustrine samples. Glacial Lake Missoula flood (sand and silt) samples at Manila Creek plot on a hyperbola slightly above and to the right of Manila Creek glaciolacustrine (silt and clay) samples, probably due to a higher proportion of hematite. Flood samples at Manila Creek plot toward the bottom right of the graph, indicating

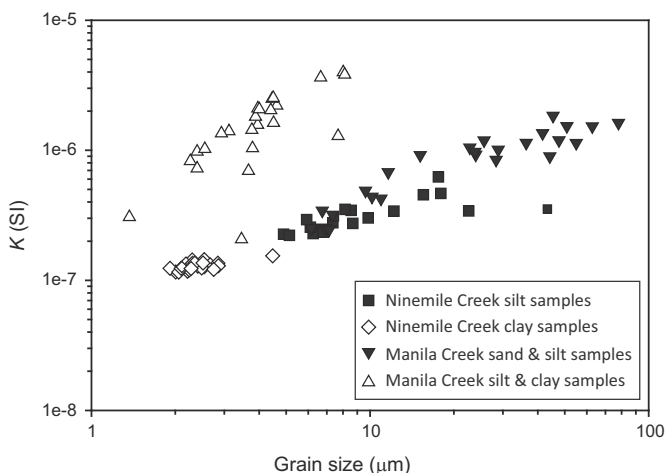


Figure 7. Plot of grain size vs. volumetric magnetic susceptibility (K). The linear trends indicate that the concentration of magnetite is directly proportional to grain size for each sediment type.

that they contain the largest magnetic grains, probably in the MD range, a conclusion supported by the low H_C values (9–16 mT).

Median grain size increases in each lithologic unit downward and to the right in the graph, consistent with the magnetic domain state. The largest magnetic grains are found in the lower flood unit at Manila Creek. The uppermost three samples from the lower flood unit (arrows in Fig. 6) have the smallest magnetic domains and grain sizes of the entire unit. The uppermost samples from the upper flood unit have the smallest grain sizes but not the smallest magnetic domains. It is possible that unsaturated hematite is underestimating both H_C and H_{CR} and also producing even lower H_C values than expected. Comparison of magnetic domains among sites is not entirely consistent with grain size. Thus, magnetic hysteresis ratios can be used as a proxy for grain size at a site, but the relationship between sites is more complicated if different magnetic minerals are involved.

Sediment provenance

The high-temperature susceptibility data (Table 1) highlight the difference in magnetic mineralogy between the varved clay deposits at Ninemile Creek (hematite) and the glacial Lake Missoula flood and glaciolacustrine deposits at Manila Creek (magnetite and titanomagnetite). Higher values of H_C and H_{CR} and lower values of J_R and J_{RS} , which characterize glacial Lake Missoula varved clay sediment, are consistent with the presence of hematite. Lower values of H_C and H_{CR} and higher values of J_R and J_{RS} confirm the presence of magnetite or titanomagnetite in both glacial Lake Columbia sediment and glacial Lake Missoula flood deposits.

The hematite at Ninemile Creek is derived from the mid-Proterozoic Belt-Purcell Supergroup, which is widespread in the glacial Lake Missoula basin (Fig. 1; Elston et al., 2002; Vuke et al., 2007). Rivers flowing into glacial Lake Missoula from the south, southeast, and east supplied sediment to the Ninemile Creek site; this bedrock is dominated by the hematite-bearing Upper and Lower Missoula, Piegan, and Ravalli groups (Elston et al., 2002). Titanomagnetite in the lower part of the glaciolacustrine (silt) units at Ninemile Creek might also have sources in the Belt-Purcell Supergroup, but it could also have been derived from monzonite and granodiorite of the Idaho Batholith south of the

site (Fig. 1; Lewis et al., 2012). Titanomagnetite was only deposited at Ninemile Creek early during glacial Lake Missoula filling cycles when sediment was derived from sources close to the site. Silt at Ninemile Creek likely contains hematite as well (as indicated by the low S -ratios around 0.98), but its weak susceptibility is masked by the stronger contributions of titanomagnetite. Once the lake deepened, the site was distant from any sediment input from the south and titanomagnetite was no longer deposited in significant amounts.

Magnetite in glacial Lake Columbia sediments at Manila Creek is likely derived locally from Eocene dacite flows (Sanpoil Volcanics) and monzodiorite (Devils Elbow suite), both of which crop out north of the study site (Fig. 1; Stoffel, 1990). Eocene, Cretaceous, and Jurassic intrusive rocks farther north in British Columbia might also have provided magnetite to western glacial Lake Columbia (Lalonde and Pattison, 2007).

Provenance of flood sediment

Jumps in NRM, K , J_S , J_{RS} , and the S -ratio at Manila Creek (Fig. 5) indicate that sediment deposition in glacial Lake Columbia changed in character at the end of each flood event when the lake transitioned back to a normal glaciolacustrine environment. This change is not discernable from grain size alone (D_{50} ; Fig. 6), which indicates a general decrease in particle size throughout the flood unit and a gradual transition into glaciolacustrine deposition. The S -ratio proved to be the most useful parameter for elucidating what occurred as the flood sediments were deposited; it also helped explain similar trends in the other magnetic parameters.

The low S -ratio reflects the presence of high-coercivity magnetic minerals, such as hematite, and displays a consistent, repetitive pattern through the strata at Manila Creek (Fig. 5). We attribute the consistent decrease in S -ratio values at the end of a flood to deposition of fine-grained hematite derived from glacial Lake Missoula. There is no major local source that could provide a large amount of hematite to the Manila Creek site. Samples that display this hematite signal were collected from the upper part of flood units, which are fine-grained, commonly massive, and can have a pinkish tinge, similar to glacial Lake Missoula sediments (2.5 YR 7/1; reddish gray; Fig. 8). This fine-

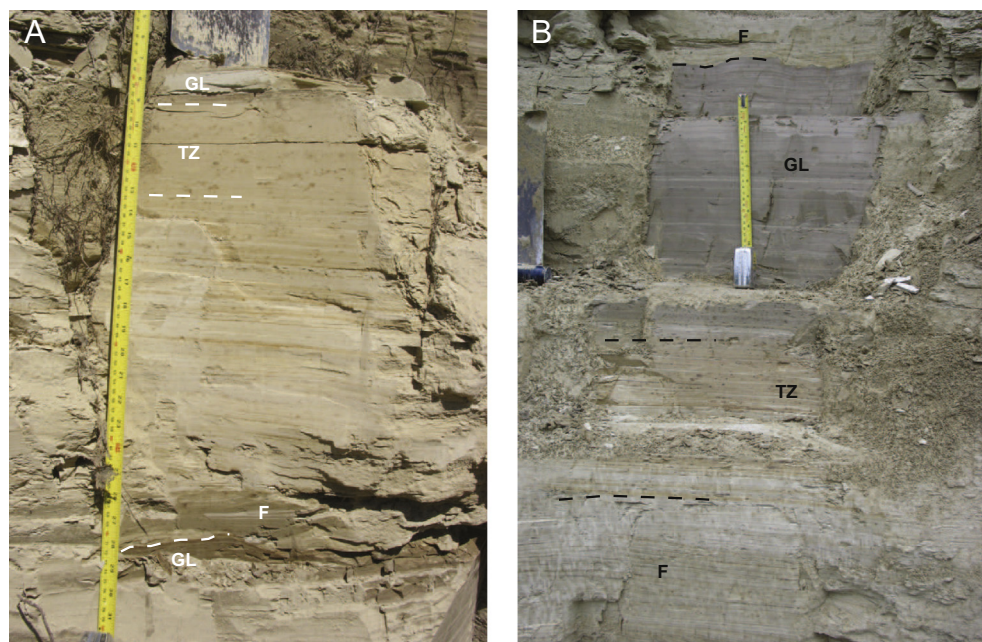


Figure 8. Flood (F) and glaciolacustrine (GL) sediments at Manila Creek. (A) The transition zone (TZ) between flood and glaciolacustrine sediments is characterized by massive, very fine silt to clay. (B) The transition zone (TZ) has a pinkish tinge similar to fine-grained, hematite-bearing, glacial Lake Missoula sediments at Ninemile Creek (see Fig. 2). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

grained sediment likely settled out of the water column in the months after the high-velocity currents of the flood had abated.³ This signal is only present at the end of floods, indicating that the hematite is focussed in the finer-grained sediment. Glacial Lake Missoula floodwaters traveled ~240 km from the ice dam to the Manila Creek site. They would have carried fine-grained, hematite-rich silt and clay eroded from the floor of glacial Lake Missoula.

Floodwaters would also have eroded and transported glacially deposited sediment from beneath the Purcell Trench lobe and glaciolacustrine sediment from eastern glacial Lake Columbia. Purcell Trench lobe deposits and some of the sediment in eastern glacial Lake Columbia would have been locally derived from granodiorite and tonalite of the Idaho Batholith (Fig. 1) and contained titanomagnetite. These more proximally derived sediments characterize the coarser flood sediments deposited in the lower part of the flood units at Manila Creek, which are dominated by titanomagnetite. If hematite is present in these coarser sediments, it is overwhelmed by magnetite and titanomagnetite, which have K values at least one order of magnitude larger than those of hematite.

This model of deposition helps to explain similar trends in other magnetic parameters at Manila Creek. A decrease in K at Manila Creek thus does not strictly represent a decrease in grain size over the course of the flood, but rather reflects the relative concentrations of hematite and magnetite. K is thus more strongly controlled by the concentration of ferromagnetic minerals than grain size. This fact highlights that there are distinct sedimentary sources for the flood and glaciolacustrine sediments. Magnetic susceptibility values change little across the erosional boundary at the beginning of a flood because larger magnetic grains of titanomagnetite eroded en route were deposited at that time. J_s and J_{RS} , which are both measures of magnetic mineral concentration, have nearly identical trends to K ; both decrease with the increasing relative concentrations of hematite. H_c and H_{CR} in the lower flood unit are generally mirror images of K , J_s , and J_{RS} , increasing upward through the unit with the increasing influence of the higher coercivity hematite. In contrast, the rock magnetic record of the second flood unit does not show a simple pattern. Fluctuations in D_{50} , K , Q , J_s , H_c , H_{CR} , and the S -ratio around the fifth sample from the bottom likely indicate current fluctuations during the flood with an increase in grain size and coarse titanomagnetite grains. The highest values of H_c and H_{CR} are not coincident with the lowest values of the S -ratio at the top of the unit. Instead, the H_c and H_{CR} values of the top five samples are lower than expected from the S -ratio. This variability in H_c and H_{CR} may indicate a larger effect of current fluctuations during the flood.

Although this study focuses on only two units at Manila Creek, the two units are representative of the majority of the 46 units studied at the site. Figure 9 shows NRM, K and Q values for the lowest 25 flood units. The sample spacing is larger, but most units show similar patterns to those documented in the detailed study of the two units: relatively gradual changes across the erosional boundary at the base of the flood sediment and sharp changes at the gradational boundary between the flood sediment and the glaciolacustrine sediment above. This pattern is not evident in the upper 21 flood units because the sampling resolution is too coarse and the uppermost eight flood units are thin (~5 cm) and do not contain coarser sand and silt grains. There is no indication visually that these late floods had a source other than glacial Lake Missoula, but Gaylord et al. (2007) ascribe some of the stratigraphically higher flood beds (not specifically identified) to meltwater from a retreating Cordilleran ice sheet on the basis of detrital zircon geochronology. Thus, with the possible exception of a few units near the top of the exposure, a similar process of deposition likely affected most of

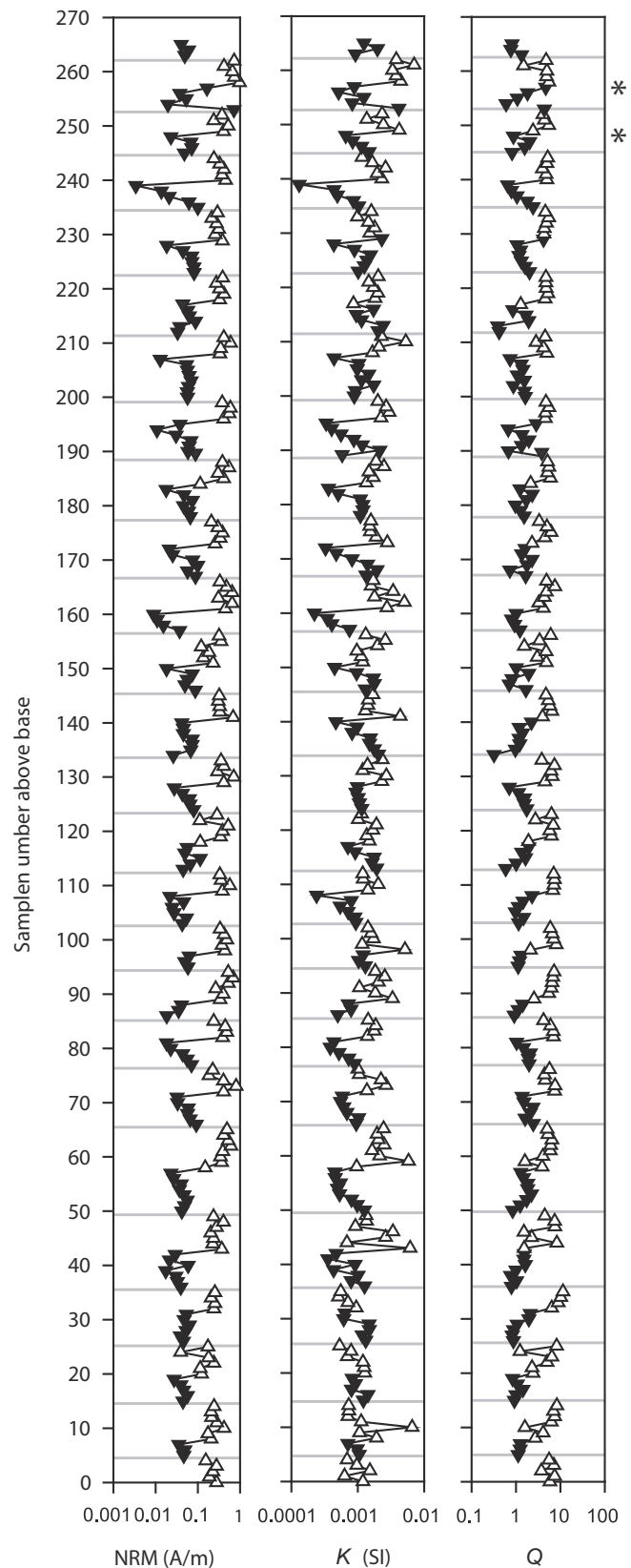


Figure 9. NRM, K , and Q for the lowest 25 units at Manila Creek. Glaciolacustrine samples are open triangles; flood samples are closed, upside-down triangles. Horizontal lines delineate the base of flood units. Note the gradual decrease in both NRM and K across erosional contacts at the base of the flood units and the sudden increase in NRM and K in the transition from flood units to glaciolacustrine units. The asterisks denote the two units in Fig. 6, although the samples represented here are from a different dataset that is not as detailed.

³ It would have taken between 8 and 22 months for the fine particles in the water column to settle to the lake floor at Manila Creek, assuming that the surface of glacial Lake Columbia was 715 m above sea level (asl) at its highest stand, that the lake floor was between 457 and 502 m asl at Manila Creek (Atwater, 1986), and that fine-grained silt to clay-size particles (4.5 μm –3 μm) settle at a rate of 0.27–0.62 mm/min.

the flood units at Manila Creek, involving sedimentation of fine-grained glacial Lake Missoula hematite at the end of each flood.

Conclusion

High-resolution rock magnetic analysis of last glacial (Marine Oxygen Isotope Stage 2), fine-grained glaciolacustrine and glacial outburst flood sediment deposited in glacial Lake Missoula and glacial Lake Columbia highlights differences in depositional processes and sediment provenance. In particular, this study shows that these techniques can be successfully used on fine-grained sediments deposited by higher-energy processes, such as glacial outburst flooding and turbidity currents.

The origin of Marine Oxygen Isotope Stage 2 flood deposits in northern and central Washington has long been debated. At the Manila Creek site, lower S -ratio, magnetic susceptibility (K), saturation magnetization (J_s), and saturation remanence (J_{RS}) indicate the presence of a higher-coercivity magnetic mineral (hematite) in the finest-grained sediment deposited at the end of each flood. There is no local source of hematite near the Manila Creek site, but thermomagnetic susceptibility measurements ($\chi_0 - T$) indicate the presence of hematite in fine-grained glacial Lake Missoula varved sediment, leading to the conclusion that flood beds at Manila Creek were deposited by glacial Lake Missoula outburst floods.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.yqres.2014.09.005>.

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