Magnetic Mineralogy of Sediments in Bear Lake and its Watershed, Utah, Idaho, and Wyoming: Support for Paleoenvironmental and Paleomagnetic Interpretations

By Richard L. Reynolds and Joseph Rosenbaum

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Magnetic Mineralogy of Sediments in Bear Lake and its Watershed, Utah, Idaho, and Wyoming: Support for Paleoenvironmental and Paleomagnetic Interpretations

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Introduction

This report describes magnetic minerals identified in lake sediments and watershed deposits of the lake-catchment system of Bear Lake, Utah, Idaho, and Wyoming. The lake sediments examined for this study came from the 1996 cores (BL96-1, -2, -3; Colman, 2005; Rosenbaum, 2005) and the GLAD800 cores (GLAD1-BL00-1D and -1E; Dean and others, 2002). The identification of magnetic minerals in these lake sediments provides important supporting information for paleoenvironmental and paleomagnetic interpretations, because different magnetic mineral types of vastly different origins, may in some cases, produce similar magnetic property signatures. For example, certain bulk magnetic properties from rock-derived detrital magnetite (Fe_3O_4) cannot be easily distinguished from properties imparted by postdepositional greigite (Fe_3S_4). Attention also was given to the possibility of postdepositional dissolution of detrital grains, such as magnetite, a common alteration in lake sediments under chemically reducing conditions (for example, Rosenbaum and others, 1996; also see Canfield and Berner, 1987). Petrographic analysis can be used to identify magnetic minerals, to determine the origins of these particles, and to recognize dissolution of detrital iron oxide minerals. In this way, we are able to distinguish between depositional and postdepositional magnetic signatures. Recognition of postdepositional alteration guides paleomagnetic interpretations and provides clues to lake-water chemistry.

Compositions of the detrital magnetic minerals, or rock fragments in which they are contained, additionally enable some interpretations regarding source areas for the lake sediments. Moreover, textures (size and shape) of the magnetic minerals in core samples may reflect erosional conditions and processes, such as glaciation, responsible for these minerals (Reynolds and others, 2004).

Properties of sediments in and near drainages within the watershed also provide valuable information for interpreting lake-sediment properties. For example, petrographic examination of watershed samples can reveal characteristics of the magnetic mineralogy, such as mineral type, size, and origin, that may be linked to the magnetic mineralogy and magnetic properties of lake sediments. This understanding further elucidates watershed processes and the sources of sediment that may change as a function of climate variability.

Methods

Magnetic minerals were separated from bulk sediment by pumping a slurry of the sediment past a stationary magnet (Reynolds and others, 2001). Grains, mounted in epoxy and polished, were examined using reflected-light microscopy under magnifications to 720 times.

Summary of Observations, 1996 Cores

Samples were chosen to represent important magnetic-property variations in the three cores collected in 1996—BL-1, -2, -3 (Rosenbaum, 2005). Magnetic minerals that are observed petrographically (table 1) can explain the major magnetic property variations and test preliminary interpretations made based on the properties (Rosenbaum, 2005). The principal observations are:

1. Detrital magnetite dominates magnetic signals in most samples. The magnetite occurs in many different forms (type, size, and shape), primarily as titaniferous magnetite, low-titanium magnetite, and particles within rock fragments.

2. Detrital hematite occurs mainly as a variety of forms in reddened rock fragments and as particles of specular hematite. The rock fragments consist of many different lithic types, but siltstone or siltite is the primary type in samples in which hematite controls magnetic properties. Hematite likely has strong influence on magnetic properties in three of the 22 samples examined (core 2, 388 cm; core 3, 103–107 cm and 135–139 cm).

3. Titanohematite, referring to a range of compositions in the hematite-ilmenite solid solution series that are highly magnetic, is a minor detrital magnetic mineral and likely is the major contributor to magnetic susceptibility and remanence in only one sample (core 1, 484–492 cm). In depositional settings where magnetite otherwise is present, as at Bear Lake, a relatively high abundance of titanohematite in samples with few magnetic minerals usually indicates postdepositional dissolution of detrital magnetite particles (see Reynolds and others, 1994). In one such sample, magnetite was observed only within rock fragments and mineral grains. For this sample, we infer that exposed particles of magnetite did not survive postdepositional alteration.

4. In sediments having relatively abundant magnetite and hematite, based on magnetic properties, the magnetite and hematite commonly occur as very small (<10 μm) silt-sized, angular particles, or within rock fragments of similar size and shape.

5. Iron sulfide minerals are uncommon in most samples. Pyrite is observed only as framboids. Greigite is found mainly in core 3 where it has only minor influence on magnetic properties and only over a small extent, mainly near the top of the core. The greigite primarily occurs within detrital plant fragments. Some aggregates of greigite exhibit unusual features of partial oxidation to ferric oxide in patterns suggesting that the aggregates represent detrital particles and not postdepositional authigenic forms. If so, these particles are evidence for sediment that was derived from marshes at the margins of the lake.

Summary of Observations, GLAD800 Core

We examined magnetic minerals separated from 13 bulk samples in cores GLAD1-BL00-1D and 1E to a depth of 118.56 m (table 2). The principal observations are:

1. Relatively abundant, homogeneous magnetite is the primary magnetic carrier in the high MS interval between 16–18 m depth. These grains are angular and typically smaller than 10 μm; the grains contribute to coarse magnetic grain size. We did not sample the GLAD800 cores in the interval of high values of hard isothermal remanent magnetization (HIRM) between 10–16 m, because the equivalent interval was examined in BL96 cores (table 1; Rosenbaum, 2005).

2. All other magnetic separates have been affected by sulfidization that has partly to completely destroyed magnetite and probably hematite except where small amounts have been protected (for example, as inclusions in silicate grains). No magnetic separate was made from the zone at about 53 m that has elevated magnetic susceptibility (MS) and HIRM but not IRM/MS (C.W. Heil, Jr., unpub. data, 2005).

3. Postdepositional iron sulfide minerals are common. Some samples contain pyrite with little or no greigite. Other samples contain abundant greigite, which has texture and occurrence diagnostic of postdepositional formation (see Reynolds and others, 1994). Abundant greigite is found in samples with very high values of IRM/MS. Much of the spikiness in the magnetic susceptibility below about 30 m probably is produced by variations in the quantity of greigite.

4. Greigite appears to be rare or absent at 0–40 m (approximately representing Marine Isotope Stages [MIS] 1–4) as well as about 60–65 m (thought to represent MIS 5e). With three exceptions, the concentration parameters through the 20–40 m depth interval are typical of samples in which greigite is not present. One

exception is the 10–20 m interval, which has much higher concentration parameters, because it contains relatively abundant detrital magnetite and hematite. The other two exceptions are MIS 5e–interval and Holocene sediments (approximately 1–9 m), which have much lower concentration parameters.

5. Titanohematite is relatively abundant in many of the samples that have undergone postdepositional sulfidization. This observation may not indicate that titanohematites were originally very abundant in the sediment; they are obvious in the separates, because they are extremely resistant to sulfidization that destroy other Fe-oxides (Reynolds and others, 1994 and references therein).

6. The sample from about 65 m (equivalent to MIS 5e) contains pyrite but only sparse titanohematite. Similar observations were made for Holocene samples from the BL96 cores (table 1).

7. Detrital pyrrhotite, commonly within fragments of laminated shale, occurs in most magnetic separates, and we thus infer that the pyrrhotite is the ferrimagnetic variety Fe_7S_8. These particles do not appear to influence magnetic properties for two reasons: (1) the pyrrhotite-bearing fragments are not abundant and (2) magnetic properties vary greatly among samples in which the pyrrhotite is found. Nevertheless, further work on this occurrence might provide clues to source areas for the lake sediments and information about the drainage history. A possibility to investigate in the future is that the pyrrhotite was derived from the Eocene Green River Shale. Such pyrrhotite was not observed in modern samples from the watershed.

Summary of Observations, Watershed Samples

Samples were collected from sediments in the watershed of Bear Lake in 1999 and 2000. A pair of samples was taken from each sampling locality (fig. 1) along drainages. Odd-numbered samples were obtained from stream or river sediments, and even-numbered samples were taken from nearby bank deposits. The samples were sieved into particle sizes that represent pebbles, coarse sand, fine sand, and the silt plus clay fraction (<63 μm; fine fraction).

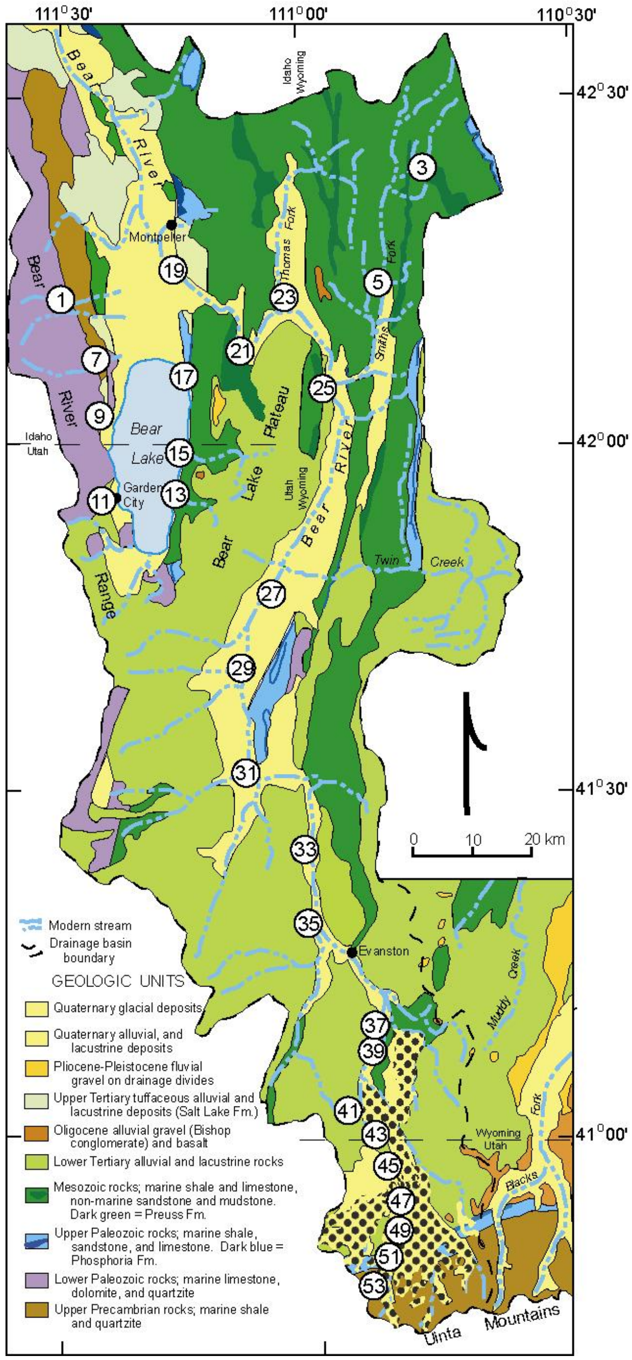

Figure 1. Surficial geologic map of the Bear Lake basin (M. Reheis, in press), showing sampling localities. Stippled pattern denotes area of glacial deposits. Reheis and others (2005) describe the surficial geology of the basin. Odd numbers represent fluvial sediment samples, and even numbers (not shown on map) represent samples from nearby streambank deposits. Locations of sediment cores BL96-1, -2, -3 are shown in Dean and others (2005). The GLAD800 core is close to core BL96-3 (see Dean and others, 2002).

Magnetic properties indicate that the fine-fraction samples are more magnetic than associated samples from the other fractions (Rosenbaum, 2005; unpub. data). For this reason, and because this fraction best represents sediments that are deposited in the lake, we did not examine magnetic minerals in the coarser fractions and describe here only the magnetic minerals identified in the fine fraction. Rosenbaum (2005) also found that magnetic properties of the fine fraction, including concentrations of magnetite and hematite, vary greatly with location in the watershed. The concentration of magnetite (indicated by MS values) is relatively high in samples in and adjacent to local drainages that flow directly into Bear Lake and is lower in samples from sites along the Bear River (fig. 2). The concentration of hematite (indicated by HIRM values) is generally low in samples from the local catchment, but it increases abruptly in and along the upper reaches of the Bear River where it flows through Precambrian red sedimentary rocks of the Uinta Mountains (fig. 2).

The principal observations (table 3) are:

1. Magnetite is the most abundant mineral in all magnetic separates. It occurs in a variety of types, mainly as optically homogeneous magnetite (perhaps representing low titanium-content) and as titanomagnetite, consisting of magnetite subdivided by ilmenite lamellae. Magnetite also is present in rock fragments and mineral grains, but these occurrences are relatively uncommon.

2. Magnetic titanohematite is present in all samples but in variable amounts.

3. Hematite occurs in a variety of forms—as specular hematite grains, including martite; as specular hematite within magnetite grains or within titaniferous oxides that formed under high-temperature oxidation conditions, such as pseudobrookite; as fine-grained forms within a variety of rock fragments that include red sedimentary rocks; and rarely as partial oxidation products of Fe sulfide minerals.

4. Most samples contain magnetic particles of fly ash and fragments of steel. Fly ash typically is produced during the combustion of coal and is a ubiquitous airborne effluent from coal-burning power plants. The steel fragments also may represent atmospheric contaminants.

5. The magnetic grains are characterized by small particle sizes. Even though the fine fraction operationally represents particle sizes as much as 63 μm, most Fe-Ti oxide grains were much smaller. Most such grains in most samples are <20 μm, and a high proportion of these grains are <10 μm. Only a few Fe-Ti oxide grains exceed 40 μm in diameter.

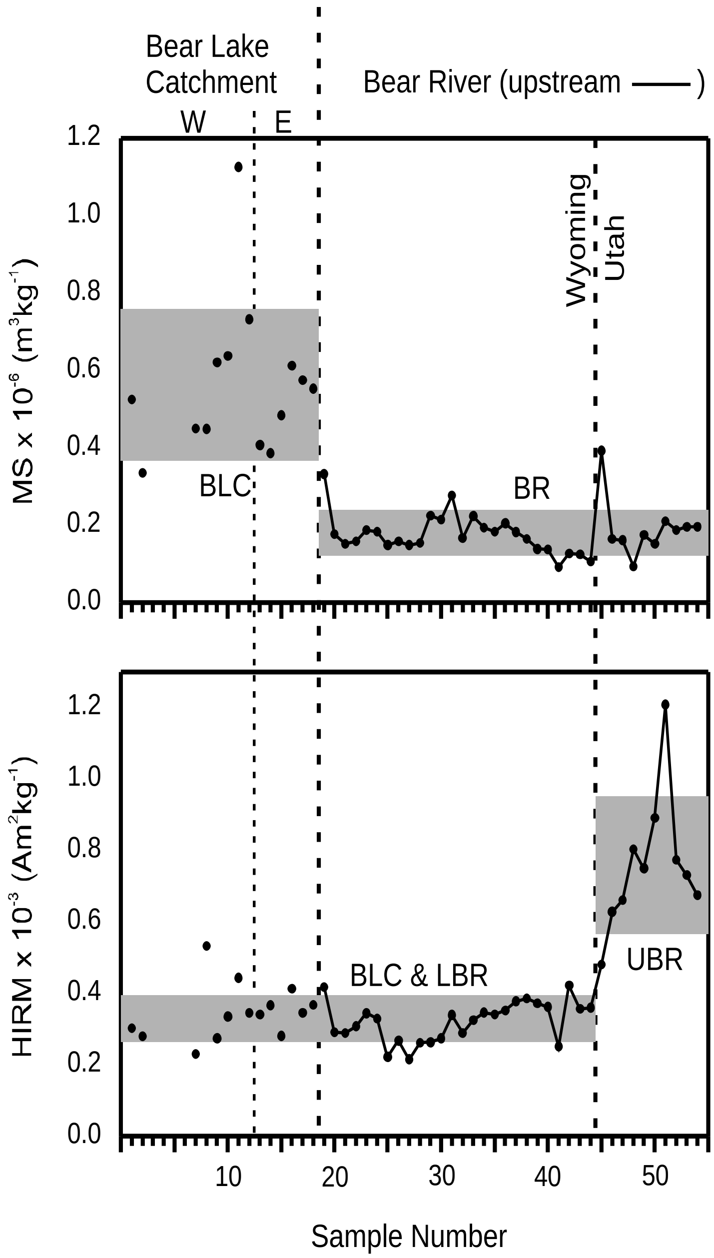

Figure 2. Plots of catchment-sample numbers against MS (magnetic susceptibility; upper panel) and HIRM (hard isothermal remanent magnetization; lower panel) in the silt and clay fraction. Shaded bars represent ±1 standard deviation from the mean for samples in the indicated zones. BLC, Bear Lake catchment; LBR, lower Bear River; UBR, upper Bear River.

Preliminary Interpretations

The wide variety of magnetic minerals in the watershed deposits indicates multiple sources for these minerals. Much of the hematite from the upper parts of Bear River likely is from hematite-bearing Precambrian metasedimentary rocks of the Uinta Mountains. Rare ferric oxide minerals formed from Fe sulfide minerals probably are derived from local carbonate bedrock.

Several observations indicate that a high proportion of magnetite in the watershed samples represent eolian dust. First, sites in the local catchment are all associated with Paleozoic limestone and dolomite substrates, rock types devoid of the types of Fe-Ti oxide minerals found at these sites. Similarly, bedrock in the Bear River watershed predominantly consists of Paleozoic and Mesozoic sedimentary rocks that typically contain little or no Fe-Ti oxide minerals of the type found in Bear River sediments, with the possible exception of the Preuss Sandstone (Fishman and others, 1989). Second, the variety of Fe-Ti oxide mineral types is typical of grains derived from multiple sources and typical of oxide minerals in eolian dust deposits in dryland settings elsewhere (Reynolds and others, in press). Third, the particle-size distribution of the Fe-Ti oxide minerals is consistent with atmospheric dust. Finally, the presence of fly-ash particles in most samples is evidence for windblown dust in these samples.

We do not attempt to identify the specific sources of airborne dust in the watershed samples. One likely magnetite-bearing source area encompasses surficial deposits of the Snake River Plain north of Bear Lake. Northwesterly winds meet little obstruction from the Snake River Plain to the bowl-shaped highlands, open to the north, that surround Bear Lake.

Petrographic study of the watershed samples provides insights to the origins of detrital magnetic minerals in the lake sediments. At least some of the magnetite was introduced to the catchment as eolian dust before fluvial transport into the lake. We do not know the extent to which some detrital magnetite in the lake sediments might have been derived directly by weathering of rocks within the watershed. For example, the Jurassic Preuss Sandstone in the Idaho-Utah-Wyoming overthrust belt locally contains abundant magnetite (Fishman and others, 1989), and this unit may contribute some magnetite to the Bear Lake system. In lake sediments having high HIRM values, we find detrital hematite. Some of this hematite occurs within fragments of fine-grained red sedimentary rocks and closely resembles hematite in samples from the upper Bear River (samples BL2000-18 and -22).

Rosenbaum (2005) discussed the magnetic property variations in the BL-96 cores in the context of the magnetic mineralogy described here. Detrital magnetite and hematite, from different sources, control magnetic properties in sediments that represent the last glacial period. Overlying Holocene sediments are characterized by low magnetization that reflects strong postdepositional destruction of detrital iron oxide minerals.

Each sample from the GLAD800 cores that contains abundant greigite also has a high value of IRM/MS, consistent with greigite occurrences elsewhere (Reynolds and others, 1994). The GLAD800 sediments below about 40 m, corresponding to MIS 5, 6, and 7, are characterized by highly variable IRM/MS (J. Rosenbaum, unpub. data; C.W. Heil, Jr., unpub. data). If much of the spikiness in IRM/MS, which varies closely with IRM, is related to greigite abundance, then greigite makes a significant contribution to remanence in much of the MIS 5–7 record.

Greigite occurrence in the GLAD800 sediments is similar in some respects to greigite in sediments from Owens Lake (southern California) that correspond with MIS 4, 5, and 6. In the Owens Lake deposits, variable greigite abundance controls strong variations in IRM/MS (Reynolds and others, 1998). Very high IRM/MS (caused by abundant greigite, as petrographically confirmed) was found at and near boundaries between isotopic stages 6/5 and 5/4. Greigite also was abundant in intervals within MIS 5 sediments. Reynolds and others (1998) concluded that greigite formed in Owens Lake during conditions intermediate between closed and stagnant vis-à-vis open and through flowing. Such greigite thus represented conditions of increased freshness in an otherwise saline environment, as well as conditions of increased salinity in an otherwise fresh, open setting. The production of greigite at the boundary zone between MIS-6 and MIS-5 sediments reflected the transition from fresh to saline waters. Saline conditions promoted pyrite formation along with destruction of detrital iron oxide minerals, given sufficient sulfur, organic matter, and iron in the system.

Although the inflow and outflow configurations at Bear Lake and Owens Lake differed considerably, we may draw some analogies between the two systems. We attribute the greigite and pyrite formation in Bear Lake sediments to differing degrees of salinity and related activity of bacterial reduction of pore-water sulfate.

Acknowledgments

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Explanation for Tables.

Samples, core segments from which magnetic particles were extracted (tables 1 and 2).

Field-sample group, catchment samples having closely similar magnetic mineral suites were combined (table 3).

Magnetic properties, primary features of magnetic property profiles described and reported by Rosenbaum (2005).

IRM, isothermal remanent magnetization.
HIRM, hard isothermal remanent magnetization.
MS, magnetic susceptibility.
ARM, anhysteretic remanent magnetization.
S, S parameter.
High and low refer to relative values within a core.
Mod, moderately high or low.

Mag Min 1, magnetic mineral having dominant effect on magnetic properties in a sample.

Mag Min 2, other magnetic mineral that likely strongly influences one or more magnetic properties in a sample.

Fe oxide, particles in rock frags (fragments) too small (<3 μm) to identify by specific type.
Mt, magnetite; opt. (optically) homogeneous mt indicates compositional homogeneity
Ht, hematite
Ti-ht, titanohematite
Py, pyrite (all framboids are composed of pyrite)
Po, pyrrhotite

Fe-S mins (tables 1 and 2), Iron sulfide minerals.

Table 1. Petrographic descriptions of magnetic mineral separates from Bear Lake cores 96-1, -2, -3.

Core	Depth (cm)	Samples	Magnetic properties	Mag Mins 1	Mag Mins 2	Magnetic minerals-details, more observations, interpretations	Fe-S mins
1	16-26	A20,28,30	mod HIRM low IRM, MS, ARM/MS S<0.9	Fe oxides		small Fe oxides in rock frags sparse ti-ht	none
	165-177	B68,72,76,80	low IRM, HIRM, MS, ARM/MS S<0.9	Fe oxides		small Fe oxides in rock frags some small oxides in rock frags are oxidized (reddened)	none
	256-344	C59,60 D46	high IRM, MS, ARM/MS mod HIRM S~0.95	mt		mt in rock frags some indivdual mt grains minor specular ht in rock fragments	none
	484-492	E86,90,94	low-mod MS, IRM high HIRM, ARM/MS, S(~0.95)	ti-ht	ht	specular ht in siltstone frags mt in rock frags and mineral grains possible mt dissolution leaves ti-ht as dominant oxide	framboids (minor)
2	186-193	B97,99 C2	low IRM, HIRM, MS, ARM/MS S~>0.85	mt		mt in rock frags and mineral grains specular ht in rock fragments sparse ti-ht possible mt dissolution	none
	220-222	C29,30	low IRM, HIRM, MS high ARM/MS, S(~0.95)	mt		mt as individual grains and in rock frags ti-ht some mt associated with minor py (may not be diagenetic)	pyrite (minor)
	236-237	C46,47	small peaks MS, IRM, ARM/MS low HIRM high S (>0.95)	mt		small mt in glass shards other mt and Fe-Ti oxides	greigite (?) in plant frag
	277-282	C86,87,89	mod MS, IRM low HIRM, ARM/MS S (~>0.80)	mt		mt in many forms: large (~70 μm) opt. homogeneous grains with maghemite margins; small (5 μm) particles in large (100 μm) rock frags; associated with ht (pre-depositional replacement) ht as specular grains and in red rock frags possible minor mt dissolution	framboids (minor)
	309	D17	mod MS, IRM ARM/MS peak	mt		mt as opt. homogeneous grains and in rock frags possible minor mt dissolution	framboids (common)
	316-319	D24,25,26	high IRM, MS, ARM/MS low HIRM, high S	mt		mt as large (many >20 μm) opt. homogeneous grains with maghemite margins, some showing ht replacement; some small, angular mt	none
	388	D96,97	high HIRM, low S (<0.5) mod MS, IRM low ARM/MS	ht	mt	ht as silt-sized (<20 μm) particles and as small (5 μm) particles in reddened rock (siltstone?) frags. mt bimodal size distribution: small (4-10 μm), angular and coarser (>20 μm) grains	pyrite (minor)
3	8-10	A21,22,23	low MS, IRM, HIRM high ARM/MS, S	mt		mostly fresh rock frags with mt; subdivided mt common	minor
	41-42	A54,55	high spike in ARM, IRM high ARM/MS, IRM/MS low HIRM, high S	mt	greigite	mt, some moderately coarse grained (>20 μm), some with wormy texture of unknown origin. Reddened igneous rock frag with specular ht. Ti-ht. greigite in organic frags	greigite framboids
	64-66	A77,78,79	high spike in IRM and IRM/MS mod high HIRM; S~0.85	mt	greigite	mt, mostly rounded (>20 μm) but many subdivided ti-mt (<10 μm) frags of sediment are common greigite common, some in plant frags; many greigite aggregates partly oxidized Redox patterns consistent with deposition of sediment and org frags containing greigite	greigite framboids
	103-107	B17,18,19	low MS, IRM very high HIRM, low S (<0.5)	ht	mt	ht, mostly in reddened, sedimentary rock frags; abundant clay-size red particles (ht) mt, mostly very small (<10 μm) but some >20 μm greigite, some associated with plant frags	greigite
	135-139	B49,50,51	high HIRM, low S (<0.6)	ht	mt	ht, mostly in reddened rock frags, specular ht (including martite) common mt, mostly very small (<10 μm) but some >20 μm greigite, some associated with plant frags; much of it oxidized	greigite
	145-165	B58,70,78	high MS, IRM relatively low HIRM, high S (>0.85)	mt	ht	mt, mostly very small (<10 μm) but some >20 μm ht, as small (<10 μm) specular ht particles and in reddened rock frags	none
	230-234	C42,45,46	relatively low MS, IRMHIRM high HIRM, low S excursion	ht/mt		ht, as specular ht particles (some <10 μm) and in reddened rock frags, some igneous origin mt, many very small (<10 μm) but also >10 μm	greigite (much oxidized)
	274-279	C86,90,91	high MS, IRM relatively low HIRM, high S (>0.85)	mt	ht	mt, mostly very small (<10 μm) but some >20 μm ht, as small (<10 μm) specular ht particles and in reddened rock frags	none
	354-356	D65,66,67	high MS, IRM relatively low HIRM, high S (>0.85)	mt	ht	mt, bimodal size distribution: many small (<10 μm) but some >10 μm ht in reddened rock frags	none
	386-388	D97,98,99	relatively low MS, IRM relatively high HIRM, low S (<0.6)	mt	ht	mt, bimodal size distribution: many small (<10 μm) but some >10 μm ht in reddened rock frags	greigite (minor)
	399-405	E10,13,14	high MS, IRM relatively low HIRM, high S (>0.85) small spike in ARM/MS	mt	ht	mt, bimodal size distribution: most small (<5 μm), angular; some >10-20 μm some rounded mt ~30 μm diameter ht in reddened rock frags (minor); rounded specular ht (rare)	pyrite (minor)

Table 2. Petrographic descriptions of magnetic mineral separates from the GLAD 800 core at Bear Lake.

GLAD1 BL00 core	Sample	Depth (m)	Magnetic properties	Mag Mins 1	Mag Mins 2	Magnetic minerals-details, observations, interpretations	Fe-S mins
1D	6H-1	16.00	mod MS, HIRM; low IRM/MS	mt		small (most <20 μm), angular opt. homogeneous mt; sparse ht	
	6H-2	17.50	high MS; low HIRM; low IRM/MS	mt		small (most <20 μm), angular opt. homogeneous mt; sparse ht	
	12H-2	35.07	mod MS; low HIRM; low IRM/MS	ti-ht		small (most <10 μm), angular ti-ht; a few mt grains most mt has been dissolved or replaced by pyrite; some mt in rock frags minor detrital po; po also within fragments of laminated shale	pyrite, some replaces mt; framboids
	14H-2	41.59	high MS; low HIRM; low IRM/MS	ti-ht?		ti-ht?; rare mt preserved inside silicate mineral po within fragments of laminated shale	detrital po
	15H-1	43.00	mod MS; low HIRM; high IRM/MS	greigite	po (?)	greigite in fine-grained agglomerates; ti-ht minor; mt dissolution po within fragments of laminated shale are common	greigite detrital po
	22A-2	65.02	low MS, HIRM, IRM/MS	ti-ht		ti-ht; mt dissolution po within fragments of laminated shale are rare	pyrite detrital po
	23A-1	67.10	high MS; low HIRM; high IRM/MS	greigite	ti-ht	greigite in fine-grained agglomerates; ti-ht minor; mt dissolution po within fragments of laminated shale	greigite; pyrite detrital po
	28E -2	78.33	high MS; low HIRM; high IRM/MS	greigite		greigite in fine-grained agglomerates po within fragments of laminated shale	greigite detrital po
	31E -1	83.2	low MS, HIRM, IRM/MS	ti-ht		ti-ht; mt dissolution po within fragments of laminated shale are rare	pyrite detrital po
	37E -1	96.2	mod MS; low HIRM; high IRM/MS	greigite		greigite; minor pyrite; rare ti-ht	greigite pyrite
	37 E -2	97.5	low MS, HIRM; mod IRM/MS	ti-ht		ti-ht; pyrite associated with plant fragments; minor greigite likely po within fragments of laminated shale are rare	pyrite
1E	43 E -2	111.57	mod MS; low HIRM; low IRM/MS	ti-ht		very few magnetic grains; ti-ht present; possible fine-grained pyrite	
1E	47 E -1	118.56	mod MS; low HIRM; high IRM/MS	greigite	ti-ht	greigite in fine-grained agglomerates and nodules; small, angular ti-ht po within fragments of laminated shale; small po particles (likely detrital)	greigite detrital po

Table 3. Petrographic descriptions of magnetic mineral separates from catchment samples.

Field-sample group	Location and site numbers (see fig. 1)	Magnetic properties (see fig. 2)	Mag Mins 1	Mag Mins 2	Magnetic minerals-details	Fly ash and other contaminants
BL99-2, -12, -13	Local catchment; slopes above Bear Lake 2, 12, 13	high MS, low HIRM	mt		mt in many forms; ti-ht and ht present; mt in rock frags. red/orange particles with ferric oxide, especially in samples 12, 13, some of which appear to be oxidized sulfide minerals	fly ash particles steel fragments in 2, 12
BL-18	Mud Lake 18	high MS, low HIRM	mt		mt in many forms; ti-ht and ht present; mt in rock frags. red/orange particles with ferric oxide; one particle formed from framboids	fly ash particle
BL- 23, -28	Lower middle Bear River 23, 28	low MS, low HIRM	mt		mt, mostly as optically homogeneous grains; less variety in Fe-Ti oxides here than in other samples; ti-ht and ht are rare	none
BL2000-3, -13	Upper middle Bear River 33, 43	low MS, low HIRM	mt		mt in many forms; ti-ht and ht present; mt in rock frags. red, hematite-rich particles	fly ash particles steel fragments
BL2000-18, -22	Upper Bear River, Unita Mountains 48, 52	low MS, high HIRM	mt	ht and ti-ht	mt in many forms; ti-ht and ht common red, hematite-rich sedimentary rock frags (siltite) specular ht present	fly ash particles steel fragments