Environmental Magnetism: a case study
The Chinese Loess
What is Environmental Magnetism?

- Characterize the iron mineralogy of a natural archive (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.
Why Magnetism?

- iron minerals are: abundant, sensitive redox indicators, often weathering products, often related to microbial activity

- magnetic measurements are: fast, inexpensive, non-destructive (mostly), quantitative and sensitive (100 ppb)
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

- Magnetic parameters (or measurements) are sensitive to 1, 2, or all 3 of these variables.
World-wide loess distribution
What is Loess?

- Terrestrial wind-blown silt deposit with secondary calcification or “loessification”
Sun, et al., 1998

Pingliang

Stratigraphy
Inclination
Declination
Polarity
GPTS (Myr)

Malan
-90 0 90 180 270 360 90

Lishi

Wucheng

Red Clay

Depth (m)

Loess
Palaeosol
Red Clay
Fluvial Sand

Stratigraphy cont.
Inclination
Declination
Polarity
GPTS (Myr) cont.

Brunhes

Matuyama

Red Clay

Depth (m)

Gauss
Gilbert
3A

Sand

3.0
4.0
5.0
7.0
Heller & Liu, 1984
Kukla, 1988
Evans & Heler, 2003
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.
Concentration

- Magnetic moments (how magnetic a sample is) 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 $92 \text{ Am}^2/\text{kg}$.

- The saturation magnetization for a sample composed of 99.9% quartz, and 0.1% magnetite $M_s = 0.092 \text{ Am}^2/\text{kg}$. 
Concentration

![Graph showing the relationship between concentration and magnetic field strength.](image-url)
Magnetic Grain Size

Superparamagnetic  Single Domain  Multidomain

Grain Size, \( d < 30 \text{ nm} \)
no remanence

Grain Size, \( 30 \text{ nm} < d < 1000 \text{ nm} \)
very large magnetization increase in small fields, i.e., very high \( \chi \). very soft, magnetically

Grain Size, \( 1 \times 10^7 \text{ nm} < d \)
small remanence

Grain Size, hard, magnetically

small magnetization increase in small fields, i.e., small \( \chi \). soft, magnetically

Grain Size

![Graph showing magnetic behavior with 'SD' and 'SP' labels]
Grain Size Dependency of Susceptibility

- Superparamagnetic grains (those grains with relaxation times on the order of the measurement time) have very high susceptibilities compared to single domain and multi domain grains (10-100 times larger)

- Moreover, superparamagnetic grains can have a frequency dependence of susceptibility.
Relaxation, magnetic viscosity, or superparamagnetism: it’s all about time

- For multidomain and single domain grains the change in magnetization with changing applied field is practically instantaneous.

- For superparamagnetic grains they reach their equilibrium magnetization exponentially—the time this takes is described by the relaxation time:

\[
\frac{1}{\tau} = f_0 \exp\left(\frac{-k_u V}{kT}\right)
\]
What exactly is susceptibility?
How susceptibility is measured

- Typically, instead of applying DC fields (constant with time), AC (non-constant with time) are used

\[ \frac{M_{\text{max}}}{H_{\text{max}}} = \chi \]
Maher & Thompson, 1991
### Mineralogy

#### Classes of magnetic materials

- **Ferromagnetic**: Like Refrigerator magnets
- **Ferrimagnetic**: Like Refrigerator magnets
- **Antiferromagnetic**: Like Refrigerator magnets

#### Paramagnetic

- Like Refrigerators

#### Important Terrestrial and Extraterrestrial Iron Minerals

<table>
<thead>
<tr>
<th>Ferrimagnetic</th>
<th>Antiferromagnetic</th>
<th>Paramagnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td>Hematite</td>
<td>Biotite</td>
</tr>
<tr>
<td>Maghemite</td>
<td>Goethite</td>
<td>Clay Minerals</td>
</tr>
<tr>
<td>Titanomagnetite</td>
<td>Ferrihydrite</td>
<td>Siderite</td>
</tr>
<tr>
<td>Greigite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
More on Mineralogy

- Magnetic anisotropy is affected by mineralogy
  - Magnetocrystalline anisotropy
  - Magnetostriction
  - Relative strength of shape anisotropy

- Phase changes can affect the magnetic properties of a mineral

- Magnetic transitions
  - Curie temperatures are different for different minerals
  - The Morin transition in hematite (240 K)
More on Mineralogy

![Graph showing magnetization curves for SSD Magnetite and Hematite.](image)
Magnetic effects of pedogenesis at two sites in China.
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
Remaining Questions

▪ How exactly is the pedogenic magnetite formed?
  ▫ Are bacteria important? Initial studies suggest yes.
  ▫ Role of organic matter

▪ The role of other iron oxides?

▪ How accurate is the paleomagnetic stratigraphy?
  ▫ Studies suggest a “lock-in” delay of about ~10ky
  ▫ Other studies suggest rapid changes in the field are recorded (i.e., paleosecular variation)

▪ Very old (age>16mya) Chinese loess?
Zhou et al., 2002