Record of middle Pleistocene climate change from Buck Lake, Cascade Range, southern Oregon—Evidence from sediment magnetism, trace-element geochemistry, and pollen

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ABSTRACT

Comparison of systematic variations in sediment magnetic properties to changes in pollen assemblages in middle Pleistocene lake sediments from Buck Lake indicates that the magnetic properties are sensitive to changes in climate. Buck Lake is located in southern Oregon just east of the crest of the Cascade Range. Lacustrine sediments, from 5.2 to 19.4 m in depth in core, contain tephra layers with ages of ≈300–400 ka at 9.5 m and ≈400–470 ka at 19.9 m. In these sediments magnetic properties reflect the absolute amount and relative abundances of detrital Fe-oxide minerals, titanomagnetite and hematite. The lacustrine section is divided into four zones on the basis of magnetic properties. Two zones (19.4–17.4 m and 14.5–10.3 m) of high magnetic susceptibility contain abundant Fe oxides and correspond closely to pollen zones that are indicative of cold, dry environments. Two low-susceptibility zones (17.4–14.5 m and 10.3–5.3 m) contain lesser amounts of Fe oxides and largely coincide with zones of warm-climate pollen. Transitions from cold to warm climate based on pollen are preceded by sharp changes in magnetic properties. This relation suggests that land-surface processes responded to these climate changes more rapidly than did changes in vegetation as indicated by pollen frequencies. Magnetic properties have been affected by three factors: (1) dissolution of Fe oxides, (2) variation in heavy-mineral content, and (3) variation in abundance of fresh volcanic rock fragments. Trace-element geochemistry, employing Fe and the immobile elements Ti and Zr, is utilized to detect postdepositional dissolution of magnetic minerals that has affected the magnitude of magnetic properties with little effect on the pattern of magnetic-property variation. Comparison of Ti and Zr values, proxies for heavy-mineral content, to magnetic properties demonstrates that part of the variation in the amount of magnetite and nearly all of the variation in the amount of hematite are due to changes in heavy-mineral content. Variation in the quantity of fresh volcanic rock fragments is the other source of change in magnetite content. Magnetic-property variations probably arise primarily from changes in peak runoff. At low to moderate flows magnetic properties reflect only the quantities of heavy minerals derived from soil and highly weathered rock in the catchment. At high flows, however, fresh volcanic rock fragments may be produced by breaking of pebbles and cobbles, and such fragments greatly increase the magnetite content of the resulting sediment. Climatically controlled factors that would affect peak runoff levels include the accumulation and subsequent melting of winter snow pack, the seasonality of precipitation, and the degree of vegetation cover of the land surface. Our results do not distinguish among the possible contributions of these disparate factors.

INTRODUCTION

In many different settings, the abundance, types, and magnetic grain sizes of magnetic minerals incorporated in sediments have varied in response to changes in climate. The influence of climate change on magnetic-mineral records is demonstrated by comparing magnetic parameters to geochemical and biological proxies for climate, as well as by spectral analysis of magnetic-property records that establishes correlation with orbitally driven climate cycles.

In deep-sea sequences, for example, strong correlations among magnetic-mineral abundance, oxygen isotopes, and calcium carbonate content have been related to the concentration and dilution of magnetic minerals caused by climatically controlled variations in carbonate accumulation (Kent, 1982; Robinson, 1986). In some cases magnetic properties that vary with oxygen isotopes have been shown to be independent of concentration-dilution processes, thus indicating an additional control of climate on fluxes and sources of terrigenous detritus, such as ice-rafted debris or eolian dust (Robinson, 1986; Bloemendal et al., 1988). Spectral analysis of magnetic-property profiles has further demonstrated the influence of orbital periodicities on magnetic mineralogy in deep-sea sediments (Mead et al., 1986; Bloemendal and deMenocal, 1989; deMenocal et al., 1991), in loess-paleosol sequences (Wang et al., 1992), and in thick lacustrine deposits in Lake Baikal (Peck et al., 1994).

The glacial-interglacial sediment record in Lake Baikal was inferred from a pattern of magnetic-property variations that indicates dilution of

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magnetite by biogenic production during warm intervals and enhanced eolian input during cold periods (Peck et al., 1994). In some other lakes the climate record expressed by magnetic properties has been established by comparison to pollen records (Snowball, 1993; Rosenbaum et al., 1994; Roberts et al., 1994; Thouveny et al., 1994). Such comparisons between magnetic properties and more direct climate indicators are essential, because factors other than climate can strongly influence the flux of magnetic minerals into lakes. Examples include tectonism (Colman et al., 1994), seismic events (Karlin and Abella, 1992), volcanism (Geirsdóttir et al., 1994), and changes in source areas (Colman et al., 1994).

If detrital minerals generate the dominant magnetic signals in lacustrine deposits, then the controls of climate on magnetic properties might arise from some combination of the following factors: (1) mechanical and chemical weathering processes in the catchment that influence the amounts, types, sizes, and availability of the detrital iron oxides; (2) hydrodynamic response of the heavy minerals, which include the magnetic iron-titanium oxides, to processes (e.g., fluvial or eolian) and energies of sediment transport; (3) frequency and magnitudes of events capable of transporting the detrital heavy minerals; and (4) depositional conditions and energies that may concentrate or disperse heavy minerals. It follows that an important goal for environmental magnetic studies is to decipher in detail how climate affected catchment processes.

Postdepositional alteration, which may degrade or obscure any climate record initially carried by detrital iron oxides, includes both the production of new magnetic minerals as well as the destruction of detrital minerals. For example, the destruction of detrital magnetite by sulfidization (e.g., Reynolds, 1982; Canfield and Berner, 1987) or by reactions involving organic compounds that remove iron (Stone and Morgan, 1987) can affect magnetic properties that indicate the amount and magnetic grain size of magnetite (Karlin and Levi, 1985; Snowball and Thompson, 1990). The dissolution of iron oxide can also strongly influence parameters that indicate relative amounts of magnetite and hematite, if one or the other is preferentially attacked (Snowball, 1993). The degree of such alteration might be related to the abundance and types of detrital organic matter, and thus perhaps be indirectly related to climate to the extent that it controls the amount and type of plant cover in the catchment. Unfortunately, most magnetic measurements of bulk samples usually do not clearly reveal postdepositional diagenesis. For this reason, magnetic studies of paleoclimate would benefit from new diagnostic tests for detrimental alterations.

In this paper, we show that broad variations in magnetic properties of a middle Pleistocene lacustrine deposit at Buck Lake, Oregon, correspond closely to the pollen record, which broadly defines warm and cold periods. We demonstrate that these properties are controlled partly by variations in heavy minerals derived from soil and weathered rock in the watershed and partly by variations in the content of fresh volcanic rock fragments. We suggest that the contents of both heavy minerals and fresh rock fragments reflect variations in peak runoff that are climatically controlled. We also discuss two important differences between the magnetic and pollen records. First, the two records are partly offset, suggesting that weathering-sediment transport factors and plant cover responded to changes in climate over slightly different time frames. Second, the magnetic properties display high-frequency variations closely similar to the broad variations and thus imply a more detailed response to climate change than provided by pollen. We also use trace-element geochemistry to recognize postdepositional dissolution of detrital magnetic minerals and to explain how dissolution has affected some magnetic properties.

SETTING OF BUCK LAKE

Buck Lake, a roughly circular grass meadow ≈2.5 km in diameter, lies at an elevation of ≈1500 m just east of the crest of the Cascade Range, southern Oregon (Fig. 1). Ephemeral streams drain into the meadow from a small (≈60 km^2) catchment of low relief (<460 m) that contains a fir-dominated forest. Additional inflow comes from springs at the western margin of the basin. The lake basin drains to the east through a perennial outlet cut across a north-northwest–trending ridge, perhaps a fault block, that parallels fault structures in the region. Tectonic activity along this ridge may have affected lake levels and sedimentation. Mafic extrusive rocks, basaltic andesite and andesite in field terms, compose the dominant rock type in the catchment.

Neither ice nor glacial runoff directly affected the Buck Lake basin during the Quaternary. The closest late Pleistocene glacial deposits lie at an elevation of 1770 m in a separate drainage system ≈5.6 km to the northeast (Carver, 1972).

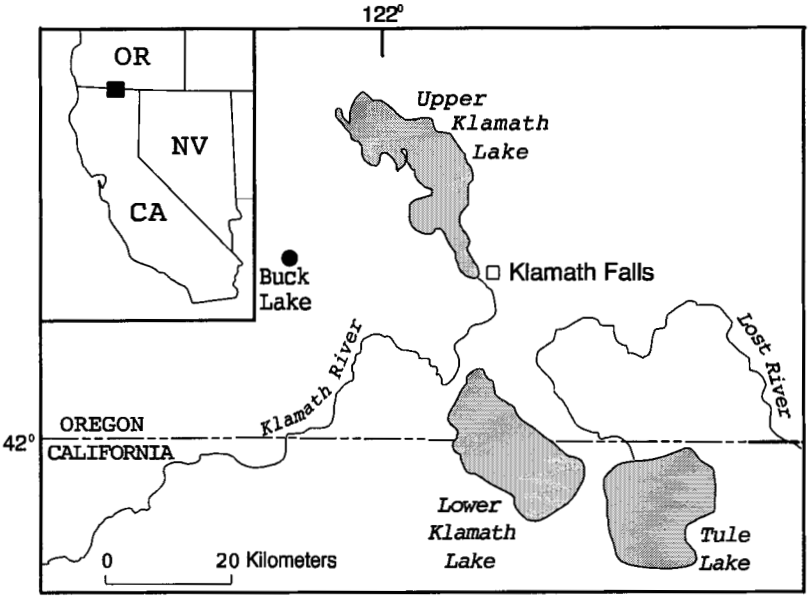

Figure 1. Map showing location of Buck Lake in south-central Oregon. (Note: The outlines of Lower Klamath Lake and Tule Lake are prior to reclamation.)

CORE LITHOLOGY, AGE, AND SAMPLING

Lithology

The 41.3-m-long core from Buck Lake was taken in two parts; the upper 4 m was taken using Shelby tubes and the interval below 5.26 m was taken using conventional rotary drilling methods. The coarse-grained interval between 4 and 5.26 m was not recovered. The coring operation was described by Adam (1993) and lithologic logs were presented by Adam et al. (1994).

Between 5.26 m and 19.4 m, the depths considered in this paper, the sediment is nearly uniform, consisting of mud with thin intervals of silty mud. Ca-rich plagioclase, the clay mineral halloysite, and cristobalite are the dominant minerals identified from X-ray diffraction analysis of the mud. Grain size analysis (between 0.2 and 50 µm) of 20 samples using an automated particle-size analyzer show subtle but systematic changes within this interval that were not detected by macroscopic core examination. Mossy laminae are found at depths between 10 and 13 m. Thin tephra beds, all <6 cm thick, make up <2% of the sediment column. Below 19.4 m, the sediment is characterized by mud and sandy mud, as well as by intermittent graded beds of cinders and tephra layers that are thicker than those above. Most sediment below ≈24 m consists of interbeds of mud with volcanic sand, as well as basaltic breccia and cobbles that represent debris flows. The bottom of the core consists of unweathered basaltic rock.

Age of Sediment

The age of the sediment is indicated by several tephra layers that are correlative with (1) the Rye Patch Dam ash bed (≈670 ka, 22.6 m), (2) the Lava Creek B ash bed (≈665 ka, 22.3 m; Izett et al., 1992), (3) the Dibekulewe ash bed (≈510 ka, 20.8 m, Rieck et al., 1992; Sarna-Wojcicki et al., 1993), (4) the Rockland ash bed (≈400–470 ka, 19.9 m; Meyer et al., 1991; Alloway et al., 1992), and (5) the Loleta ash bed–Bend pumice (≈350 ka, 9.5–9.6 m; Sarna-Wojcicki et al., 1989, 1991). Progressive alternating-field demagnetization of the natural remanent magnetization yields normal polarity paleomagnetic inclinations for >350 specimens down to a depth of 24.1 m, indicating deposition during the Brunhes normal-polarity chron (<780 ka).

Sampling

Plastic cubes (3.2 cm^3), marked with respect to the core top, were placed over pedestals of sediment carved from the core at 5 cm intervals between 5.26 and 24.1 m. The sediment displaced by carving each specimen represented a 2–4 cm interval, centered on the middle of the plastic cube, and was put into a vial for other analyses, including geochemical analysis. At ≈1 m intervals, a sample of 10–20 g was collected over an interval of 10–20 cm for magnetic mineral separations.

METHODS

A combination of magnetic, petrographic, and geochemical methods was used to determine the amounts, types, and magnetic grain sizes of magnetic minerals, to identify variations in heavy-mineral content, and to decipher the origins and possible postdepositional alteration of the magnetic minerals. Common magnetic minerals can be placed in two groups; low coercivity ferrimagnetic minerals (e.g., magnetite, titanomagnetite, and maghemite), and high-coercivity ferric oxide minerals (e.g., hematite and goethite). Here we use the terms magnetite and hematite, because results presented later indicate that titanomagnetite and hematite are the dominant magnetic minerals in the Buck Lake sediment.

The concentration of magnetite was estimated using magnetic susceptibility (MS). MS was measured with a susceptometer operating at 600 Hz and an induction of 0.1 milliTesla (mT). MS values can also be influenced by grain size of magnetite or by iron-bearing paramagnetic minerals such as ilmenite and siderite, especially when the magnetite content is low. To test for these possibilities, we compared MS with saturation magnetization measured using a vibrating sample magnetometer for a subset of the samples.

Magnetic mineral content can also be estimated from isothermal remanent

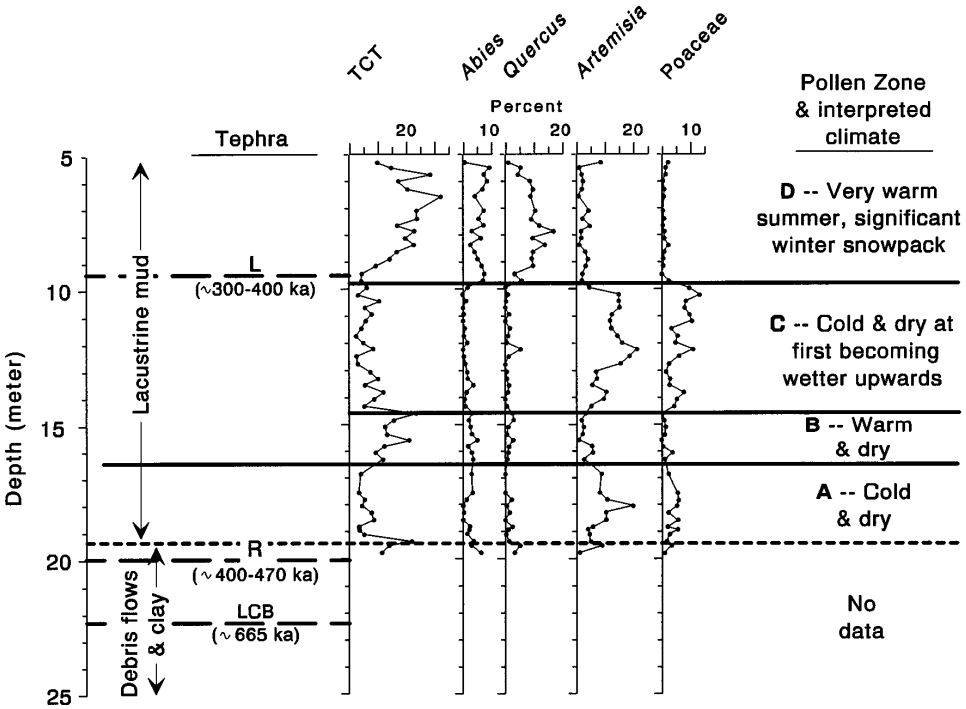

Figure 2. Summary of lithology, tephrochronology, and pollen in core from Buck Lake, Oregon. L, R, and LCB indicate the positions of tephra correlative with the Loleta ash bed–Bend pumice, the Rockland ash bed, and the Lava Creek B ash bed, respectively. Climate interpretations within the lacustrine muds are inferred from the pollen record, from which TCT (Taxodiaceae-Cupressaceae-Taxaceae), *Abies*, *Quercus*, *Artemisia*, and Poaceae are shown.

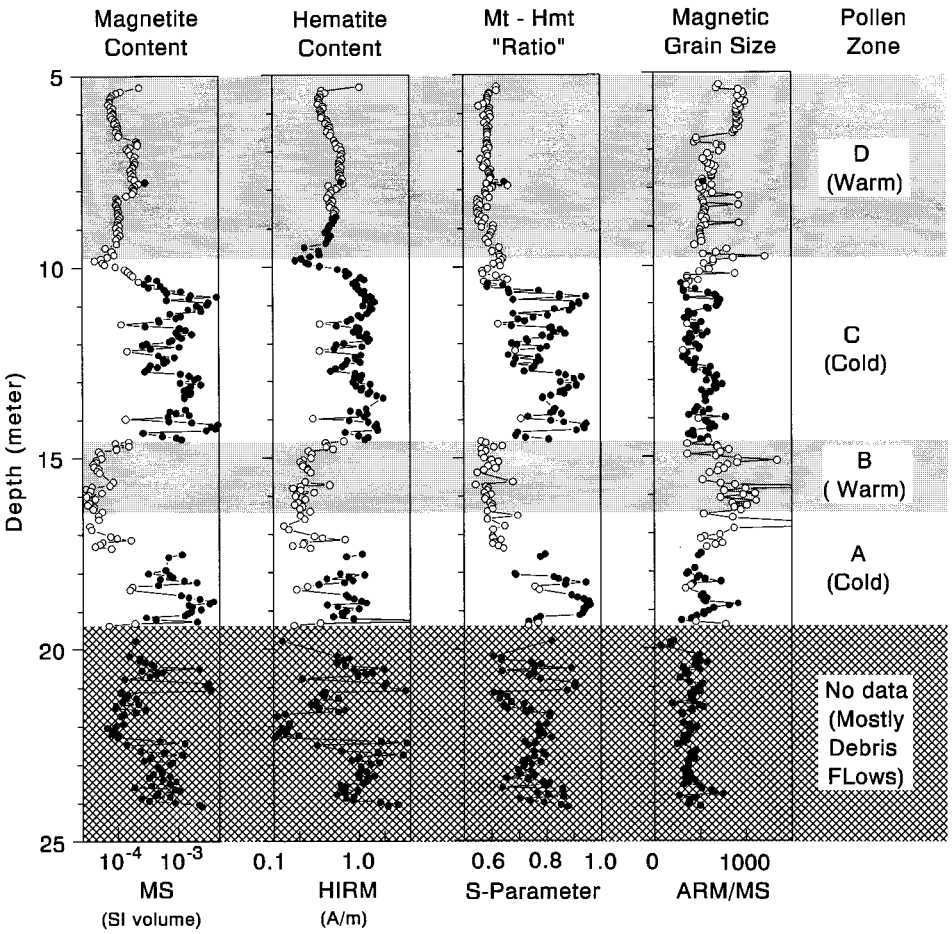

Figure 3. Plots of magnetic properties with depth. Magnetic susceptibility (MS) is primarily a measure of magnetite content. Within the lacustrine muds (above 19.4 m) solid and open symbols distinguish between high and low MS zones, numbered 1 through 4, described in the text. "Hard" isothermal remanent magnetization (HIRM) is a measure of the concentration of high-coercivity magnetic minerals (e.g., hematite). The S parameter reflects the ratio of magnetite (Mt) to hematite (Hmt); higher values indicate relatively more magnetite. For magnetite-bearing sediments the ratio of anhysteretic remanent magnetization to MS (ARM/MS) is used as a measure of magnetic grain size. Higher values of this ratio commonly indicate smaller magnetic grain size, but high values may also arise from low ratios of magnetite to hematite. Pollen zones are as in Figure 2.

magnetization (IRM; Thompson and Oldfield, 1986; King and Channell, 1991). IRMs were imparted in a forward induction of 1.2 T ($IRM_{1.2}$) and a backfield (oppositely directed induction) of 0.3 T ($IRM_{-0.3}$) in an impulse magnetizer and were measured using a spinner magnetometer. Magnetite saturates below 0.3 T, so that differences in IRM between 0.3 T and 1.2 T are caused by hematite. The quantity HIRM (for "hard" IRM, $[IRM_{-0.3} + IRM_{1.2}]/2$) is thus a measure of hematite. The ratio, $-IRM_{-0.3}/IRM_{1.2}$, called the S parameter, is a measure of the proportion of magnetite to hematite. High S values indicate large amounts of magnetite relative to hematite (a maximum value of 1) and decreasing values indicate increasing proportions of hematite.

Information about the grain size of magnetite may be obtained from the magnitude of anhysteretic remanent magnetization (ARM), normalized by a measure of magnetite content such as MS (Banerjee et al., 1981). The ratio, ARM/MS, is affected not only by physical grain size, but also by grain shape, composition, mineral intergrowths, and the presence of other magnetic minerals. It is therefore important to distinguish between magnetic grain size as determined by magnetic properties and the actual physical size of magnetite particles. ARM was imparted in a decaying alternating field with a peak induction of 100 mT and a D.C. bias of 0.1 mT. The ratio ARM/MS increases as magnetic grain size decreases and is particularly sensitive to single domain and small pseudo-single domain grain sizes. Most hematite, which is weakly magnetic compared to magnetite, occurs as single domain grains (Thompson and Oldfield, 1986) that yield high ratios of ARM/MS. If the ratio of magnetite to hematite is so low that weakly magnetic hematite contributes substantially to ARM, then interpretations of ARM/MS in terms of magnetite grain size may not be possible.

The identification of magnetic minerals inferred on the basis of bulk magnetic properties was supplemented by mineralogic studies of selected samples. Magnetic minerals separated from 26 bulk samples were used for (1) X-ray diffraction (XRD; using Cu-Kα radiation); (2) thermomagnetic analysis to determine Curie temperatures; and (3) petrographic examination of polished grains under reflected light. The separations were done by pumping a sediment slurry past a permanent magnet using a technique similar to that described by Petersen et al. (1986).

Energy-dispersive X-ray fluorescence analyses for Fe, Ti, and Zr, provide information about the distributions of detrital heavy minerals. Ti and Zr occur in heavy minerals (Ti in titanomagnetite, ilmenite, ilmenohematite, rutile, anatase, sphene, and others; Zr in zircon) and are immobile under most postdepositional conditions (see Winchester and Floyd, 1977). Variations in Ti and Zr therefore provide proxies for detrital heavy-mineral content at the time of deposition, and changes in the ratio of Ti to Zr may indicate changes in the source of detritus (Muhs et al., 1990; 1995). In contrast, magnetic Fe oxide minerals are relatively unstable, and Fe is relatively mobile under some common postdepositional conditions. For these reasons, comparisons among magnetic properties, Fe, Ti, and Zr elucidate both the detrital magnetic signal and postdepositional alteration.

CLIMATE RECORD FROM POLLEN

The lacustrine section can be divided into four zones using pollen percentages from 55 samples (Fig. 2). Pine pollen (not shown) predominates (40%–80%) throughout the lacustrine beds. The lowest zone (zone A, 20–16.5 m) is characterized by relatively high frequencies of sagebrush

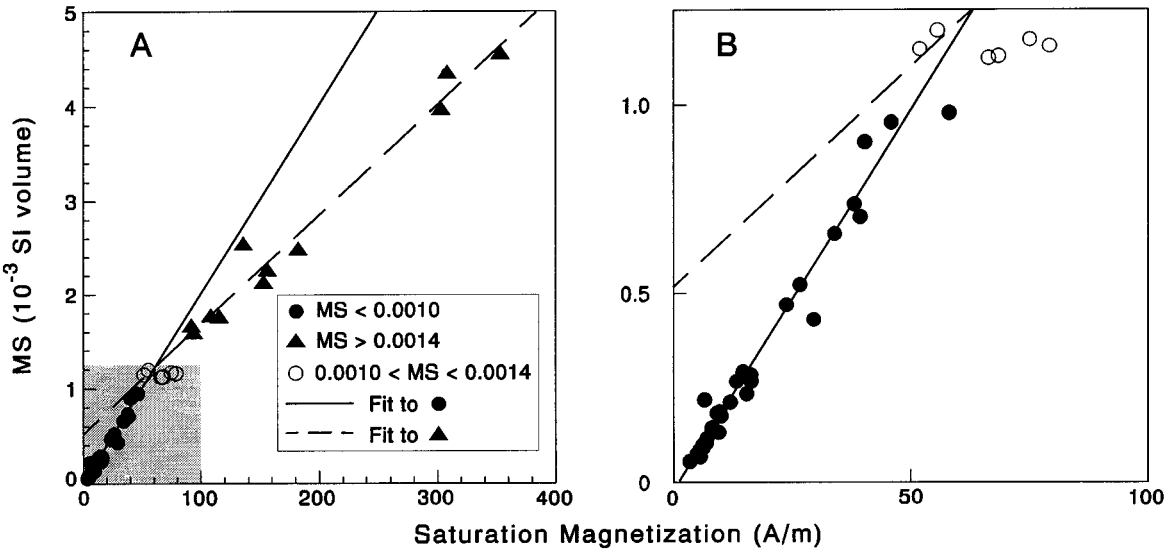

Figure 4. Magnetic susceptibility (MS) correlates strongly with saturation magnetization, indicating that MS is an acceptable measure of variations in magnetite content. B is an enlargement of the shaded area in A. Saturation magnetization is insensitive to magnetic grain size, whereas MS decreases with decreasing magnetic grain size (Thompson and Oldfield, 1986). The change in slope, at a saturation magnetization of ≈100 A/m, suggests that the more strongly magnetic samples contain finer magnetic grain sizes than the less-magnetic samples.

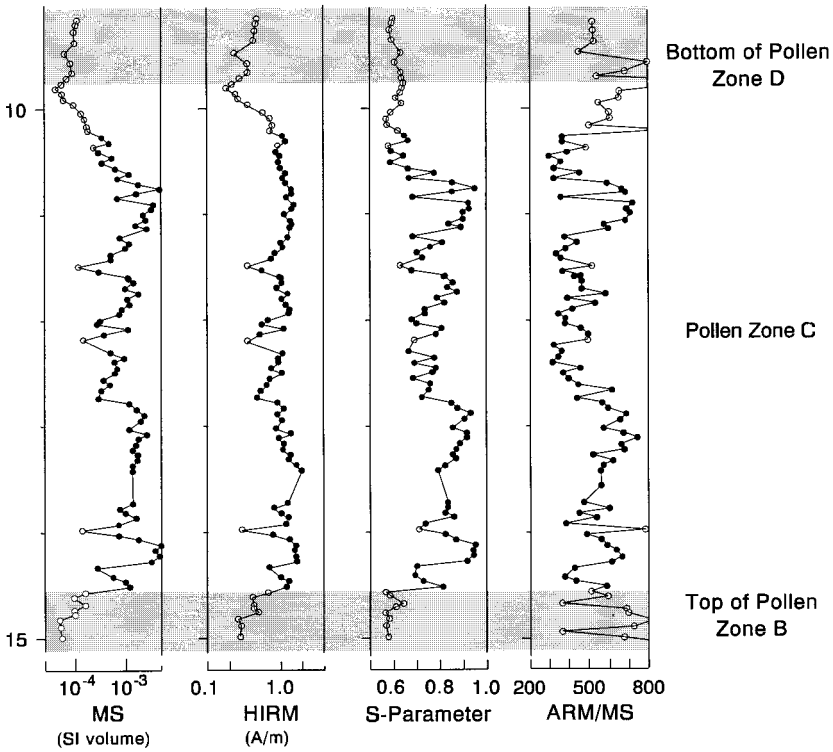

Figure 5. Expanded plots of magnetic properties with depth for magnetic susceptibility zone 3. Variables are as described for Figure 3. The lower shaded interval corresponds to pollen zone B; the upper shaded interval to pollen zone D.

(*Artemisia*) and grass (Poaceae) pollen. Zone B, between 16.5 and 14.5 m, has moderately high frequencies of Taxodiaceae-Cupressaceae-Taxaceae pollen (probably *Calocedrus* and/or *Juniperus*, 9%–23%) and low sagebrush and grass percentages. Zone C, between 14.5 and 9.8 m, shows high frequencies of sagebrush (≤21%) and grass (≤13%) and low frequencies of fir (*Abies*) and oak (*Quercus*), similar to the lowest zone. A peak in spruce (*Picea*) pollen (not shown) occurs near the top of the zone. The uppermost zone (zone D, 9.8–5.3 m) shows high frequencies of Taxodiaceae-Cupressaceae-Taxaceae (≤32%), oak (≤17%), and fir (≤9%) as well as low frequencies of sagebrush, grass, and spruce pollen.

Climatic interpretation of the zones from bottom to top indicates the following sequence: zone A, cold and dry; zone B, warm and dry; zone C, cold and dry at the beginning but wetter toward the top; and zone D, very warm in summer (warmer than present on the basis of the presence of sig-

nificant amounts of oak pollen), but with heavy winter snowpack as indicated by large amounts of fir pollen (see Adam, 1988; Adam and West, 1983). These pollen zones may correlate with deep-sea oxygen isotope stages. Neither the Rockland nor the Loleta ash, however, can be placed unequivocally in a specific oxygen isotope stage because of the large uncertainties in their ages (Fig. 2). Therefore, without better temporal control, it is not possible to test the hypothesis that the pollen stages are correlative with oxygen isotope stages.

MAGNETIC-PROPERTY VARIATIONS AND COMPARISONS WITH THE POLLEN RECORD

Magnetic Susceptibility

Broad variations define alternating zones of relatively high and low MS in the MS-depth profile (Fig. 3). From the bottom of the lacustrine beds, the zones are: high MS (zone 1; 19.4–17.4 m); low MS (zone 2; 17.4–14.5 m); high MS (zone 3; 14.5–10.3 m); and low MS (zone 4; 10.3–5.3 m). The boundaries between the zones were arbitrarily defined at the MS value of 2.5×10^{-4} (SI volume) midway on the transition from high MS zone 3 to low MS zone 4. This value also clearly separates low MS zone 2 from its bounding high MS zones.

Four other features of the MS results are noteworthy. First, the range of MS values is very great, covering about two orders of magnitude. Second, the high MS zones are characterized by well-defined MS variations having maxima $>10^{-3}$ and minima ranging below 2.5×10^{-4}. In contrast, the low MS zones are characterized by more uniform MS values. Third, the low MS zone 4 at the top can be separated into three intervals. A middle interval (8.15–6.65 m), characterized by relatively high MS, separates intervals having lower MS. Finally, MS values taken together show a strong positive correlation with saturation magnetization (Fig. 4). The change in slope illustrated in Figure 4 probably reflects differences in magnetic grain size between the more highly magnetic and less magnetic samples. Nevertheless, MS appears to be an acceptable measure of magnetite content.

Comparison of Magnetic Susceptibility with the Pollen Record

The four zones defined from MS correspond generally to the four zones defined from pollen frequencies (Fig. 3). High-MS zones 1 and 3 largely overlap respective pollen zones A and C that indicate cold and dry climate. Low-MS zones 2 and 4 largely overlap respective pollen zones B and D that indicate warm climate. The boundary between low MS zone 2 and high MS zone 3 coincides with the boundary between pollen zones B and C, representing a change from warm to cold climate. In contrast, the two changes from high to low MS precede the changes from cold to warm climate. This relation is clearly expressed at the change from MS zone 3 to zone 4, where the systematic decrease in MS begins ≈1 m below the boundary between pollen zones C and D. Although no such systematic decay in MS is found at the boundary between MS zones 1 and 2, the shift from high MS to much lower MS also occurs ≈1 m below the change in climate interpreted from pollen frequencies.

Other Magnetic Parameters

Changes in hematite content (HIRM), as well as in the relative amounts of magnetite and hematite (S parameter), coincide with changes in magnetite content (MS), in both long-term and short-term variations (Figs. 3 and 5). Although magnetite and hematite contents increase and decrease together (Fig. 6A), the relative amount of magnetite to hematite does not remain constant (Fig. 6B). As magnetite content increases, so does magnetite relative to hematite. A few exceptions to this general observation can be seen in the magnetic property-depth profiles: (1) at the top of MS zone 3 (Fig. 5), the decline in the S parameter (relative enrichment in hematite) appears more abrupt and occurs at greater depths than the declines in absolute amounts of magnetite (MS) and hematite (HIRM); (2) the small decrease in absolute magnetite content centered at 9.8 m is associated with an increase in relative magnetite content (S parameter; Fig. 5); and (3) the interval of slightly higher MS in the middle of low MS zone 4 near the top of the core lacks an expression in the S parameter (Fig. 3).

The ratio ARM/MS, used commonly to infer relative magnetic grain size, also varies with magnetite content but not in a simple manner. In general, average values of the ratio are lower in the high MS zones than in the low MS zones. ARM/MS decreases with relative depletion of magnetite for samples with S parameters >0.7, but ARM/MS varies greatly at lower S values (Fig. 6C). The high ARM/MS values in the low MS zones are probably strongly influenced by the dominance of hematite (S parameters less than ≈0.7) in these zones and thus do not reflect magnetic grain size of magnetite. In the high MS zones that contain relatively more magnetite, however, ARM/MS can be used to infer magnetic grain size of the magnetite. In these zones, smaller magnetic grain size (higher ARM/MS ratio) corresponds to greater amounts of magnetite, both absolute and relative to hematite (Figs. 5 and 6C).

Magnetic Properties as a Record of Climate Change at Buck Lake

The close correspondences between the magnetic properties and the pollen zones strongly suggest that the magnetic record reflects climate. If so, high MS reflects cold and dry conditions, whereas low MS reflects warm conditions in this setting. The different positions of the magnetic-property and palynological boundaries, which represent cold to warm transitions, might then reflect different temporal responses to climate of the dominantly physical and biological processes that controlled magnetic mineralogy and plant cover, respectively.

CAUSES FOR MAGNETIC-PROPERTY VARIATIONS

To maximize the usefulness of magnetic-property variations as a record of climate change, it is important to understand how the magnetic properties are related to processes in the watershed and to recognize any effects of postdepositional alteration. First, we identified the magnetic minerals and assessed their origins, whether detrital or authigenic. Second, we compared variations in magnetic parameters and Fe content to geochemical results that indicate variations in the flux of detrital heavy minerals.

Evidence for Detrital Magnetic Record

The presence of magnetite and hematite in magnetic separates is confirmed by combined XRD, thermomagnetic, and petrographic analyses. Siderite occurs sporadically but mostly in the high MS zones, and, on the basis of textural evidence from scanning electron microscope (SEM) examination, appears to have formed after deposition. Greigite, the ferrimagnetic iron sulfide (Fe_3S_4) that has been identified in some other lake sediments (Skinner et al., 1964; Hilton, 1990; Dell, 1972; Snowball, 1991; Snowball and Thompson, 1990), is absent.

The composition, texture, and occurrences of magnetite from Buck Lake indicate a detrital origin. Curie temperature determinations reveal that ferrimagnetic grains are Ti-bearing magnetite, with Curie temperatures between 510 and 550 °C (Fig. 7). The Ti-bearing magnetite was derived from igneous rocks, in which Ti is incorporated into magnetite during initial

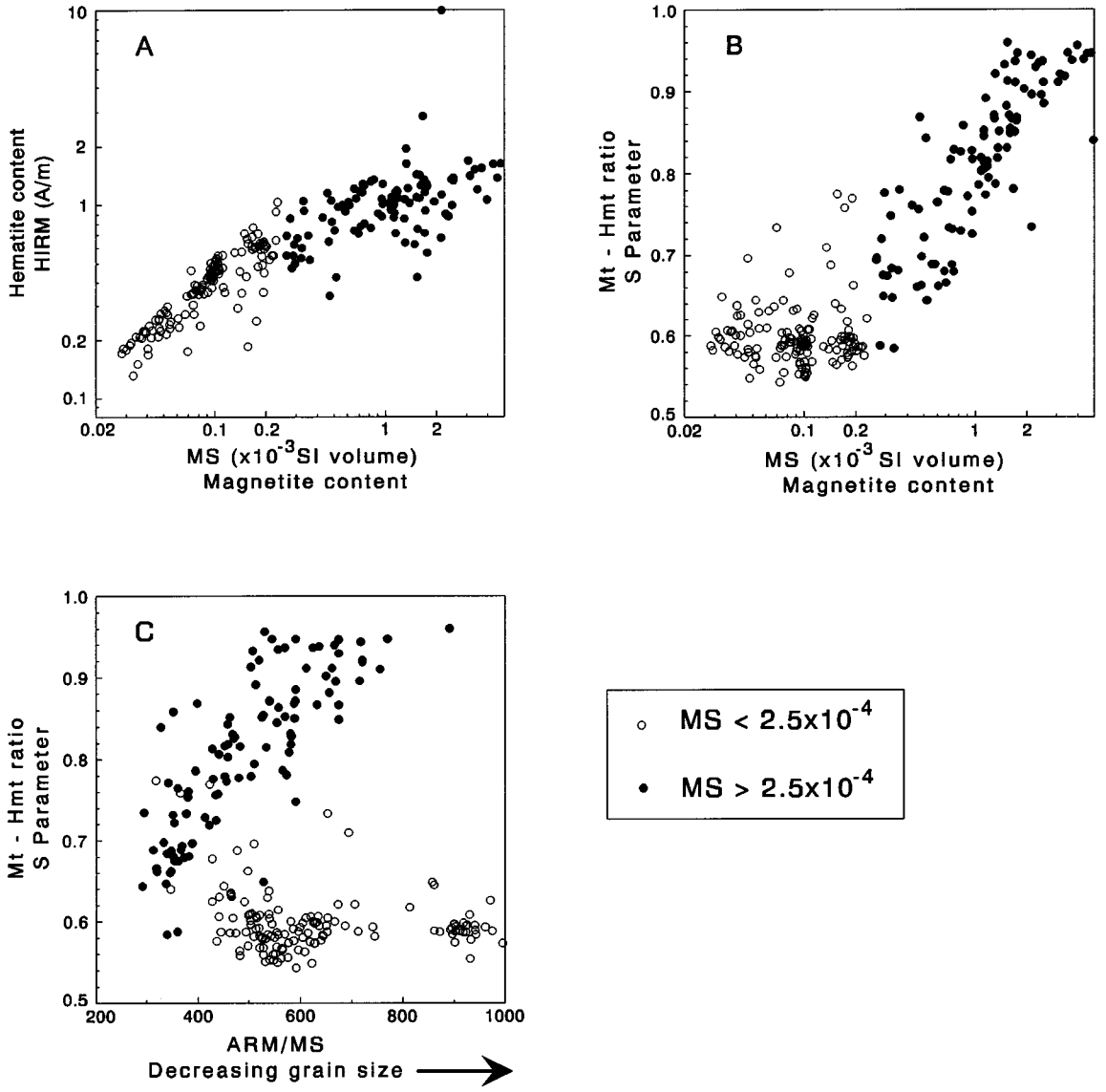

Figure 6. Plots of "hard" isothermal remanent magnetization (HIRM) and S parameter versus magnetic susceptibility (MS), and of the S parameter versus the ratio of anhysteretic remanent magnetization (ARM) to MS (see text and Figure 3 for descriptions of these parameters). (A) Hematite generally increases as magnetite increases. (B) The ratio of magnetite to hematite increases as the amount of magnetite increases. (C) For values of S parameter above ≈0.7, magnetic grain size decreases as magnetite content increases. For lower values of S parameter, values of ARM/MS probably reflect high hematite content rather than magnetic grain size.

crystallization. Nearly all petrographically observed magnetite grains occur in some association with titaniferous minerals. Many particles consist of magnetite with ilmenite or TiO_2 lamellae on the {111} crystallographic planes (Fig. 8A). Such metatitanomagnetite grains result from high-temperature oxidation during initial cooling (e.g., Haggerty, 1976). Other common occurrences of detrital magnetite grains, which range from≈2 µm (the lower limit of our optical capacity for mineral identification) to nearly 100 µm, include those surrounded by a TiO_2 margin, those associated with spinel, and those within igneous rock fragments (Fig. 8B). The dominance of titaniferous magnetite indicates that bacteriogenic magnetite (Lovley et al., 1987; Petersen et al., 1989; Snowball, 1994), which may form in the water or sediment column and which lacks titanium, does not contribute significantly to the magnetic record.

The close positive correlation between magnetite and hematite contents (compare MS and HIRM, Figs. 3, 5, and 6) strongly implies that hematite did not form at the expense of magnetite via postdepositional oxidation, but is instead detrital. This implication is supported by the excellent preservation of pollen; any oxidation sufficiently severe to have produced diagenetic hematite from magnetite would probably also have degraded pollen grains. The correlation between magnetite and hematite contents further suggests that both minerals responded to sediment transport processes as heavy minerals having similar specific gravities. The occurrences of hematite are similar to those of magnetite. Hematite, which formed in the source rocks during initial cooling, is found in the Buck Lake sediment as primary intergrowths with ilmenite as well as within metatitanomagnetite grains and by itself in association with related primary oxidation phases, such as rutile, pseudo-

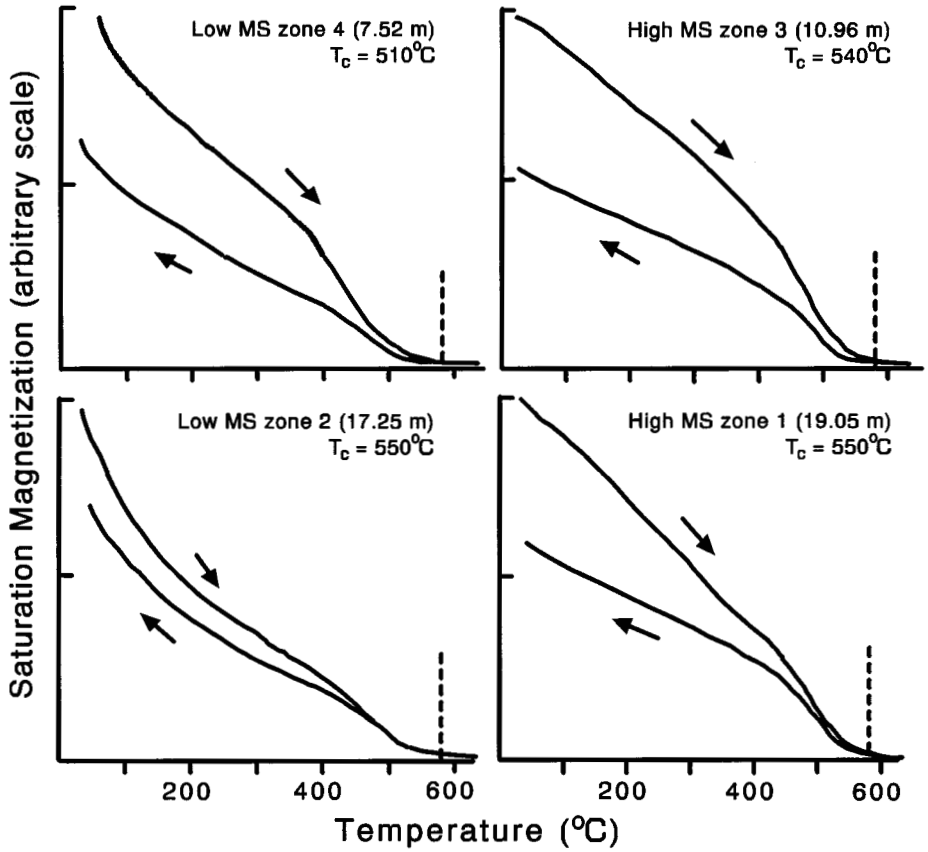

Figure 7. Saturation magnetization versus temperature curves for magnetic separates. The measured Curie temperatures (T_c), determined from the heating curves, are all significantly lower than the Curie temperature of pure magnetite, 580 °C (indicated by the dotted lines), and therefore indicate the presence of titanomagnetite.

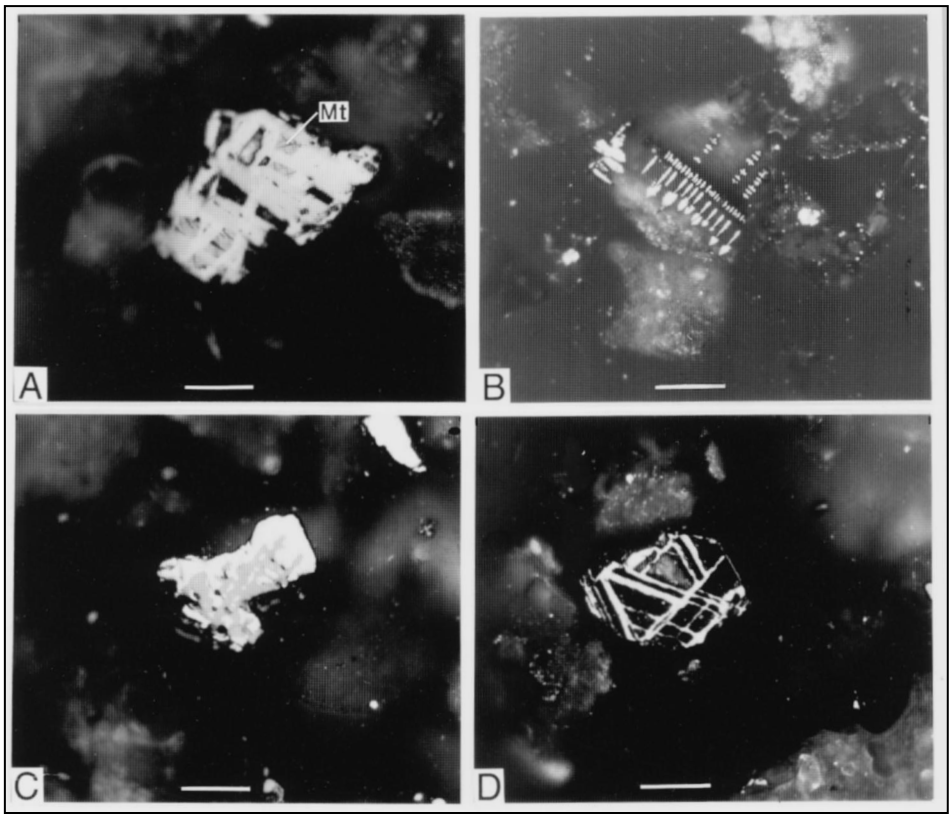

Figure 8. Reflected-light photomicrographs of iron-titanium oxide particles from Buck Lake in polished grain mounts. (A) Zones of magnetite (Mt) with pleonastic spinel (thin black intergrowths) are cut by lamellae of ilmenite formed from high-temperature oxidation during initial cooling. (B) Skeletal magnetite in igneous rock fragment. (C) Grain of hematite (white) and probable pseudobrookite (gray) that resulted from high-temperature oxidation. (D) Former titanomagnetite grain from which magnetite zones have been removed by alteration, leaving ilmenite lamellae in a distinctive trellis pattern. Scale bars represent 20 μm in all photomicrographs.

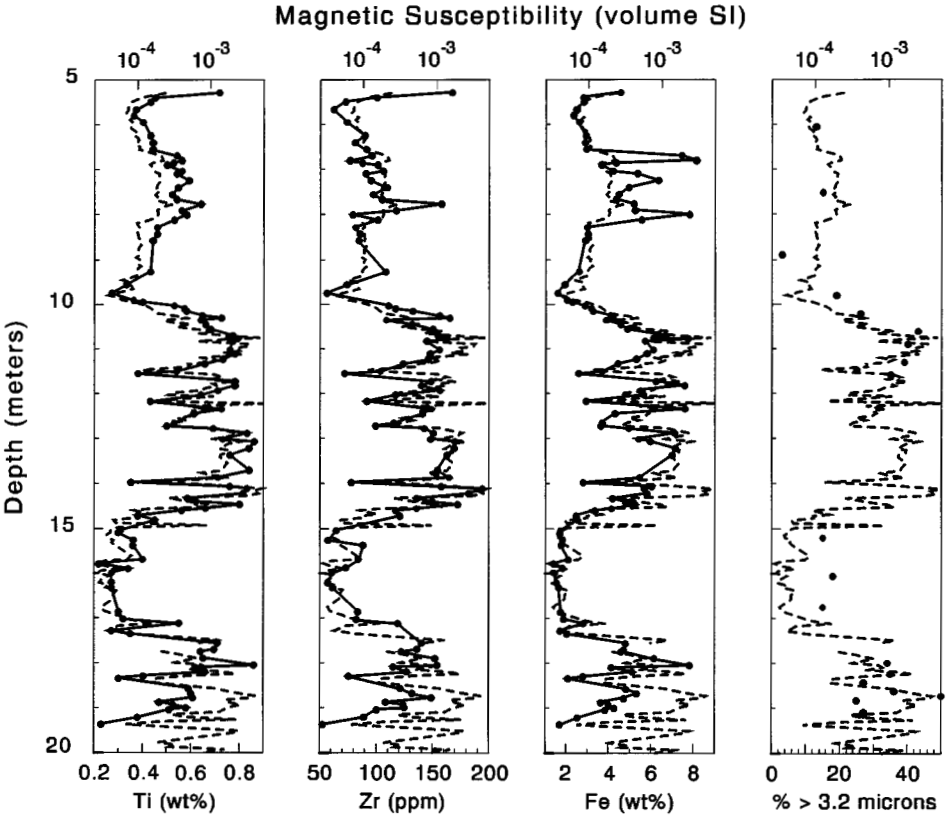

Figure 9. Plots of Ti, Zr, Fe, and bulk grain size with depth. Magnetic susceptibility (MS) is shown as a dotted line on each plot. There is great similarity between variations in heavy mineral input to the sediments, as indicated by Ti and Zr, and variations in MS. Note, however, that MS (plotted on a logarithmic scale) varies by nearly two orders of magnitude, whereas the elemental data vary by a factor of about three. Coarser bulk sediment grain size corresponds to high magnetic and heavy-mineral content.

brookite, and ilmenorutile (Fig. 8C). Hematite is found within rock fragments in each of these occurrences and as separate grains. At least some hematite, perhaps large quantities, formed in the catchment by oxidation of magnetite in surficial weathering environments. Such hematite includes specularite particles and hematite that replaced magnetite, found as solitary grains or within rock fragments, especially near their margins.

Conclusive evidence that the magnetic record is a detrital one comes from a comparison of the variations in the concentrations of magnetic minerals and variations in Ti and Zr (Fig. 9). There is a strong linear correlation between Ti and Zr (Fig. 10A), indicating that changes in both Ti and Zr record changes in the input of heavy minerals. The contents of Ti, Zr, and Fe vary closely with variations in MS (Fig. 9). In fact, the changes in Ti content and MS are nearly coincident over the entire sequence. Zr and Fe contents also vary with MS in great detail, except in the middle interval (8.15–6.65 m) of low MS zone 4 where the amplitude of change appears suppressed for Zr and enhanced for Fe, relative to the association between Ti and MS. The strikingly close chemical-magnetic relations indicate that the variations in MS, even the fine-scale variations, represent changes in the input of detrital magnetite. Similarly, the variations in hematite (HIRM) and in the relative abundances of magnetite and hematite (S parameter) reflect changes in the flux of detrital oxide minerals.

Bulk sediment grain size appears to change in correspondence with changes in heavy mineral content (Fig. 9). Relatively higher proportions of silt in the mud characterize the zones of high MS and high Ti and Zr contents, whereas lower silt proportions characterize zones of low MS and low Ti and Zr contents.

Heavy-mineral content and sediment grain size may reflect either changes in lake level or changes in the detritus delivered to the lake by alluvial processes. Higher depositional energies at the core site, a possible effect of lower lake levels, would result in higher concentrations of heavy minerals and coarser grain size. Alternatively, variations in heavy-mineral content and grain size may reflect changes in alluvial transport energy.

Effects of Alteration

The magnetic and geochemical data, however, show a great disparity. The magnitudes of variations—that is, the relative differences between high and low values—in the contents of magnetite (MS) and hematite (HIRM) are much greater than those in contents of Ti and Zr (Figs. 9 and 10). Values of both Ti and Zr vary by a factor of about three. If the relative amounts of various heavy minerals remain constant, then the contents of magnetic Fe-oxide minerals would also vary by a factor of three. Instead, the relative amounts of magnetite and hematite vary, not only with respect to each other, but with respect to Ti and Zr. MS values vary by nearly two orders of magnitude, and HIRM values vary by a factor of about eight. Several mechanisms could contribute to this apparent enhancement of variations in magnetic mineral content, including (1) changes in provenance; (2) postdepositional destruction of some of the detrital magnetite and hematite; and (3) predepositional alteration of magnetic oxides that might affect the availability of magnetite and hematite for subsequent transport and deposition.

Geochemical data indicate little variation in the ratio of Ti to Zr (Fig. 10A). The observed relation is expected for detritus derived from one source area or from areas of similar composition. Changes in provenance (e.g., by changes in flux of eolian material) that produced large variations in the relative amounts of magnetic minerals would probably reflect large differences in bedrock composition. Therefore, changes in provenance are probably not an important factor in producing changes in the observed magnetic properties.

Postdepositional dissolution of Fe oxides is inferred from comparisons of Fe content and magnetic properties to Ti content (Fig. 10). For most

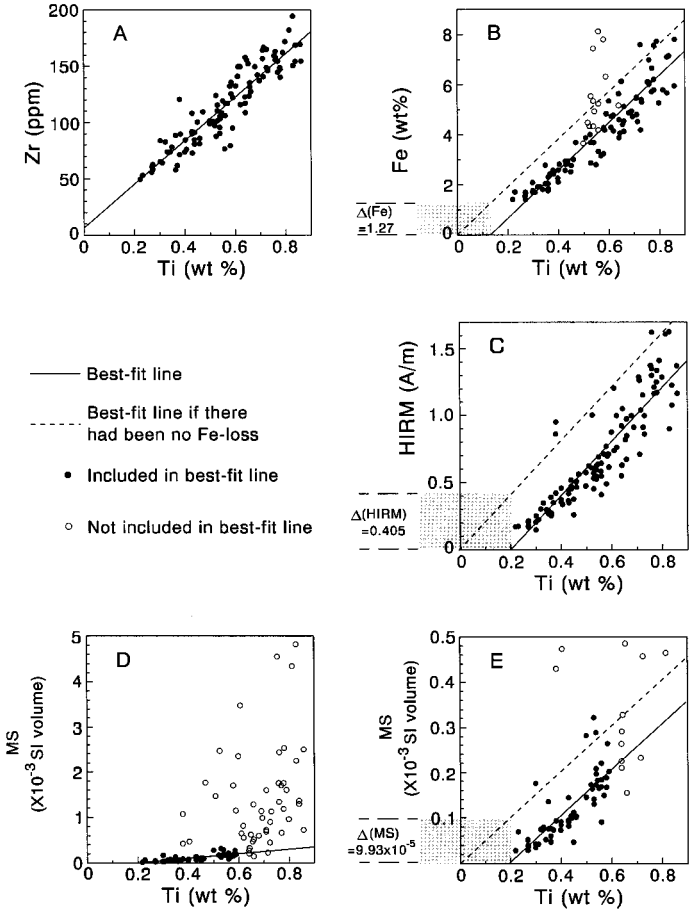

Figure 10. Plots of Zr, Fe, and magnetic properties versus Ti content. (A) A strong linear relation (R^2 = 0.82) that passes through the origin exists between Ti and Zr, which occur only in heavy minerals. Variations in these chemically immobile elements reflect changes in the quantity of heavy-mineral detritus derived from an unchanging source. (B) The best-fit line for Fe and Ti (R^2 = 0.81) does not pass through the origin. (Samples in the interval 8.15–6.65 m lie off this trend and were not included in the analysis.) The quantity Δ(Fe), which may be added to the Fe values to cause the best-fit line to pass through the origin, is interpreted as an estimate of postdepositional Fe loss. (C) A strong linear relation exists between "hard" isothermal remanent magnetization (HIRM) and Ti (R^2 = 0.80). Δ(HIRM) reflects postdepositional dissolution of hematite. (D and E) The relation between MS and Ti is complex. With few exceptions, samples with Ti content <0.6 wt% define a linear trend (R^2 = 0.49) that does not pass through the origin. Δ(MS) reflects postdepositional dissolution of magnetite. Samples with Ti contents >0.6 wt% contain highly variable amounts of magnetite.

samples there is a strong linear relation between Fe and Ti. In contrast to the relation between Ti and Zr, the best-fit line for Ti and Fe does not pass through the origin. The observed relation, a linear trend with a negative intercept on the Fe axis, is consistent with a postdepositional loss of a nearly constant amount of Fe (ΔFe ≈ 1.4 wt%). Samples between 8.15 and 6.65 m (the relatively high MS interval in zone 4) lie off this trend and have apparently retained or have been enriched in Fe. Similarly, a postdepositional loss of a constant amount of hematite may be inferred from the relation between HIRM and Ti. The relation between MS and Ti is more complex. A linear trend indicating significant loss of magnetite is apparent for samples with Ti contents less than ≈0.6 wt%; however, MS values for samples with higher Ti contents generally lie far above this trend.

It is instructive to compare variations in hematite and magnetite at the time of deposition to changes in heavy-mineral content. Values of HIRM and MS at the time of deposition can be calculated as the sum of the estimated postdepositional losses due to dissolution of Fe oxide, Δ(HIRM) and Δ(MS), and the observed values (Fig. 11). For purposes of comparison, Ti values have been converted to equivalent HIRM and MS values using the slopes of the best-fit lines in Figure 10. Examination of Figure 11 indicates that the amplitudes of HIRM variation throughout the core and of MS variation within the low MS zones can be explained by variations in the initial heavy-mineral content and subsequent dissolution of Fe oxides. Within the high MS zones, MS values are generally too high and their amplitude of variation is too great to be explained in this way. Some other factor is needed to account for the range of the variation in magnetite content in the high MS zones.

Petrographic observations strengthen the interpretation that Fe oxides have been dissolved after deposition and help explain the disparity between the magnitudes of variation in MS and variation in contents of hematite and other heavy minerals. Numerous particles, originally magnetite, show evidence for the removal of Fe, leaving relicts of ilmenite and TiO_2 lamellae in a fragile network (Fig. 8D). These grains, typically found as solitary particles, are present in all samples regardless of MS zone. The shapes of some hematite grains similarly show evidence of postdepositional dissolution. In contrast, Ti magnetite in rock fragments typically shows little evidence for the removal of Fe. Instead, Ti magnetite occurs as subdivided grains in which the magnetite is retained between titaniferous lamellae, and as optically homogeneous grains, typically in skeletal or cuneiform textures that reflect rapid cooling. We interpret these relations—the common presence of altered magnetite as individual particles and of abundant, relatively fresh magnetite in rock fragments, often in the same sample—as evidence for the postdepositional removal of Fe from the altered grains. Solitary Fe oxide grains and weathered rock fragments are found in all samples. Fresh rock fragments, only a few with slightly weathered margins, are a major component of the magnetic fraction in samples that define the MS peaks in the high MS zones. We attribute the anomalously high MS, with respect to Ti, to abundant, fresh magnetite in the rock fragments (Fig. 11).

Peak Runoff—A Possible Link Between Climate Change and Magnetic Properties

Variations in magnetic properties in sediments from Buck Lake may be largely explained by a combination of three factors: (1) changes in the quantity of heavy minerals, (2) changes in the quantity of fresh rock fragments, and (3) postdepositional dissolution of nearly constant amounts of magnetite and hematite. The contributions of these factors to values of HIRM and MS are depicted in Figure 11. There is a strong relation between variations in the content of heavy minerals and the contribution of fresh rock fragments to MS as illustrated by two observations. First, fresh volcanic clasts are abundant and dominate MS only at high concentrations of heavy minerals. Second, variations in the portion of MS due to fresh clasts correspond closely to variations in heavy-mineral content. The dissolution of Fe oxides has little effect on the pattern of magnetic-property variations at Buck Lake. However, postdepositional destruction of detrital magnetic minerals may have profound effects in other basins, particularly if all magnetite or hematite is removed from some stratigraphic intervals or if the amount of Fe removed is highly variable (e.g., Snowball, 1993).

Processes that could control the amounts of heavy minerals or fresh rock fragments include changes in lake level, in breakage of clasts by frost ac-

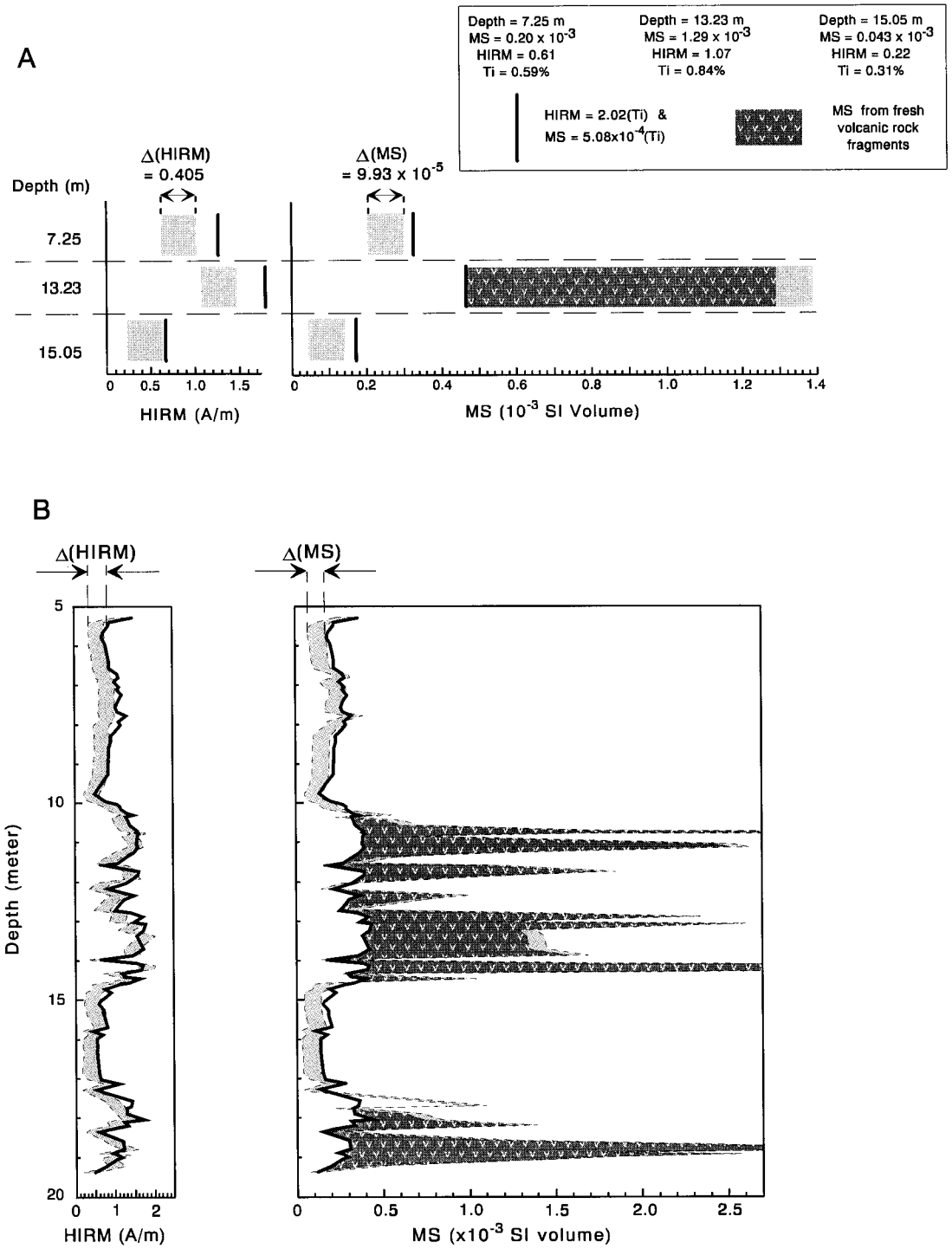

Figure 11. (A) Comparison of changes in Ti (a proxy for heavy-mineral content) in three samples to values of "hard" isothermal remanent magnetization (HIRM) and magnetic susceptibility (MS) before and after correction for loss of constant amounts of hematite and magnetite. The left side of each shaded box represents the measured value of HIRM or MS. The width of each box represents the estimated postdepositional decrease in HIRM (MS) due to dissolution of hematite (magnetite), as shown in Figure 10. Therefore, the right side of each box represents HIRM (MS) at the time of deposition. For purposes of comparison, Ti values (solid lines) have been converted to equivalent HIRM (MS) using the slopes of the best-fit lines shown in Figure 10. Where MS exceeds the value computed from the Ti content, the difference is interpreted to arise from the presence of fresh volcanic rock fragments. (B) Variations with depth of Ti content (solid line) and HIRM and MS (shaded area) before and after correction for postdepositional dissolution as in A. Similarity of the corrected HIRM and Ti curves indicates that variation in hematite content is primarily due to variation in heavy-mineral content. Variation in MS is produced in part by variation in heavy-mineral content and in part by variation in the content of fresh volcanic rock fragments.

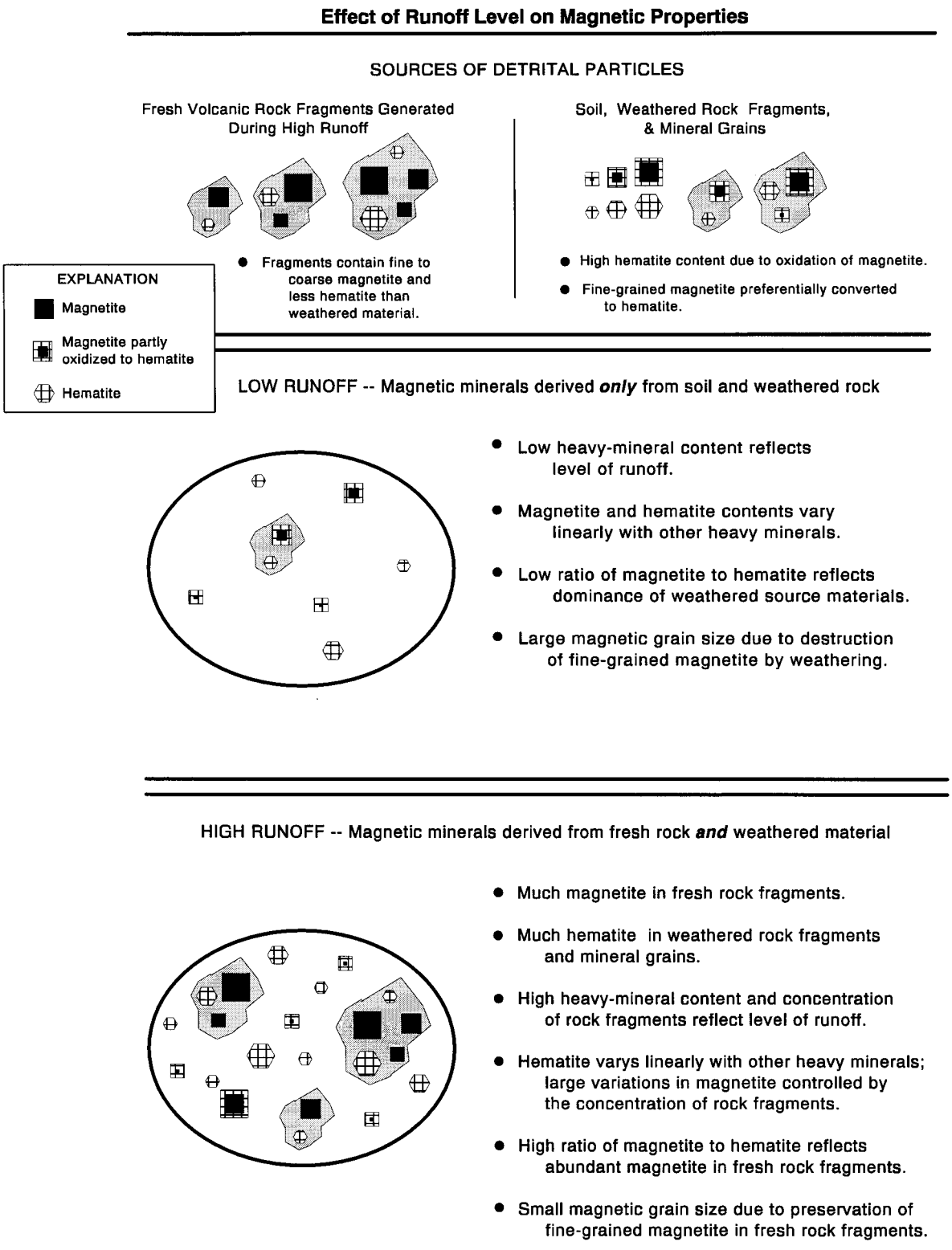

Figure 12. Illustration of the model showing the connection between the peak runoff of streams feeding Buck Lake and variations in sediment magnetic properties. Magnetic minerals are derived from two end members, (1) fresh volcanic rock fragments and (2) soil and chemically weathered rock. During periods of low runoff, variations in magnetic minerals reflect different inputs of heavy minerals derived only from soil and weathered rock. Above a certain threshold, magnetite-rich fresh rock fragments, generated by breakage of cobbles during high runoff, become a magnetically significant detrital component.

tion, and in peak runoff in streams feeding the lake. Lake-level changes could produce changes in heavy-mineral content but have no obvious control on the presence or absence of fresh lithic fragments. Breakage of clasts by frost action would increase the availability of unweathered volcanic clasts, but has no apparent control on heavy-mineral content. Of these processes, only runoff provides an explanation of the relation between heavy-mineral content and the abundance of fresh volcanic rock fragments. A simple model, in which the quantities of magnetic minerals derived from two end members vary as a function of peak runoff, can explain all of the observed magnetic properties (Fig. 12). One end member comprises soil and highly weathered material in which most of the magnetite has been oxidized to hematite. The other end member consists of fresh volcanic clasts that contain abundant magnetite. At low and moderate levels of peak runoff sediment is derived almost exclusively from the highly weathered material, and the magnetic properties reflect heavy-mineral content. These sediments (e.g., between 17.4 and 14.5 m; above 10.3 m, Fig. 11) are characterized by relatively low values of Ti, Zr, MS, and HIRM (due to low heavy-mineral content), low S parameter (due to low proportion of magnetite relative to hematite), and relatively low silt content. Changes in peak runoff produce variations in the flux of detrital heavy minerals derived from the weathered material with little variation in the relative amounts of specific minerals, including magnetite and hematite. Above a threshold runoff level (e.g., as occurred at intervals between 14.5 and 10.3 m in the core; Fig. 11) fresh rock fragments are generated by the breaking of cobbles and compose a volumetrically small, but magnetically significant, component of the sediment. Corresponding samples also contain a relatively high proportion of silt. Extreme variations in MS and in the S parameter reflect varying amounts of fresh volcanic clasts. Variations in Ti, Zr, and hematite, which are all derived largely from the weathered material, correspond closely to the high-amplitude variations in MS because heavy-mineral content and generation of fresh clasts are both controlled by the level of peak runoff.

In the above model, peak runoff is the primary control on the observed variations in magnetic properties, and it provides a link between magnetic-property variations and climate. Low levels of runoff correspond to low MS, in zones 2 and 4, and warm climates. High peak runoff produced high magnetite content in MS zones 1 and 3, which correspond to generally cold climates. High peak runoff during cold periods could result from climatically controlled factors including (1) the melting of deep winter snow pack, (2) lack of vegetation and ground cover, or (3) flash flooding due to severe storms. The data do not help establish the relative contributions of these factors. It is noteworthy, however, that in this interpretation warm climate zone D, which had significant winter snow pack (Fig. 2), is characterized by higher peak runoff than the warm and dry period of climate zone B. From this interpretation, we suggest that winter snow pack was a contributing factor to runoff and thus to variations in magnetic properties.

In the model presented here variation in peak runoff level is not only responsible for differences among the four MS zones, but also for the short-wavelength features in the magnetic-property record within zones 1 and 3. If this interpretation is correct, then these short-wavelength features probably reflect similar climatic influence as the broader features.

CONCLUSIONS

(1) Broad variations in magnetic properties of middle Pleistocene lacustrine sediment at Buck Lake correspond closely to changes in pollen that define four climate zones. Cold zones correspond to sediment that contains high contents of magnetite and hematite, as well as high relative amounts of magnetite to hematite. Warm zones correspond to sediment that contains low absolute amounts of magnetite and hematite, as well as very high relative amounts of hematite to magnetite.

(2) Magnetic-property variations are related to changes in the amounts and types of detrital magnetic Fe oxides, titanomagnetite and hematite. The evidence for a detrital origin of the magnetic record emerges from: (a) combined petrographic and thermomagnetic analyses of magnetic-mineral separates that show the dominant presence of detrital titanomagnetite and hematite; and (b) remarkably similar variations in magnetic properties and the contents of Ti, Zr, and Fe.

(3) Trace-element geochemistry, employing analyses for Ti, Zr, and Fe, provides a powerful tool to measure variations in detrital heavy-mineral content, to detect postdepositional dissolution of detrital magnetic minerals, and to quantify the magnetic effects of such dissolution. In the Buck Lake sediments, dissolution affects the magnitude of variations in the magnetic properties but not the pattern of the magnetic record.

(4) The magnetic and pollen records are slightly offset over two cold to warm transitions. The magnetic properties change below the climate-change boundary picked on the basis of pollen, suggesting that factors responsible for the distribution of magnetic Fe oxide minerals responded more quickly to climate change than did plant cover.

(5) Variation in peak runoff is the primary control on magnetic properties in a simple model that fully explains magnetic, geochemical, grain size, and petrographic data. Peak runoff may be the primary link between magnetic-property variations and climate. High peak runoff produced high magnetite content in the high MS zones that correspond closely to cold climatic intervals. Low levels of runoff correspond to the low MS zones and warm climates.

(6) The proposed model accounts for both the high-frequency variations in magnetic properties within the cold climatic intervals and the broad variations that correspond to climate zones defined by pollen. We infer that the short-wavelength and long-wavelength variations arose from similar causes. If so, the shorter wavelength features add great detail to the climate-change record.

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