Environmental Magnetism

- What is it?
- Environmental Magnetism Toolkit
- Examples and Applications

Environmental Magnetism and Climate Change Records

- Characterize the iron mineralogy of natural archives (e.g., sediment) with magnetic measurements.
- Interpret these measurements in terms of environmental forcing, e.g., changes in climate.
  - To make this link one must have a working model of the processes that control the formation, transport and preservation of the iron mineralogy

Books and Review Articles on Environmental magnetism

Books

Recent Review Articles

Apparent Correlation between Paleointensity and Glacial Cycles observed in deep sea sediments

Lithological and paleomagnetic data from marine sediments

High CaCO₂ → glacial periods, Low CaCO₂ → interglacial periods

Kent, 1982

Primary Sources of Magnetic Minerals
- crust
- cosmic flux
- biogenic

Secondary Sources of Magnetic Minerals
- soil (pedogenesis)
- authigenic production
- fly ash from fossil fuel combustion

Variations in Magnetic Properties of Sediments (Climate and Tectonics)
- changes in sediment source
- changes in weathering regime of source region
- concentration of eolian and fluvial magnetic minerals
- dilution by paramagnetic/diamagnetic minerals
- dissolution by chemical/biological processes
- authigenic/pedogenic growth of secondary magnetic minerals

Why Magnetism?
- iron minerals are: abundant, sensitive redox indicators, often related to microbial activity
- magnetic measurements are: fast, inexpensive, non-destructive (mostly), quantitative and sensitive (100 ppm)

The Magnetic Properties of a Sample are a function of:
1) the concentration of magnetic material
2) the kinds of magnetic minerals
3) the particle size of the magnetic material (granulometry)

Magnetic parameters (or measurements) are sensitive to 1, 2, or all 3 of these variables.

Liu et al., 2012

Transformation pathways for iron oxides and iron sulfides in (a) oxic, (b) sulfatic, and (c) nonsulfatic anoxic environments.
**Depth plots:** useful for core correlation, variations in concentration, mineralogy and grain size as a function of depth.

A simple (first order) interpretation: glacial (cold) and interglacial (warm) periods tapped different source areas in the drainage basin to deliver magnetite (higher $\gamma$) and hematite (lower $\gamma$) during different climatic periods.

**Rock magnetic data from Buck Lake [Rosenbaum et al. 1996]**

**Biplots:** useful for detecting changes in grain size, concentration, mineralogy, etc.

Fine-grained (SO) vs. coarse-grained (MD)

Low-coercivity (ferrimagnets) vs. high-coercivity (antiferromagnets)

Complications:

Superparamagnetism
Magnetic interactions
Mixtures of states

Maher, Thompson, Hounslow, 1999; Maher, 2011

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**Anhysteretic Remanent Magnetization (ARM)**

ARM is produced by an alternating field (AF) of gradually decreasing amplitude ($H_a$) simultaneously with a steady, unidirectional DC field ($H_d$). The ARM is measured when both AF and DC fields are zero.

Typical experimental conditions: $H_a \sim 100-200$ mT, $H_d \sim 10-100$ $\mu$T

Magnetic moment of a particle during an ARM cycle

Weak-field remanence (50-100 $\mu$T)
Analogue for TRM, but induced at room temperature

**Anhysteretic Remanent Magnetization (ARM)**

ARM is used in a variety of applications in paleomagnetism.

1. estimate absolute paleointensity from igneous rocks and relative paleointensity from lake and marine sediments
2. characterize magnetic carriers and determine domain state and grain size
3. detect magnetic fabrics in rocks and sediments
4. study the fundamental aspects of magnetism.
**ARM acquisition curves**

Effects of Magnetostatic Interactions between particles

Biogenic SD Magnetite (magnetosomes)

Samples containing dispersed PSD/SD grains of magnetite in different concentrations. (from Sugiura, 1979).

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**Anhysteretic Remanent Magnetization**

\[ \chi_{ARM} \left[ m^3/kg \right] = \frac{ARM \left[ Am^2/kg \right]}{h_{dc} \left[ A/m \right]} \]

Egli and Lowrie, 2002

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**Hysteresis Loop**

Hysteresis Parameters
- Saturation Magnetization: \( M_s \)
- Saturation Remanence: \( M_{r,s} \)
- Coercivity: \( H_c \)
- Coercivity of Remanence: \( H_{c,r} \)
- Initial Susceptibility: \( \chi_0 \)

\[ \frac{M_s}{M_s - T_c} \]

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**Anoxic-Oxic Interface**

Filtered water samples containing magnetotactic bacteria from a small coastal pond

Moslowitz et al., 2008

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**Theoretical Value**

Non-interacting uniaxial SD grains (Egli and Lowrie, 2002)

\[ \chi_{ARM/SIRM} > 1.5 \times 10^{-3} mA^2 \]

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**Water Depth (m)**

Samples containing dispersed PSD/SD grains of magnetite in different concentrations.
Concentration

- Magnetic moments are linearly proportional to the concentration of magnetic material in a sample (given that mineralogy and grain size are held constant).

- For example,
  - The saturation magnetization ($M_s$) for pure magnetite is 92 Am$^2$/kg.
  - The saturation magnetization for a sample composed of 99.9% quartz and 0.1% magnetite is 0.092 Am$^2$/kg.

Dust on Snow (San Juan Mts) ~0.1% magnetite

Granulometry: Grain Size Variation

- Changes due to variation in domain state
- Domain state is volume dependent → grain size

Granulometry: Grain Size Variation

- Grain size dependence in hysteresis parameters. Crushed grains (red) indicated by “C”, glass ceramic grains (blue) indicated by GC; Hydrothermal grains (green) indicated by “H”. [Data compiled by Hunt et al., 1995.] d) Variation of susceptibility with grain size. [Data compiled by Heider et al., 1996.]

Magnetic Domains and Particle Size

- Magnetic domains and particle size
- Multidomain behavior
- Single domain behavior
- Superparamagnetism

Granulometry: Grain Size Variation

- Hysteresis parameters for dispersions of magnetite particles with different grain sizes (Dunlop and Gradenic, 1997)

<table>
<thead>
<tr>
<th>Grain size</th>
<th>Mr/Ms</th>
<th>Hr/Hc</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD &gt;0.1 μm</td>
<td>0.5</td>
<td>1.09</td>
</tr>
<tr>
<td>PSD 0.1-0.5μm</td>
<td>0.87</td>
<td>1.08</td>
</tr>
<tr>
<td>MD &lt;0.1</td>
<td>&gt;3-4</td>
<td></td>
</tr>
</tbody>
</table>

Diagnostic values for SD, PSD, and MD grains

- Theoretical SD values

<table>
<thead>
<tr>
<th>Anisotropy</th>
<th>Mr/Ms</th>
<th>Hr/Hc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_e$ = 0, [111]</td>
<td>0.83</td>
<td>1.04</td>
</tr>
<tr>
<td>$K_e$ = 0, [100]</td>
<td>0.83</td>
<td>1.04</td>
</tr>
</tbody>
</table>
Distorted Loops

Mixtures of Magnetic Phases
Composition and Grain Size

Susceptibility logs can be used for
 correlation of sediment cores from a
 single lake

Down core variations
Changes in drainage basin
Fluctuations in intensity of weathering

Theoretical Day Plots for
Magnetite (Dunlop, 2002)

Figure 4.18 Hysteresis properties of the Rosetta low/peak phase sequence. SD, PSD, and MD fields
according to Day et al. (1977). All samples regardless of lithology cluster tightly in the PSD field (see
discussion in Chapter 2).

Evans and Heller, 2003

Magnetic Susceptibility

<table>
<thead>
<tr>
<th>Magnetic Susceptibility</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-field susceptibility</td>
<td>( \chi_{hf} )</td>
</tr>
<tr>
<td>High-frequency susceptibility</td>
<td>( \chi_{hf} )</td>
</tr>
<tr>
<td>Initial susceptibility</td>
<td>( \chi_{int} )</td>
</tr>
<tr>
<td>Frequency-dependent susceptibility</td>
<td>( \chi_{fd} )</td>
</tr>
<tr>
<td>Ferrimagnetic susceptibility</td>
<td>( \chi_{ferri} )</td>
</tr>
<tr>
<td>In-phase susceptibility</td>
<td>( \chi' )</td>
</tr>
<tr>
<td>Out-of-phase susceptibility</td>
<td>( \chi'' )</td>
</tr>
</tbody>
</table>

\[
\chi = \chi_{dia} + \chi_{ferri} + \chi_{hem}
\]

\[
\chi_{hem} = \chi' - \chi''
\]

Figure 3. Whole core initial susceptibility records from Lake Vznětovský, Iceland (after Figure 1 of Thórarinsson and
Farrar, 1985). Even numbers indicate susceptibility maxima which can be correlated between cores (core numbers are
labeled at the bottom of each susceptibility curve).
Real and Imaginary Susceptibility

DC Susceptibility: Made in a dc field (constant with time)

\[
\frac{M}{H} = \frac{M_0}{H_0} = \chi
\]

AC susceptibility: Made in an externally-applied time-varying magnetic field

\[ H(t) = H_0 \cos(\omega t) \]

If magnetization responds perfectly (in-phase) with AC field: \( M(t) = M_0 \cos(\omega t) \)

The ratio \( \frac{M(t)}{H(t)} \) does not vary with time but maintains a constant value, equal to \( \frac{M_0}{H_0} = \chi \).

Real and Imaginary Susceptibility

There are three major physical mechanisms that produce out-of-phase AC signals:

1. Viscous relaxation (thermally-activated approach to an equilibrium state)
2. Electrical eddy currents (induced by the AC field in conductive materials)
3. Weak-field hysteresis (nonlinear and irreversible dependence of \( M \) on \( H \)).

Mechanisms (1) and (2) result in a frequency dependence of both in- and out-of-phase responses, whereas (3) yields signals that are independent of AC frequency (but dependent on AC amplitude).

Real and Imaginary Susceptibility

Néel theory

\[
dM/dt = (M_{eq} - M)/\tau
\]

\[ \tau'(M, H, T) = \tau \left( \frac{VM(T)H(T)}{2kT} \right) \]

\[ M(t) = M_0 e^{-\omega t/\tau} + M_{eq}(1 - e^{-\omega t/\tau}) \]

In a weak AC field both \( M \) and \( M_{eq} \) are time dependent

\[ M_{eq}(t) = \frac{VM_0(T)}{kF} - M_{eq}(H_0) \cos \omega t \]

solution

\[ M(t) = M_{eq}(t) \left[ \cos(\omega t) + \frac{\omega \tau M_{eq}}{1 + \omega^2 \tau^2} \sin(\omega t) \right] \]

In-phase

\[ \chi' = \frac{M_{eq}}{H_0(1 + \omega^2 \tau^2)} \]

Out-of-phase

\[ \chi'' = \frac{\omega \tau M_{eq}}{H_0(1 + \omega^2 \tau^2)} \]

\( M_{eq} \) = equilibrium magnetization in constant field \( H_0 \)
Viscous Relaxation and Superparamagnetism

\[ \chi' = \frac{M_{\infty}}{H_s(1 + \omega^2 \tau^2)} = \frac{\chi_{\infty}}{1 + \omega^2 \tau^2} \]

\[ \chi'' = \frac{\alpha \tau M_{\infty}}{H_s(1 + \omega^2 \tau^2)} = \frac{\alpha \tau \chi_{\infty}}{1 + \omega^2 \tau^2} \]

Néel showed that for non-interacting grains with a distribution of relaxation times, the quadrature signal is proportional to the frequency-dependence of the in-phase susceptibility.

\[ \chi' = \frac{\pi}{2} \frac{d \chi''}{d \ln(f)} \]

Néel Relationship

Tiva Canyon Tuff (Yucca Mtn): CS916

\[ \chi' = \frac{\pi}{2} \frac{d \chi''}{d \ln(f)} \]

Superparamagnetic behavior depends on the time scale of observation (the choice for \( \tau \)). Susceptibility can also be measured as a function of the applied oscillating field.

Tiva Canyon Tuff (Yucca Mtn): CS916

\[ \chi'' = \mu_0 \chi' \]

\[ \chi'' = \frac{\mu_0 \chi'}{3kT} \]
**Real and Imaginary Susceptibility**

OK, now suppose that you have measured a sample and discovered a significant $\chi'$. How can you decided between various sources?

<table>
<thead>
<tr>
<th>Source of $\chi'$</th>
<th>Candidate Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>conductive eddy currents</td>
<td>native gold or iron, or perhaps graphite</td>
</tr>
<tr>
<td>hysteresis</td>
<td>pyrrhotite, hematite, iron or titanomagnetite</td>
</tr>
<tr>
<td>short-period viscosity</td>
<td>Superparamagnetic particles</td>
</tr>
</tbody>
</table>

Measure in ac fields of different amplitude and different frequency. The relationships between $\chi'$ and the frequency- and amplitude-dependence of $\chi'$ allow identification of the origins of the quadrature signal.

viscous component: $\chi'' = -\pi / 2 \times d\chi'/d\ln(f)$

hysteretic component: $\chi'' = 4 / (3\pi) \times d\chi'/d\ln(H)$

**Frequency dependence of susceptibility**

$$X_M = X_0(f) - X_0(f_2) - X_0(f_1) \log(f_2/f_1) \times 100\%$$

$$f_1 < f_2$$

SPM particles described by Langevin Function

$$M = M' + iM'' = L\left(\frac{nM'H}{kT}\right)$$

$$X_0 = \frac{M}{H} = \frac{nM'}{kT}$$

$$\left(\frac{M'}{M}\right)^2 > \left(\frac{X_0}{M}\right)$$

Experimental results show that the % decrease in $\chi$ per decade of frequency is:

- 1-20% SPM grains
- <1% SD,MD grains

**Example:** Magnetosomes from recent samples from the Irish Sea salt marsh sediments

Hunt, et al., 1995

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**Susceptibility vs. Frequency**

- Paleosol
- SPM
- Loess
- MD

**Frequency (Hz)**

- **Susceptibility (m^3 kg^-1)**
  - $X_M = 7.8$
  - $X_M = 0.8$

Oldfield et al., 2009
Magnetic Grain size changes between Loess and Paleosols

Frequency-dependent susceptibility data vs. χARM/SIRM ratios

least weathered loesses plot towards the coarse-grained, multi-domain (MD) magnetite grains (≥5 μm)

the most developed soils plot towards the SP/SD size range

Inset: mathematical unmixing of the magnetic minerals and grain sizes in these loess and paleosols (Maher & Thompson, 1992).

Maher, 2009

Low-coercivity minerals

Saturation <300 mT

Fe₃O₄, γ-Fe₂O₃

High-coercivity minerals

Saturation >1000 mT

Open loop to high fields 'imperfect' Antiferromagnets
α-Fe₂O₃, α-FeOOH

Atmospheric Particulates

Magnetic discrimination of atmospheric dust and source regions

Figure B. Plot of SIRM/ARM versus frequency-dependent susceptibility (χf) for dust samples from the North Sea, North Atlantic, Sea of Japan, and Barbados (after Figure 1 of Oldfield et al., 1985). The data demonstrate that magnetic measurements can clearly differentiate between industrially derived dusts and those generated by wind erosion of different source areas. Reprinted with permission from Nature, 1985, Macmillan Magazines Limited.

High Coercivity Component: Canted AF phases

IRM Acquisition Curves

Goethite, Clay (Sh)
Synthetic Goethite (SG)
Hematite (Mn)
Synthetic Hematite (SG2014)

Soil samples (China)
Lake sediment (China)

France and Oldfield (2000)

Natural goethite
Step 1

High Coercivity Component
S ratio and HIRM

\[ SIRM = M_{\text{soft}} + M_{\text{hard}} \]

Step 2

Canted AF phases

\[ \text{IRM}_{bf} = -M_{\text{soft}} + M_{\text{hard}} \]

HIRM is mass normalized: concentration of AF phases (hard component)

S-ratio: relative contribution of Canted AF vs. Ferrimagnetic phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>( \text{IRM}_{1000\text{mT}} )</th>
<th>( \text{IRM}_{300\text{mT}} )</th>
<th>S-ratio</th>
<th>HIRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td>+SIRM</td>
<td>-SIRM</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>Hematite</td>
<td>+IRM</td>
<td>+IRM</td>
<td>-1</td>
<td>&gt;0</td>
</tr>
</tbody>
</table>

Classic S-ratio

Paleoclimate proxies in lake sediments

ARM-\( \chi \) method

Proxy record of Little-Ice Age (400-600 yrs BP)

During Little Ice Age:
Fine-grained material\( \rightarrow \) increase precip/runoff

Banerjee et al., 1981, redrawn by Tauxe, 2008
Archeological Example

ARM/\gamma model of various natural and anthropogenic soils from the Cahokia site showing relative variations in magnetite concentration and grain size


Paleoclimate proxies in marine sediments
North Atlantic Ocean (41°N)

Glacial periods
Low CaCO₂ productivity
High ice-rafted sediments

Decomposition of IRM acquisition/demagnetization curves into several components with the use of model function (e.g., log-Gaussian coercivity distributions)

Coercivity Component Analysis of Remanent Magnetization Curves (Unmixing)

LAP: linear acquisition plot
GAP: gradient of acquisition plot
\( B_{1/2} \): field required to magnetize half the population
DP: dispersion parameter

Acquisition curves can be differentiated (GAP) and then decomposed into different components assuming some distribution of coercivity (in this case log-normal).

Example (Red Bed)
Comp 1 (magnetite) \( B_{1/2} = 36 \text{ mT}, \text{DP} = 0.37, 14\% \)
Comp 2 (hematite) \( B_{1/2} = 471 \text{ mT}, \text{DP} = 0.44, 86\% \)

From Verosub and Roberts, 1995


Quantification of coercivity components by the analysis of acquisition curves of isothermal remanent magnetization

Egli, M., MAG-MIX, 2005

5/31/2013
**Coercivity Component Analysis of Remanent Magnetization Curves**

**Generalized Coercivity Distributions**

The resulting coercivity distribution is modeled using a linear combination of so-called skewed generalized Gaussian distribution functions (SGG), defined as:

\[
S^G(x, \mu, \sigma, q, p) = \frac{1}{\sigma \Gamma(p)} \left( \frac{q-1}{p} \right)^{-\frac{1}{p}} \left( 1 + \left( \frac{x-\mu}{\sigma} \right)^2 \right)^{-\frac{q}{p}} \exp \left( -\frac{1}{2} \left( \frac{x-\mu}{\sigma} \right)^2 \right)
\]

Gaussian function: \( q = 1, p = 2 \).
Symmetrical functions: \( q = 1 \).
Left-skewed functions: \( 0 < q < 1 \).
Right-skewed functions: \( -1 < q < 0 \).

**Mean coercivity Dispersion**


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**Coercivity Deconvolution: Magnetic Components**

**Magnetic Components**

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>biogenic soft</td>
</tr>
<tr>
<td>BH</td>
<td>biogenic hard</td>
</tr>
<tr>
<td>EX</td>
<td>ultrafine extracellular magnetite</td>
</tr>
<tr>
<td>D</td>
<td>detrital particles transported in water systems</td>
</tr>
<tr>
<td>PD</td>
<td>pedogenic magnetite/maghemite</td>
</tr>
<tr>
<td>ED</td>
<td>windblown particles (eolian dust)</td>
</tr>
<tr>
<td>UP</td>
<td>atmospheric particulate matter produced by urban pollution</td>
</tr>
<tr>
<td>L</td>
<td>maghemite component in loess</td>
</tr>
</tbody>
</table>

**MDF_{ARM} vs. \( \chi_{ARM}/SIRM \)**

Non-interacting SD > 1.5 mm/A

Egli, 2004

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**Magnetic properties of a Holocene soil profile (Wind River Range, Wyoming)**

Magnetic coercivity distributions (backfield demagnetization curves up to 2 T)

Two components of the magnetic coercivity distributions: a soft component (characterized with two curves) and a hard component
Paleoclimate proxies in continental eolian deposits

Kukla et al.’s (1988) demonstration that oceanic temperatures (glacial/interglacial) from $\delta^{18}O$ data are reflected in the $\chi$ records from two sites in central China

Kukla, G. J et al., Pleistocene climates dated by magnetic susceptibility, Geology, 16, 811-814, 1988

Two models were initially evoked to explain the relationship between stratigraphy and susceptibility

- Both necessitate that $\chi$ is only a function of concentration of magnetite, grain size and mineralogy are constant

1) Heller & Liu (1984) suggested that carbonate dissolution during soil formation increases the concentration of magnetite.
   - This model does not work because the maximum amount of carbonate is 20%.

2) Kukla (1988) suggested that there was a constant input of magnetite but the other detrital material varied with the strength of the winter monsoon
   - This model is incorrect because the grain size of the magnetite is not constant.

Stratigraphy and magnetic susceptibility records for three sites spanning the Chinese Loess Plateau

More developed soil magnetic enhancement
(wetter sites, south and east)


What drives the variation in magnetic properties of the Chinese loess?

- Paleosols have greater amounts of fine-grained magnetite than loess intervals.
- Based on chronologies from wiggle matching with $\delta^{18}O$ records accumulation rate of magnetite is greater in paleosols.
- Thus at least some of the variation in susceptibility is likely due to pedogenic formation of fine-grained magnetite.
  - At the present the favored hypothesis is that the during warmer/wetter interglacials pedogenesis is enhanced and thus so is the formation of pedogenic magnetite

Stratigraphy and magnetic susceptibility records for three sites spanning the Chinese Loess Plateau

Arid site (west)  More humid site (east)  Most humid site (south)
Turning susceptibility into paleorainfall

Relationship between pedogenic (soil-formed) $\gamma$ and annual rainfall for modern soils and modern (last 30-year averages) rainfall.

Statistical examination of the relationships between the soil magnetic properties and major climate variables (temperature, rainfall, etc.) identifies annual rainfall as the most significant factor.

The relationship between soil magnetism and rainfall can thus be expressed as the equation shown in the figure. (Maher et al., 2002)

Magnetic Parameters and Ratios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPM</th>
<th>SD</th>
<th>MD</th>
<th>FM phases</th>
<th>AFM phases</th>
<th>Grain size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_r/M_s$</td>
<td>0</td>
<td>&lt;&lt;0.05</td>
<td>&gt;0.4</td>
<td>&lt;0.05</td>
<td>+</td>
<td>Yes</td>
</tr>
<tr>
<td>$B_r/B_c$</td>
<td>&gt;10</td>
<td>1-1.5</td>
<td>3-4</td>
<td>+</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$ARM/\gamma$</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>+</td>
<td>*</td>
<td>Yes</td>
</tr>
<tr>
<td>$\chi_{eff}/SIRM$</td>
<td>&lt;0.0015</td>
<td>m/A</td>
<td>&gt;0.0015</td>
<td>m/A</td>
<td>+</td>
<td>*</td>
</tr>
<tr>
<td>$SIRM/\gamma$</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>+</td>
<td>*</td>
<td>Yes</td>
</tr>
<tr>
<td>$\chi_{eff}/\gamma$</td>
<td>&gt;0%</td>
<td>~0</td>
<td>~0</td>
<td>+</td>
<td>SPM</td>
<td></td>
</tr>
<tr>
<td>$HIRM$</td>
<td>~0</td>
<td>&gt;0</td>
<td>~0</td>
<td>~0</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

High susceptibility: MD or SPM
Low remanence: MD or SPM
Low $\gamma$: Difficult to magnetize

Paleorainfall estimated from the $\gamma$/rainfall climofunction for

- the last 10,000 years (Duowa, western Loess Plateau)
- the last 1.1 million years (Xifeng, central Plateau).

During the last glaciation (around 20 ky BP), rainfall was reduced across the whole region, while in the last interglacial (~120-125 ky BP), rainfall was much higher especially in the western Plateau, which is semi-arid at present.

Separation of local signals from the regional paleomonsoon record
(from Banerjee et al., 1993)

Variation in the SPM component between two nearby sites with arid (Baicaoyuan) and humid (Xifeng) microclimates. A mountain range causes a rain-shadow in the arid site, whereas high rainfall at Xifeng produces higher SPM content.

Variations in the SPM content may represent past changes in the summer paleomonsoon intensity.

At Time $T_s$ (5-10 Ka): SPM content equal suggesting summer monsoons came from south (removing rain shadow effect)