Journal of Paleolimnology **31:** 253–265, 2004.
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Basis for paleoenvironmental interpretation of magnetic properties of sediment from Upper Klamath Lake (Oregon): effects of weathering and mineralogical sorting★

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Received 27 February 2003; accepted in revised form 2 July 2003

Key words: Fluvial sediment, Hydrodynamic sorting, Lacustrine sediment, Sediment magnetism, Weathering

Abstract

Studies of magnetic properties enable reconstruction of environmental conditions that affected magnetic minerals incorporated in sediments from Upper Klamath Lake. Analyses of stream sediment samples from throughout the catchment of Upper Klamath Lake show that alteration of Fe-oxide minerals during subaerial chemical weathering of basic volcanic rocks has significantly changed magnetic properties of surficial deposits. Titanomagnetite, which is abundant both as phenocrysts and as microcrystals in fresh volcanic rocks, is progressively destroyed during weathering. Because fine-grained magnetite is readily altered due to large surface-to-volume ratios, weathering causes an increase in average magnetic grain size as well as reduction in the quantity of titanomagnetite both absolutely and relative to hematite. Hydrodynamic mineralogical sorting also produces differences in magnetic properties among rock and mineral grains of differing sizes. Importantly, removal of coarse silicate and Fe-oxide grains by sorting concentrated extremely fine-grained magnetite in the resulting sediment. The effects of weathering and sorting of minerals cannot be completely separated. These processes combine to produce the magnetic properties of a non-glacial lithic component of Upper Klamath Lake sediments, which is characterized by relatively low magnetite content and coarse magnetic grain size. Hydrodynamic sorting alone causes significant differences between the magnetic properties of glacial flour in lake sediments and of fresh volcanic rocks in the catchment. In comparison to source volcanic rocks, glacial flour in the lake sediment is highly enriched in extremely fine-grained magnetite.

Introduction

Magnetic properties of lacustrine sediments commonly reflect certain environmental conditions in the catchment. These conditions can be interpreted from an understanding of the magnetic properties of surficial deposits. Although this principal seems obvious, detailed and coordinated studies of both catchment and lacustrine sediments are rarely conducted. As noted by Reynolds et al. (2004 – this issue), the magnetic properties of late Pleistocene sediments in Upper Klamath Lake are relatively simple, in large part because magnetic minerals were unaffected by authigenesis. In these sediments, variations in magnetic properties largely

★This is the eighth in a series of eight papers published in this special issue, resulting from paleoenvironmental studies in the Upper Klamath Lake Basin. These studies were conducted by the U.S. Geological Survey and its collaborators as part of a paleoclimate research effort called the Correlation of Marine and Terrestrial Records Project. Steven M. Colman served as guest editor of this special issue.

reflect changes in catchment processes and conditions. The bedrock geology of the Upper Klamath Lake catchment is dominated by basalt and basaltic andesite. Sediments derived from these rocks have been variably affected by chemical weathering, mechanical weathering (including glacial processes), and hydrodynamic sorting.

Colman (1982) determined that alteration of basic volcanic rocks during chemical weathering results from a number of factors, including incorporation of water, leaching of bases, depletion of silica, and oxidation of iron. Elements are lost at different rates with Ca, Na, Mg, and Si being the most rapidly depleted, and Ti, the least mobile of the major elements, being relatively enriched. Alteration occurs more quickly in fine-grained groundmass than in phenocrysts, presumably because of the large surface to volume ratio of the fine-grained material. Stones in stable deposits develop weathering rinds that thicken with time, although the rate of rind formation depends on numerous factors including rock type and climate (Colman and Pierce 1981). For basaltic and andesitic stones in glacial deposits of the western United States, average rind thickness increases from one to several tenths of a millimeter in the youngest Pleistocene tills to one to several millimeters in older Pleistocene deposits.

Chemical weathering of volcanic rocks can be expected to produce significant changes in magnetic properties. Fresh basalt and basaltic andesite are relatively magnetic, containing abundant titanomagnetite both as phenocrysts and as small grains within the groundmass. Although titanomagnetite resists alteration in weathering environments, it does alter with time to less magnetic products such as hematite and amorphous oxide-hydroxides (Colman 1982). With modern instruments, high-sensitivity measurements of bulk magnetic properties are routine and rapid. Therefore, relatively small differences in the quantities of magnetic minerals and in magnetic grain sizes among sample populations can be assessed.

Hydrodynamic sorting during transport by streams and during settling in still water will produce differences in mineralogy (and thereby in magnetic properties) between catchment rocks and sediments. As an example, in a study of fluvial sediments in Guys Bight Basin on Baffin Island, Nesbitt and Young (1996) found that in the absence of weathering mafic minerals were significantly enriched in finer-grained sediments as shown by elevated concentrations of MgO, FeO, and TiO_2. This concentration probably reflects generally small grain-size diameters of heavy mafic minerals so that they are hydrodynamically equivalent to less dense minerals such as quartz and feldspar.

Variations in magnetic properties of Upper Klamath Lake sediments deposited during marine oxygen isotope stages 2 and 3 have been interpreted to reflect changes in the contents of fresh, highly magnetic glacial flour and more weathered, less magnetic lithic material (Reynolds et al. 2004 – this issue; Rosenbaum and Reynolds 2004 – this issue). Here we present magnetic property data, geochemical data, and petrographic observations for alluvial material from throughout the Upper Klamath Lake catchment. These observations are an important part of the basis for interpreting the influences of chemical weathering and hydrodynamic sorting on the lake sediment record.

Methods

Sampling and size fractions

In order to obtain detrital material from throughout the catchment, samples of alluvial sediment were collected from sites along streams flowing into Upper Klamath Lake (Figure 1). At most sites, two samples were collected, one from the streambed and the other from the stream bank or overbank deposit. An attempt was made to include representative material of all grain sizes smaller than a few centimeters in diameter. In addition, 2.5-cm diameter cores were drilled from boulders at several sites west of the lake.

Since the surface-to-volume ratio of particles increases with decreasing size, and because weathering of lithic clasts proceeds from the surface inwards (Colman and Pierce 1981), the fraction of weathered material in a clast should increase with decreasing clast size. Inspection of Figure 2 indicates that silt-sized grains with incipient weathering rinds (<0.01 mm) contain much greater percentages of weathered material than pebbles with well-developed rinds several mm in thickness. Thus, physical and chemical properties of material

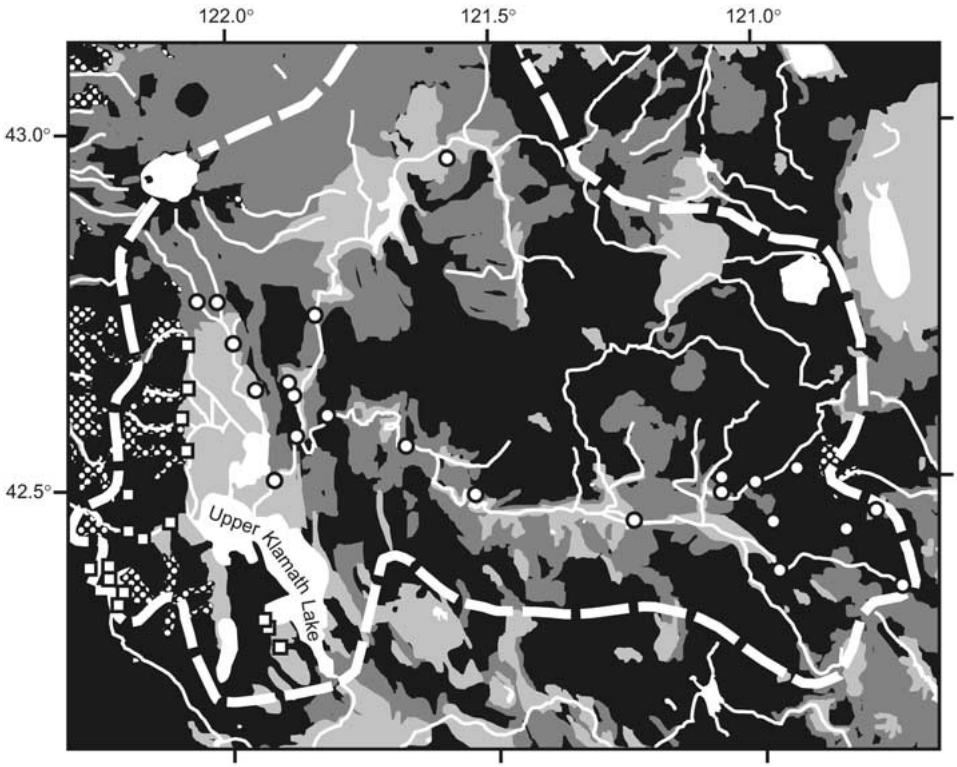


Figure 1. Map of the Upper Klamath Lake catchment showing simplified geology (after Walker and MacLeod 1991) and sample locations. Heavy dashed white line outlines catchment. Circles and squares indicate east-side and west-side sample localites, respectively. Map patterns: black, basalt and andesite; dark gray, dacite and rhyolite; light gray, Quaternary and Tertiary sediments and Quaternary alluvium; stippled, glacial deposits.

separated on the basis of grain-size should reflect differences in the degree of weathering. The samples were divided into five grain-size categories. Cylinders, 2.5 cm in length and comprised entirely of unweathered rock, were cut from the inner part of each cored boulder (B). The other samples were sieved into four grain size splits referred to here as pebbles (P, about 4 mm to several cm), coarse sand and granules (CS&G, 0.4 to about 4 mm), fine and medium sand (F&MS, about 0.05–0.4 mm), and silt (less than 0.05 mm). The pebbles were coarsely crushed so that small splits contained a representative mix of lithologies, whereas the cores from boulders were left intact.

Magnetic property measurements

Magnetic properties reflect the types, amounts, and magnetic grain sizes of magnetic minerals in geological materials (Thompson and Oldfield 1986; Verosub and Roberts 1995). For the volcaniclastic materials sampled in this study, saturation magnetization, magnetic susceptibility (MS), anhysteretic remanent magnetization (ARM), and isothermal remanent magnetization (IRM) largely reflect the content of the low-coercivity minerals, magnetite and titanomagnetite (hereafter referred to simply as magnetite), but differ in their sensitivity to variations in magnetic grain size (Dunlop and Özdemir 1997). Hard IRM (HIRM) is a measure of the high-coercivity mineral hematite. Saturation magnetization is the best measure of magnetite content, being essentially independent of grain size. For magnetite grains large enough to carry remanent magnetization ($\geq$0.03 μm), MS has a weak dependence on magnetic grain size, increasing somewhat as grains increase from single-domain to multi-domain; MS has been shown to be an excellent measure of magnetite content in Upper Klamath Lake sediments (Reynolds et al. 2004 – this issue). For such remanence-carrying grains, both IRM and ARM decrease with

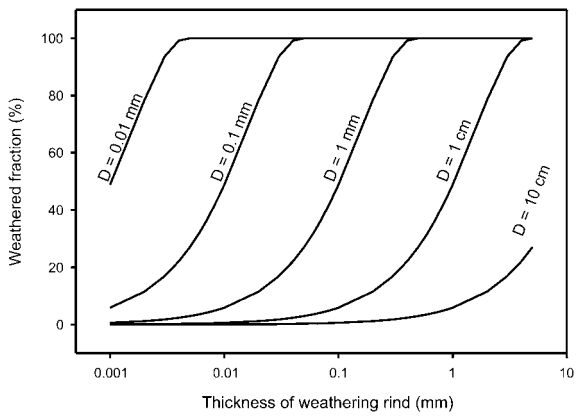


Figure 2. Theoretical change in fraction of weathered material as a function of weathering rind thickness (T) for spherical grains ranging in diameter (D) from 0.01 mm to 10 cm. The weathered fraction F was calculated as $F = 1 - (D/2 - T)^3/(D/2)^3$.

increasing grain size so that large multi-domain grains contribute relatively little in comparison to smaller grains. In comparison to IRM, ARM varies more strongly for very small grains (<1 μm) with ARM being particularly strong for magnetite grains with diameters on the order of 0.1 μm or smaller. Even smaller (superparamagnetic) grains carry no remanent magnetization, but have extremely high MS, as much as two orders of magnitude higher than remanence carrying grains.

Splits of each grain-size (other than boulders) were placed in non-magnetic 3.2-cm^3 plastic boxes. Magnetic susceptibility (MS) was measured in a 600-Hz alternating field with amplitude of about 0.1 milliTesla (mT). Anhysteretic and isothermal remanent magnetizations (ARM and IRM) were measured with a high-speed spinner magnetometer. ARM was imparted using an alternating field with a peak intensity of 100 mT and a bias field of 0.1 mT. After measurement of ARM, IRM was first imparted in a 1.2-T field ($\mathrm{IRM}_{1.2\mathrm{T}}$) and then in the opposite direction in a field of 0.3 T ($\mathrm{IRM}_{-0.3\mathrm{T}}$). Hard isothermal remanent magnetization (HIRM) and the S parameter (King and Channel 1991) are given by:

$$\mathrm{HIRM} = (\mathrm{IRM}_{1.2\mathrm{T}} - \mathrm{IRM}_{-0.3\mathrm{T}})/2$$

and

$$\mathrm{S} = \mathrm{IRM}_{-0.3\mathrm{T}}/\mathrm{IRM}_{1.2\mathrm{T}}.$$

In addition, saturation magnetizations were determined with a vibrating sample magnetometer for the P fractions of six samples.

Geochemistry and petrography

In order to help interpret the magnetic property data, abundances of Fe, Mn, Ti, and Zr were determined by energy dispersive X-ray fluorescence for selected stream sediment samples. The quantities of these elements may vary as a function of source rock composition, weathering (Colman 1982), and mineralogical sorting due to sediment transport or sieving of samples.

Standard petrographic methods were used to observe textures and mineralogy of volcanic rocks and surficial deposits derived from them. Reflected-light microscopic techniques further enabled the identification of magnetite (and titanomagnetite) and forms of hematite both in polished magnetic-grain mounts and in polished thin sections of sediment in different size fractions.

Results and discussion

Observations

Grouping of samples

Examination of the magnetic properties and geochemical data shows significant differences between sites located along the relatively short steep streams west of Upper Klamath Lake and sites located along streams draining gentler terrain north and east of the lake. No significant differences were found between samples taken from stream bottoms and stream banks. Therefore, averaged magnetic properties (Table 1) were computed for two groups of samples referred to here by their geographic positions as west and east groups (Figure 1). The west-group samples contain more magnetite and hematite than the east-group samples (Figure 3). The west group also contains more Mn and Fe and less Zr than the east group (Figure 4), indicating that, on average, the west-group samples are more mafic than the east group samples. This result was expected from the distribution of rock types in the catchment (Figure 1).

Table 1. Average magnetic properties.

	N	MS × 10^{-6} (m^3/kg)	IRM × 10^{-2} (Am^2/kg)	ARM × 10^{-4} (Am^2/kg)	HIRM × 10^{-4} (Am^2/kg)	S parameter	IRM/MS × 10^2 (A/m)	ARM/MS (A/m)
West-side samples								
Boulders	45	$4.78^{+0.58}_{-0.52}$ (102%)	$11.4^{+1.90}_{-1.63}$ (102%)	$15.4^{+3.20}_{-2.65}$ (101%)	$14.6^{+8.24}_{-5.27}$ (107%)	0.958 ± 0.012	273 ± 43	412 ± 87
Pebbles	25	$4.69^{+0.71}_{-0.62}$ (100%)	$11.2^{+1.78}_{-1.53}$ (100%)	$15.3^{+3.05}_{-2.54}$ (100%)	$13.7^{+5.40}_{-3.87}$ (100%)	0.967 ± 0.009	252 ± 39	353 ± 57
Coarse sand & granules	27	$3.91^{+0.75}_{-0.63}$ (83%)	$6.54^{+1.84}_{-1.43}$ (58%)	$12.6^{+3.36}_{-2.65}$ (82%)	$14.6^{+3.41}_{-2.77}$ (107%)	0.953 ± 0.007	177 ± 21	334 ± 33
Fine & medium sand	27	$3.97^{+0.95}_{-0.77}$ (85%)	$4.63^{+1.29}_{-1.01}$ (41%)	$11.3^{+2.69}_{-2.17}$ (74%)	$13.1^{+2.57}_{-2.15}$ (96%)	0.940 ± 0.008	129 ± 19	316 ± 41
Silt	27	$2.67^{+0.85}_{-0.64}$ (57%)	$3.97^{+1.44}_{-1.06}$ (35%)	$13.2^{+4.91}_{-3.58}$ (86%)	$13.3^{+3.65}_{-2.86}$ (97%)	0.928 ± 0.012	152 ± 12	505 ± 38
East-side samples								
Pebbles	31	$4.12^{+1.09}_{-0.86}$ (100%)	$8.65^{+2.24}_{-1.78}$ (100%)	$11.9^{+2.99}_{-2.39}$ (100%)	$10.7^{+7.74}_{-4.48}$ (100%)	0.949 ± 0.020	237 ± 40	334 ± 66
Coarse sand & granules	46	$1.75^{+0.57}_{-0.43}$ (42%)	$2.04^{+0.88}_{-0.62}$ (24%)	$3.94^{+1.37}_{-1.02}$ (33%)	$5.64^{+2.01}_{-1.48}$ (53%)	0.935 ± 0.012	129 ± 18	235 ± 20
Fine & medium sand	47	$3.40^{+1.46}_{-1.02}$ (83%)	$1.81^{+0.75}_{-0.53}$ (21%)	$3.54^{+1.22}_{-0.91}$ (30%)	$6.17^{+2.13}_{-1.59}$ (58%)	0.918 ± 0.012	60 ± 11	124 ± 22
Silt	47	$1.16^{+0.56}_{-0.38}$ (28%)	$1.13^{+0.55}_{-0.37}$ (13%)	$3.41^{+1.40}_{-0.99}$ (29%)	$4.31^{+1.43}_{-1.07}$ (40%)	0.907 ± 0.014	103 ± 11	341 ± 72
Lake sediment components								
Non-glacial material	5	0.62	1.01	2.96	11.2	0.775	165	492
Glacial flour	13	5.43	9.33	45.1	15.9	0.960	171	819

For the stream sediments, values of MS, IRM, ARM, and HIRM are geometric means. Percentages for these parameters are relative to the value for the pebble grain-size fraction. Values for the S parameter, IRM/MS, and ARM/MS are arithmetic means. Indicated ranges are 95% confidence intervals. For the lake sediment components, values are those determined from five post-glacial samples and 13 glacial flour-rich samples from a core in Upper Klamath Lake (see Rosenbaum and Reynolds 2004 – this issue).

Magnetic property data

For both groups of samples, the quantity of magnetite (as indicated by MS, IRM, and ARM) generally decreases with bulk-sediment grain size (Table 1 and Figure 3). There is no significant difference between the B and P fractions indicating that magnetic properties of the pebbles are representative of fresh, whole rocks (at least for the west-side samples). Thus, values given in the discussion below are expressed as a percentage of the P-fraction value and represent progressive changes with grain size as rock material becomes more weathered and disaggregated. IRM values for both groups decrease monotonically with decreasing grain size. For the east-side and west-side groups, IRM values of the silt fractions are about 13 and 35%, respectively. Similarly, MS values for the silt fractions are about 28 and 57%, respectively, but the change in MS with grain size is not monotonic. For the east-side group, MS falls to 42% for the CS&G fraction, rises to 83% in the F&MS fraction, and then falls again in the silt fraction. For the west-side group, MS decreases to 83% in the CS&G fraction, remains nearly constant in the F&MS fraction, and then decreases in the silt fraction. For the east-side group, ARM values fall sharply from the P fraction to CS&G fraction and then remain virtually constant with the silt value about 29%. For the west-side samples, ARM values decrease only a small amount from the P to CS&G fraction and then remain essentially constant.

Magnetic grain size also varies with sediment grain size. Magnetic grain size generally increases (IRM/MS and ARM/MS decrease) from the P to the F&MS fraction, although for the west side group changes in ARM/MS are probably insignificant. This trend does not continue for the

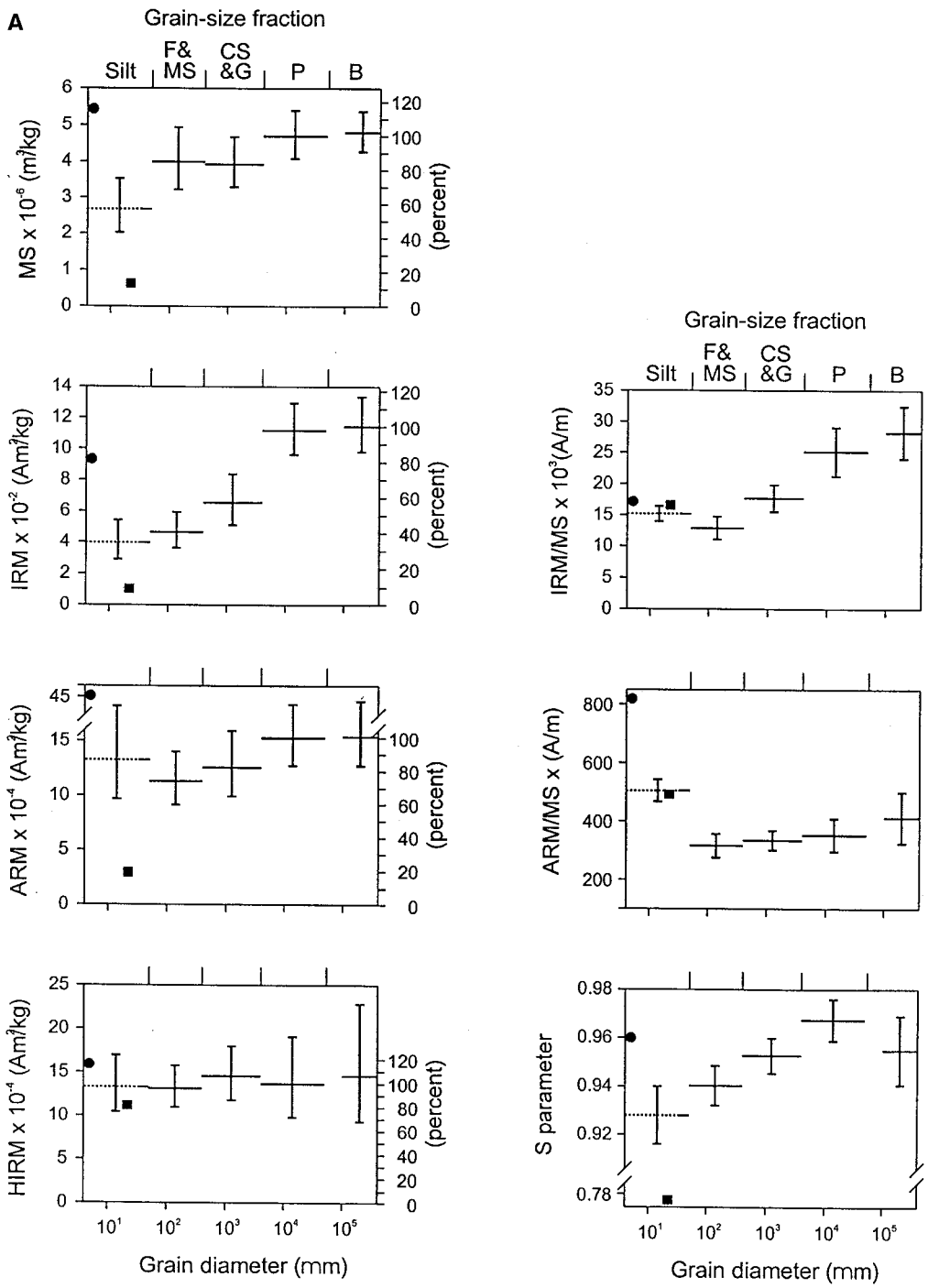
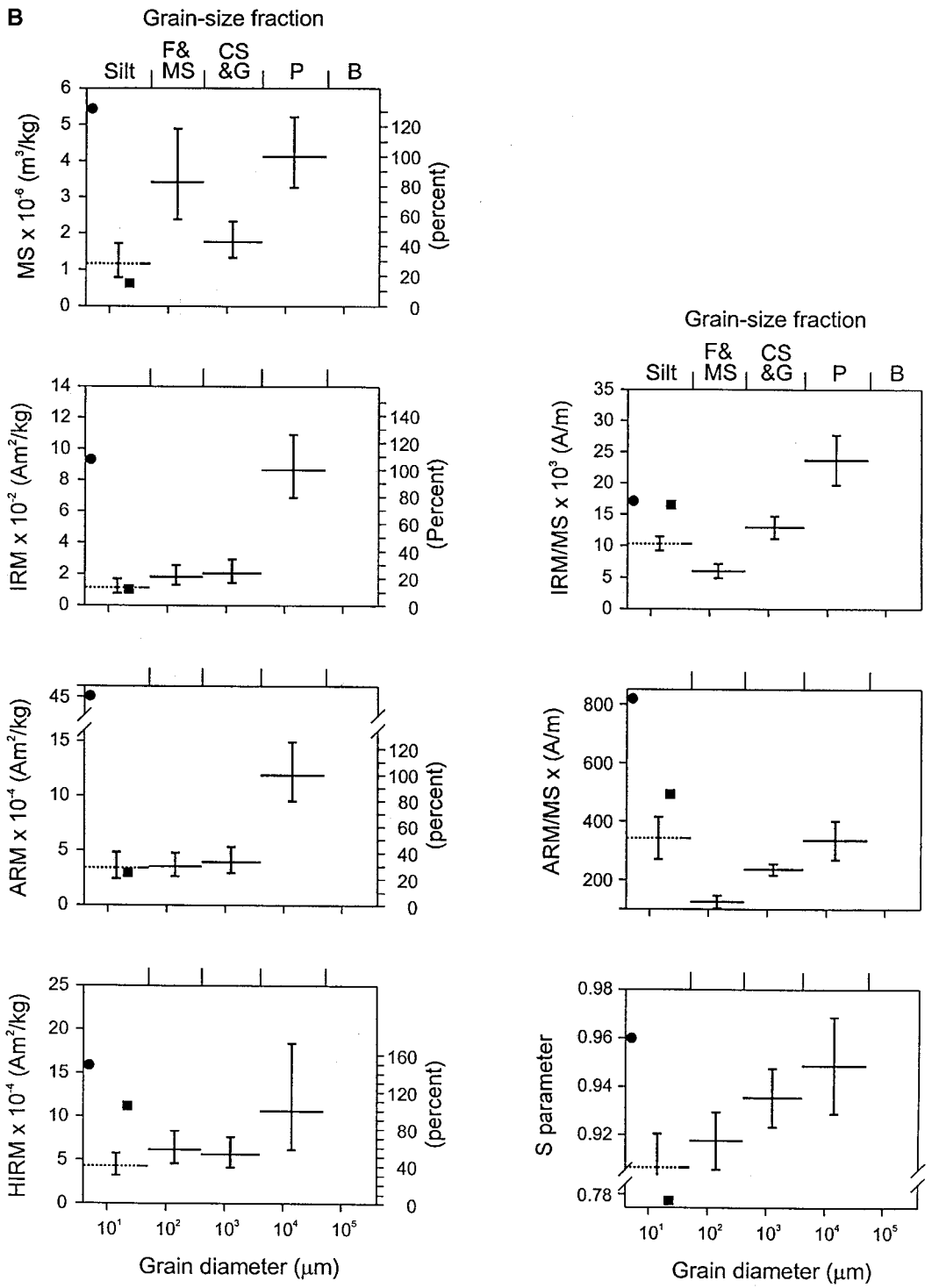


Figure 3. Average magnetic properties for grain-size fractions from catchment samples (horizontal bars), and for glacial flour (circle) and non-glacial lithic material (square) in cored sediment samples from Upper Klamath Lake (see Rosenbaum and Reynolds 2004 – this issue); (A) west-side samples; (B) east-side samples. For catchment samples, values for magnetic susceptibility (MS), isothermal remanent magnetization (IRM), anhysteretic remanent magnetization (ARM) and 'hard' isothermal remanent magnetization (HIRM) are geometric means. For these parameters, percentages relative to the P grain-size fraction are given on the right axis. Other values are arithmetic means. Vertical bars indicate 95% confidence intervals. The extents of the horizontal bars indicate grain size ranges; dashed line for the silt fraction indicates that the grain size distribution of this fraction probably is heavily skewed to the coarse end of the range.



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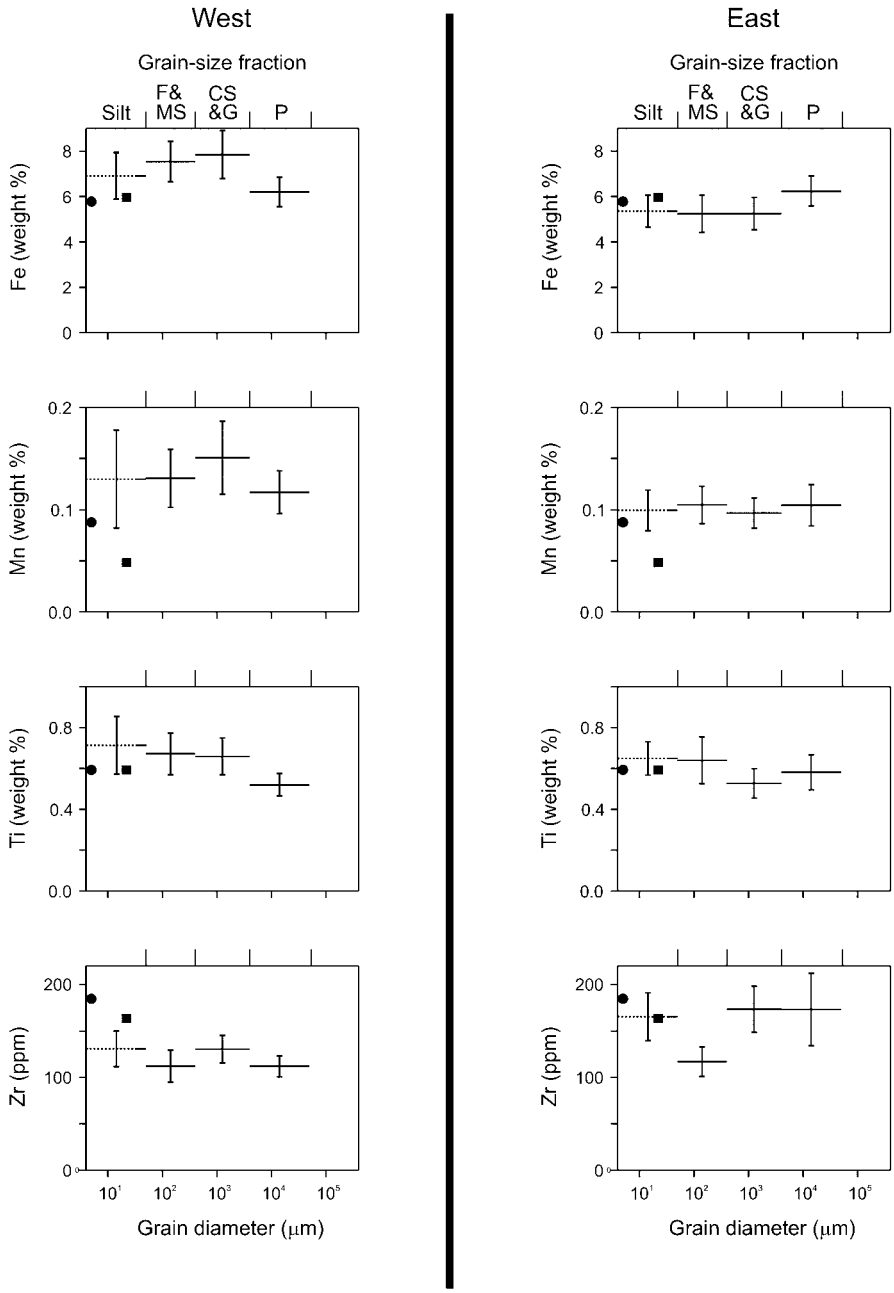

Figure 4. Average contents of Fe, Mn, Ti, and Zr in catchment samples (horizontal bars), and for glacial flour (circle) and non-glacial lithic material (square) in cored sediment samples from Upper Klamath Lake (see Rosenbaum and Reynolds 2004 – this issue). Vertical bars indicate 95% confidence intervals. The extents of the horizontal bars indicate grain-size ranges; dashed line for the silt fraction indicates that the grain size distribution of this fraction is probably heavily skewed to the coarse end of the range.

silt fraction. The fine magnetic grain sizes of the silt fractions are strongly expressed by the ARM/MS values, which are higher for the silt fractions than for any other sediment size category.

The amount of hematite relative to magnetite, indicated by the *S* parameter, progressively increases with decreasing grain size. The changes in *S* are due entirely to changes in magnetite content because *S* increases with increasing magnetite content (IRM) and hematite content (HIRM) does not vary significantly.

Geochemical data

In comparison to magnetic properties, concentrations of Ti, Mn, Fe, and Zr display little variation among the grain size fractions. Mean values of Ti do increase somewhat with decreasing grain size, but, given the size of the 95% confidence intervals, the trend is probably not significant (Figure 4). One point of note, however, is the low Zr content of the F&MS fraction for the east-side samples.

Petrographic observations

The volcanic rocks have a wide variety of textures, but in general contain groundmass, consisting of glassy to finely crystalline material, and phenocrysts. Most silicate phenocrysts have maximum dimensions <500 μm. Magnetite and titanomagnetite occur as somewhat smaller phenocrysts (maximum dimension typically ≤ 200 μm), as small crystals in the groundmass, and as tiny to large inclusions in silicate minerals.

Polished thin sections from the F&MS and silt fractions contain mainly rock fragments, single-mineral grains (made up of all or part of a former phenocryst), and fragments of surficial deposits and soil consisting of very fine-grained sediment. Rock fragments were categorized as either 'oxidized' or 'fresh' on the basis of appearance. Oxidized fragments were reddened throughout by an abundance of fine-grained hematite and commonly contained grains of specular hematite, whereas fresh fragments contained observable magnetite particles and lacked a red groundmass. For each site, the number of oxidized rock fragments is significantly greater in the silt fraction than in the F&MS fraction (Figure 5).

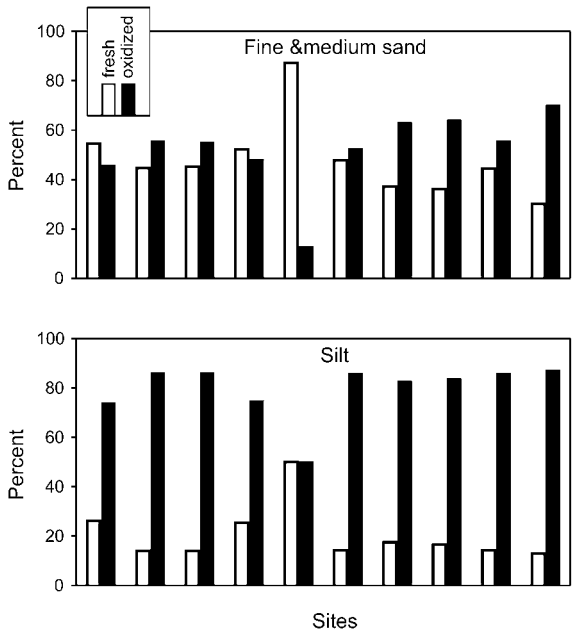

Figure 5. Percentages of fresh and oxidized rock fragments in the fine and medium sand fraction and in the silt fraction of samples from ten catchment sites.

Interpretation of catchment data

Three petrographic observations are important for interpreting the climatic implications of the magnetic property data: (1) the silt fraction contains a greater percentage of oxidized rock fragments than the F&MS fraction; (2) most phenocrysts are smaller than the lower bound (0.4 mm) of the CS&G fraction; and (3) tiny magnetite grains occur as inclusions in silicates. The first of these observations supports the major hypothesis of this study, that finer grain sizes are on average more weathered than coarser grain sizes. The second observation indicates that the three coarsest size fractions (B, P, and CS&G) are comprised entirely of rock fragments, so that differences among these size fractions cannot be produced by mineralogical sorting. The third observation indicates that some of the very fine-grained magnetite may be protected from the effects of weathering.

We therefore interpret general trends in magnetic properties that extend over the B, P, and CS&G grain sizes to reflect differences in the degree of weathering. With decreasing bulk sediment grain size, these trends show a decrease in the

quantity of magnetite, an overall increase in magnetic grain size, and a decrease in magnetite relative to hematite. The results indicate that weathering destroys magnetite, with smaller grains being more readily destroyed than larger ones. Preferential alteration of fine-grained magnetite should have a greater impact on IRM than on MS as is observed (Table 1 and Figure 3). Such alteration, however, should have an even larger effect on ARM than on IRM but this is not observed. Apparently, a significant proportion of the finest-grained magnetite is somehow protected from alteration, perhaps as inclusions in silicate minerals. Although petrographic observations of reddened rock fragments indicate that hematite has been produced during weathering, hematite content, as measured by HIRM, is not elevated in the smaller grain sizes. Either the quantity of hematite produced by weathering is insignificant in comparison to hematite produced during initial cooling of the volcanic rocks, or much of the hematite produced by weathering is too fine grained to carry remanent magnetization.

Not all of the magnetic property data can be explained by preferential destruction of fine-grained magnetite in more highly weathered (i.e., smaller) particles. The effects of mineralogical sorting are evident in both the geochemical and magnetic property data. Zircon does not occur as phenocrysts in the volcanic rocks, and Zr therefore must occur mostly in the groundmass. For the east-side samples, the low value of Zr in the F&MS fraction (Figure 4) reflects concentration of large mineral grains (broken and intact former phenocrysts), and therefore depletion of groundmass, in this size fraction. MS values of these samples are higher than for the CS&G fraction, whereas IRM and ARM are roughly equal for the two fractions (Figure 3B). The Zr data reflect concentration of all types of large mineral grains in the F&MS size fraction, whereas magnetic properties reflect enrichment of large magnetite grains. Because the large magnetite grains are multi-domain, they raise MS but contribute little to either IRM or ARM. Similar mineralogical sorting has probably affected the west side samples, but to a lesser extent.

Mineralogical sorting also affects indicators of magnetic grain size. The coarse magnetic grain size of the F&MS fraction (low values of IRM/MS and ARM/MS) is the combined result of destruction of fine-grained magnetite by weathering and concentration of coarse magnetite grains. Coarse mineral grains are concentrated in the F&MS fraction and are therefore depleted in the silt fraction so that in the smaller fraction the effects of weathering and mineralogical sorting are in opposition. The trend toward coarser magnetic grain size with decreasing particle size is reversed in the silt fraction because the effects of weathering are more than offset by depletion of coarse-grained magnetite. That is, higher values of ARM/MS and IRM/MS in the silt fraction reflect the presence of fine-grained magnetite in samples relatively depleted in coarse magnetite grains.

MS, IRM, and ARM values of the stream sediments are affected to varying degrees by weathering, by mineralogical sorting, and by differences in composition. Concentration or removal of coarse, multidomain magnetite has a large effect on MS but little effect on either IRM or ARM. IRM appears to be more sensitive to alteration than ARM because very fine-grained magnetite, which contributes strongly to ARM, is apparently in part protected from alteration. Therefore, the S parameter, which is derived from the IRM measurements and is independent of magnetite concentration, is probably the best measure of weathering. The effect of differences in composition on values of S is unclear. For each grain-size fraction, average values of S for the west-side sites are slightly greater than average values for the east-side sites (compare Figure 3A and B). These small but consistent differences could reflect either (1) a lower degree of weathering of rocks on the relatively steep west side of the lake relative to rocks on the east side, or (2) the more mafic composition of west-side rocks relative to east-side rocks.

Properties of lake sediment components

Magnetic properties of glacial flour and of non-glacial lithic material in the Upper Klamath Lake sediments differ significantly from those of the catchment samples (Table 1 and Figure 3). Rosenbaum and Reynolds (2004 – this issue) interpret the glacial flour to be comprised of fresh highly magnetic volcanic rock particles, and the non-glacial material to be less magnetic weathered volcanic clasts. The glacial flour is very fine silt (median grain size of ≈ 5 μm) derived from

glaciated drainages on the west side of the lake (Figure 1), and the non-glacial material is coarser silt (median grain size $\approx$24 μm) derived from both east-side and west-side streams. The non-glacial component of the lake sediments is probably finer grained than the silt fraction, but direct grain-size comparisons of the lake and stream sediments are not possible because grain-size distributions were not obtained for the stream sediments.

Three factors contribute to the observed differences between the non-glacial component and the silt fractions of the stream sediments. First, non-glacial material is a mixture from sources (in unknown proportions) on the east side and west side of the lake. Second, bulk sediment grain-size distributions of the sediment types differ. Third, the non-glacial component has been affected by mineralogical sorting during suspension and subsequent deposition in the lake, with coarser mineral grains having been preferentially removed. The effects of these factors cannot be fully separated.

Determining the ratio of east-side and west-side material in the non-glacial component is problematic. Comparisons of Zr concentrations suggest that the non-glacial component is derived largely from east-side rocks (Figure 4), whereas comparisons of HIRM values suggest that about 75% of the non-glacial component was derived from the west-side streams (Figure 3 and Table 1). If east-side material is dominant, then hematite was concentrated by mineralogical sorting. If west-side material is dominant, then elevation of Zr relative to the west-side rocks indicates depletion of coarse mineral grains and concentration of groundmass.

In any case, the low value of the *S* parameter for the non-glacial component of the lake sediments indicates that magnetite in this component is more highly weathered than in the most weathered size fraction (silt fraction) of the catchment samples (Figure 3). MS, ARM, and IRM values indicate that magnetite of all magnetic grain sizes is depleted in the non-glacial material by a small amount relative to the east-side silt fraction, or by a much larger amount relative to the west-side silt fraction. If this depletion were due to increased weathering (because of smaller bulk sediment grain size) alone, the non-glacial component should have coarser magnetic grain sizes (smaller values of IRM/MS and ARM/MS) than the silt fractions. This is not the case; therefore, the magnetite depletion must be due to mineralogical sorting that removes coarser magnetite grains, or to a combination of mineralogical sorting and a higher degree of weathering.

The origin of the magnetic properties of the glacial flour is more straightforward. This component was derived solely from the west-side streams (Figure 1). The *S* parameter indicates that glacial flour is unweathered (Figure 3), and differences in magnetic and chemical properties between glacial flour and unweathered material in the stream sediments (B and P fractions) are largely due to mineralogical sorting during fluvial transport and deposition in the lake. Loss of some fine-grained magnetite is indicated by an IRM value for the glacial flour that is 83% of that for unweathered catchment material. Because mineralogical sorting should remove coarser grained magnetite more efficiently than finer grained magnetite, sorting should lower MS by an amount equal to or greater than the reduction in IRM. MS, however, is about 15% higher in the glacial flour than in the coarse stream sediments. A possible reason for this elevated value of MS is presented in the following discussion.

The greatest difference between the glacial flour and unweathered catchment rocks is in the ARM values. ARM of glacial flour is nearly three times that of the B and P fractions indicating that the glacial flour contains a great deal more extremely fine-grained magnetite. Either extremely fine-grained magnetite that formed in the volcanic rocks has been highly concentrated, or similarly fine-grained magnetite (e.g., biogenic magnetite) has formed in the sediments within the lake. Rosenbaum and Reynolds (2004 – this issue) calculated the contents of glacial flour in Upper Klamath Lake sediments based independently on MS, ARM, and bulk sediment grain size. Variations in glacial flour content were essentially identical regardless of the method used. Therefore, the high ARM is most likely due to magnetite in the rock flour, and not to a later addition of biogenic magnetite to the sediment. In addition, the Zr concentration in the glacial flour is significantly higher than in the west-side stream samples (Figure 4), indicating that groundmass has been concentrated due to loss of coarse mineral grains. We therefore conclude that (1) the extremely fine grained magnetite, which contributes strongly to ARM in the volcanic rocks, occurs mostly in the groundmass,

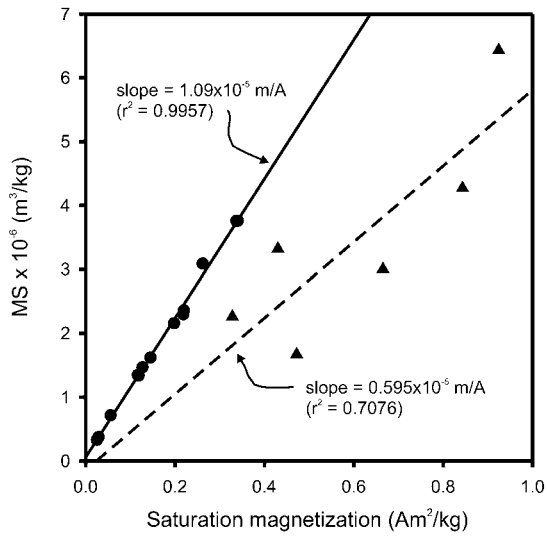

Figure 6. Magnetic susceptibility (MS) *versus* saturation magnetization for lake sediment samples (circles) and the pebble fraction from six catchment sites (triangles).

perhaps as inclusions in microcrystals of silicate minerals (e.g., plagioclase), and (2) this material has been highly concentrated by mineralogical sorting during suspension and deposition in the lake.

The grain-size distribution of the extremely fine-grained magnetite includes a significant quantity of superparamagnetic grains ($\leq$0.03 μm). The frequency dependent MS (Thompson and Oldfield 1986) of glacial-age sediments in Upper Klamath Lake ranges between 3 and 5% (Rosenbaum et al. 1997) indicating the presence of superparamagnetic grains. Because superparamagnetic magnetite has a much higher MS than coarser-grained magnetite, even a small amount of superparamagnetic material would increase the MS of the lake sediments. This possibility is strongly supported by the observation that MS is much higher in the lake sediments than in the catchment rocks relative to the quantity of magnetite (indicated by saturation magnetization) (Figure 6). Therefore, the high MS of glacial flour relative to catchment rocks results from the concentration of superparamagnetic magnetite in sediment that more than offsets the loss of coarse-grained magnetite.

Summary

Fresh volcanic rocks in the catchment of Upper Klamath Lake contain abundant magnetite and titanomagnetite with a wide range of grain sizes, from submicroscopic superparamagnetic grains (<0.03 μm) to multidomain phenocrysts (>100 μm). Both weathering and mineralogical sorting play major roles in determining the amounts and grain sizes of magnetic minerals in lake sediments derived from these rocks.

The effects of sorting are most clearly seen by comparing the properties of glacial flour and catchment rocks. Although the glacial flour is unweathered, its magnetic properties differ significantly from those of fresh rocks. Mineralogical sorting removed much of the phenocrystic material, both silicates and Fe–Ti oxides, thereby concentrating the groundmass. The concentration of extremely fine-grained remanence carrying magnetite in the groundmass is sufficient to increase ARM values by a factor of three. The contribution of small amounts of superparamagnetic magnetite to MS is masked in the catchment rocks by the large quantity of coarse-grained magnetite, but this contribution is readily apparent in the glacial flour. Despite being depleted in coarse-grained magnetite, glacial flour has higher MS than fresh rocks because of the higher concentration of superparamagnetic material.

The non-glacial lithic component of the lake sediment has been affected by weathering as well as by mineralogical sorting. In large part the great differences between the magnetic properties of the glacial flour and non-glacial material can be attributed to the effects of weathering, although differences in source area may have additional effects. In general, weathering preferentially destroys fine-grained magnetite thereby increasing magnetic grain size. In this setting, the *S* parameter, which reflects changes in fine-grained magnetite and is minimally affected by mineralogical sorting, is an excellent measure of weathering, with *S* values decreasing as the degree of weathering increases.

Acknowledgements

We are grateful for the laboratory assistance of W. Rivers in making many of the magnetic measurements, and of F. Luiszer and J. Drexler for the geochemical analyses. The manuscript benefited from constructive reviews by H. Goldstein, J. Hagstrum, and W. MacDonald. We gratefully

acknowledge the use of the vibrating sample magnetometer at the Institute for Rock Magnetism, which is funded by the W.M. Keck Foundation, the National Science Foundation, and the University of Minnesota. This work was supported by the Earth Surface Dynamics Program of the US Geological Survey.

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