Today’s Schedule

• Introduction to Geomagnetism, Paleomagnetism and Rock Magnetism
• BREAK
• Lab Tour: Institute for Rock Magnetism (Shepherd Labs, second floor)
• ADJOURN
Incorporated Research Institutions for Seismology (IRIS)
Consortium for Materials Properties Research in Earth Sciences (COMPRES)
UNAVCO, A Geodetic Consortium
GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source (GSECARS)
Purdue Rare Isotope Measurement Laboratory (PRIME Lab)
NSF - University of Arizona Accelerator Mass Spectrometer (AMS) Laboratory
Institute for Rock Magnetism (IRM)
UCLA SIMS Laboratory (UCLASIMS)
Arizona State University SIMS Laboratories
University of Texas High-Resolution X-ray Computed Tomography Facility (UTCT)
National Center for Airborne Laser Mapping (NCALM)
Amino Acid Geochronology Laboratory (AAGL)
Drilling, Observation and Sampling of the Earth’s Continental Crust, Inc. (DOSECC)
Arizona LaserChron Center (ALCC)
The University of Wisconsin SIMS Lab (Wisc-SIMS)
What is Rock Magnetism?

- **Geomagnetism**
  Study of the Earth’s magnetic field, short-term time variations and origins

- **Paleomagnetism**
  Study of the Earth’s magnetic field over geological time, as recorded in remanent magnetization in naturally occurring magnetic minerals

- **Rock Magnetism (fundamental)**
  Study of the physical/chemical basis of paleomagnetism

- **Rock Magnetism (applied)**
  Magnetic characterization of rock/sediment fabric, iron mineralogy and size distributions
Why Study Paleomagnetism and Geomagnetism?

• Probe of Deep Earth Dynamics

(Glatzmaier and Roberts, Nature 377: 203-209, 1995
Glatzmaier and Olson, SA, 2005)
Probe of Deep Earth Dynamics: Role of Inner Core?

Paleointensity and Growth of Inner Core
(Tarduno et al., 2006)
Probe of Deep Earth Dynamics: Reversal Paths and CMB Heterogeneity?

Record of polarity transition recorded at Steens Mountain (Figure from Tauxe, 2005)

Core-mantle boundary topography (figure from Costin & Buffett, 2004)
Probe of Deep Earth Dynamics: Reversals and Paleointensity Variations

Long-term Paleointensity
Tauxe & Staudigel, GGG 2004
Why Study Paleomagnetism and Geomagnetism?

Geochronology
Why Study Paleomagnetism and Geomagnetism?

• Geologic and Geophysical History of lithospheric plate motions
Why Study Paleomagnetism and Geomagnetism?

Regional Tectonics

Tectonostratigraphic terranes of the North American Cordillera. (From Butler, 1992)
Why Study Paleomagnetism and Geomagnetism?

Environmental Magnetism (Paleoclimatic reconstructions, sediment source tracing)

Egli, 2005
Environmental Magnetism (Paleoclimatic reconstructions, sediment source tracing)

Chinese Loess

Verosub & Roberts, 1995
Environmental Magnetism (Paleoclimatic reconstructions, sediment source tracing)

Paleoprecipitation maps for the Chinese Loess Plateau, based on magnetic properties
Why Study Paleomagnetism and Geomagnetism?

Geomicrobiology

Magnetotactic bacteria synthesize chains of magnetic nanoparticles that help them navigate in the geomagnetic field.

Magnetofossils in Marine sediments (S. Atlantic, Angola Basin, 50 ma)

Possible oldest magnetofossils ~2 Gyr stromatolithic chert (Chang et al., 1989)

Favre and Schuler, 2008
Martian Magnetofossils???

Nanoparticles of magnetite as potential biomarkers

(K.L. Thomas-Keprta, GCA, 2000)
Martian Magnetic Anomalies

Mars Global Surveyor, 1999
What Makes Paleomagnetism Possible?

• **SIGNAL**: Planetary Magnetic Field (>3 Ga)
  – Fe is 4th most abundant element in crust
  – Fe has the property of permanent magnetism

• **Recording Media**: Fe forms oxides and sulfides, some of which are magnetic minerals
  – Fe-oxides are common accessory minerals in rocks, sediments, soils (<1% vol)

• **Recording Processes**: Earth’s magnetic field can be recorded during various geological processes

*Tauxe, 2008*
# Types of NRM

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<tr>
<th>Type</th>
<th>Process</th>
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<td><strong>Primary NRM</strong></td>
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<tr>
<td>Thermoremanent Magnetization (TRM)</td>
<td>Cooling through $T_c$</td>
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<td>Detrital Remanent Magnetization (DRM)</td>
<td>Deposition of magnetic grains</td>
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<td>Chemical Remanent Magnetization (CRM)</td>
<td>Growth (alteration) of magnetic grains</td>
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<td><strong>Secondary NRM</strong></td>
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<td>Viscous Remanent Magnetization (VRM)</td>
<td>Long-term exposure to $H_a$</td>
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<td>Isothermal Magnetization (IRM)</td>
<td>Lighting strikes Exposure to large $H_a$</td>
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<td>Chemical Remanent Magnetization (CRM)</td>
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<td>Partial TRM (pTRM)</td>
<td>Reheating below $T_c$</td>
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What Makes Paleomagnetism Possible?

- Sensitive magnetometers are available to measure the weak magnetic signals in earth (and planetary) materials.
How is Rock Magnetism Different from the Study of Magnetic Recording and Permanent Magnets?

**Hard Disk:** highly ordered magnetic system designed to carry maximum information content in smallest possible space

**Rock:** Not optimized for magnetic recording

- Disordered system of irregular shaped particles with complex compositions, geometries, and crystal defects
- Magnetic minerals form only a small (<1%) fraction of most rocks
- Multiple magnetic phases occurring over a broad range of particle sizes
- Magnetic fields in Nature are weak

“**Rock**” = an assemblage of ferrimagnetic/antiferromagnetic phases in a paramagnetic/diamagnetic matrix

(Krása et al., 2005)
Physics of Magnetism

Electricity → Magnetism

Hans Christian Oersted (1777-1851)

Current flowing in a wire deflects a compass needle

Discovers magnetism due to electric currents.

André-Marie Ampère (1775-1836)

Explains magnetism in terms of forces between electric currents

O’Handley, 2000

O’Handley, 2000
<table>
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<th>Magnetic field source</th>
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<td>$10^{-11}$</td>
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<td>Galactic field</td>
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<td>Good magnetic screen, conventional</td>
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<td>Field anomalies produced by crustal rocks (Earth)</td>
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<td>Strong magnetic storm (Earth)</td>
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<td>Earth magnetic field (mid latitudes)</td>
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<td>Superconducting magnet (2008)</td>
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Physics of Magnetism

**Magnetism → Electricity**

Michael Faraday (1791-1867)

1831 Faraday’s Law

A time varying magnetic field induces an electric current in a coil

James Clerk Maxwell (1831-1879)

1873 Maxwell’s Equations

Unified Electricity, Magnetism, and Optics

\[
\nabla \times E = -\frac{\partial B}{\partial t}
\]

\[
\nabla \times B = \mu_0 \left( J + \varepsilon_0 \frac{\partial E}{\partial t} \right)
\]

\[
\nabla \cdot E = \frac{\rho_c}{\varepsilon_0}
\]

\[
\nabla \cdot B = 0
\]

*Then there was light*
Magnetism of Solid Materials

Atomic dipole moments
  – Microscopic current loops

Magnetic moments are produced by electrical currents associated with the motion of electron about atomic nuclei

Bar magnet

Current-carrying solenoid
Earth as a Magnet

Geomagnetic Field at surface is similar to a magnetic dipole

- Magnetic inclination is related to geographic latitude
- North magnetic pole ≈ aligned with rotation axis
Components of the Magnetic Field

\[ B_n = B \cos(I) \]

\[ B_v = B \sin(I) \]

\[ B (\text{units}) = \text{Tesla} \]

\[ B_{\text{earth}} \sim 30-60 \times 10^{-6} \text{ T} \ (30-60 \, \mu\text{T}) \]

**Angle of Declination** \( D \)
Compass direction \( 0^\circ \leq D \leq 360^\circ \)

**Angle of Inclination** \( I \)
\( -90^\circ \leq I \leq 90^\circ \)

*Butler, 1992*
Declination
(Isogonic maps)

Inclination
(Isoclinic maps)

IGRF Model 2005
International
Geomagnetic
Reference Field

Total Intensity
(Isodynamic maps)

http://www.ngdc.noaa.gov/wist/magfield.jsp
Magnetic Poles

Magnetic North Pole where the magnetic field is straight down ($I = +90$).

Geomagnetic North Pole where the axis of the best tilting dipole pierces the surface.

Geographic North Pole

Virtual Geomagnetic Pole (VGP). Geocentric dipole which would give rise to the observed magnetic field direction at a given latitude ($\lambda$) and longitude ($\phi$)

Paleomagnetic Pole. Ancient pole position averaged over $10^6$-$10^8$ years
Magnetic field of the Earth measured at the surface comes from three sources:

- Main field generated by dynamo action in the outer core
- External field generated in space in the magnetosphere
- Crustal field from remanent magnetization

External field varies with time scales of minutes to days
Core field varies with time scales from years to millions of years

(Constable, 2007)
Crustal Magnetic Field

NGDC-720: $B_z$ at Earth’s Surface

Permanent (remanent) magnetization only possible above the Curie depth
Direction of remnant magnetization depends on main field direction at time rocks became magnetized

http://www.ngdc.noaa.gov/geomag/EMM/emm.sht
REVISED AEROMAGNETIC DATA FOR MINNESOTA
2007
Val W. Chandler and
Richard S. Lively, MGS
Time Variations in GMF

- Most of surface field (~99%) is generated in liquid outer core
  - Flow is influenced by rotation of Earth and geometry of inner core
  - Flow produces secular variation in magnetic field
- Crustal magnetic sources makes a small, static contribution
- External field (outside of solid earth)

Interactions of charged particles and $B_E$

Olson et al., 2007
Secular Variation of Geomagnetic Field

- Historical record of geomagnetic field direction at Greenwich, England.
- Change in Declination in Minnesota (1900-2005)

Time variation
→ internal motions of km’s/year

Butler, 1992
Computer-simulated magnetic dipole reversal

Glatzmaier and Coe, 2007
Reversal History

Geomagnetic polarity timescale from marine magnetic anomalies for 0–160 Ma.
Reversal History

Early Mesozoic, Paleozoic, Precambrian

Exposed stratigraphic sections on land GPTS much less refined

On average field spends about 50% of its time in each polarity

1-2% in transitional state

Butler, 1992
Origins of the Geomagnetic Field

1. **Remanent Magnetization of Crust?**
   Too weak

2. **Remanent Magnetization of Mantle or Core?**
   Too hot, Cannot exist (T>Curie Temperature)

3. **Primordial Magnetic Field?**
   - equatorial current flow
     Too old, Subject to diffusion (time<10⁴ yr)

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**Geodynamo action in liquid outer core**
Current must be maintained

**3 Basic Conditions for generating Planetary magnetic Field**

- Large volume of electrically conductive fluid
- Thermal/chemical convection (energy source)
- Rotation (fluid motion)

3D magnetic field from Glatzmaier-Roberts geodynamo model
Mineral Magnetism

Chemical composition

Crystallographic structure

Temperature

Applied magnetic fields

Magnetite octahedra from Cerro Huanaquino, Bolivia.
# Magnetic Periodic Table

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<td></td>
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<tr>
<td>Es</td>
<td>100</td>
<td>Flerovium</td>
<td>289.00</td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- Nonmetal
- Metal
- Diamagnet
- Paramagnet
- Ferromagnet $T_C > 290$K
- Antiferromagnet $T_N > 290$K
- Antiferromagnet/Ferromagnet with $T_N/T_C < 290$ K

**Magnetic Properties:**
- Ferromagnet $T_C > 290$K
- Antiferromagnet $T_N > 290$K
- Antiferromagnet/Ferromagnet with $T_N/T_C < 290$ K

**Typical Ionic Charge:**
- $1^+$
- $2^+$
- $3^+$

**Antiferromagnetic $T_N(K):$**
- $179.85$

**Ferromagnetic $T_C(K):$**
- $182.50$
Classification of Magnetic Materials

3 Main Types

T=300 K, B=1 T, H=80,000 A/m

SiO₂ (quartz)
M=-0.0005 Am²/kg

Fe₂SiO₄ (fayalite olivine)
M=0.1 Am²/kg

Fe₃O₄ (magnetite)
M=92Am²/kg

Diamagnetism

Paramagnetism

Ferromagnetism
**Diamagnetism** (no magnetic atoms)

An external field can modify electron orbitals producing a small induced magnetization opposite to the applied field.

Diamagnetic materials are pushed away from strong fields (magnetic levitation).

Diamagnetism is very weak and usually masked by paramagnetism and ferromagnetism.

\[ \chi(x10^{-8} \text{ m}^3/\text{kg}) \]

- Quartz (SiO$_2$) -0.62
- Calcite (CaCO$_3$) -0.48
- Water -0.90
**Paramagnetism** (magnetic atoms not ordered)

Magnetic Energy: Application of field causes alignment of moments
\[ E_m = \mu B \cos \theta \]

Thermal Energy: Randomizes moment
\[ E_T = kT, \ k=\text{Boltzmann’s constant} \ (k=1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}) \]

**Example**
Fayalite \((\mu=5\mu_B)\)

<table>
<thead>
<tr>
<th>B, T</th>
<th>(E_m)</th>
<th>(E_T)</th>
<th>(E_m/E_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B=0.01 T, T=300K</td>
<td>4.6x10^{-25} J</td>
<td>4.1x10^{-21} J</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>B=1T, T=10K</td>
<td>4.6x10^{-23} J</td>
<td>1.38x10^{-22} J</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Ferromagnetism  (magnetic atoms spontaneously aligned)

Key features of ferromagnetic materials

Shape of M-H curve

![Graph showing the shape of M-H curve for Magnetite with d=50 nm.](image)

Magnetite

Hysteresis
Spontaneous (saturation) Magnetization

- \( \text{Fe}_3\text{O}_4 \): 480 kA/m
- Fe: 1700 kA/m

Shape of M-T curve

![Graph showing the shape of M-T curve for Magnetite.](image)

Magnetic Ordering Temperature

(\( T_c \), Curie Temperature)

- \( \text{Fe}_3\text{O}_4 \): 580°C
- Fe: 780°C
- Ni: 358°C
- Co: 1121°C
Magnetically Ordered Materials

When the applied field is zero, the internal field is still present and leads to magnetic ordering and spontaneous magnetization.

<table>
<thead>
<tr>
<th>Magnetic Order</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromagnetism</td>
<td>Fe, Ni, Co, NiFe, Gd</td>
</tr>
<tr>
<td>Antiferromagnetism</td>
<td>MnO, FeTiO₃ (ilmenite)</td>
</tr>
<tr>
<td>Ferrimagnetism</td>
<td>Fe₃O₄ (magnetite), MO•Fe₂O₃, where M=transition metal</td>
</tr>
</tbody>
</table>
Main Types of Magnetic Ordering

(c) Ferromagnetism

(d) Antiferromagnetism

(Fe, Ni) 

(ilmenite, FeTiO₃)

(a) Ferrimagnetism

(b) Canted antiferromagnetism

(magnetite, Fe₃O₄)

(hematite, α-Fe₂O₃)

(goethite, α-FeO(OH))
## Antiferromagnetic Minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>$T_N$ (K)</th>
<th>$M_s$ (Am$^2$/kg)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ilmenite ($\text{FeTiO}_3$)</td>
<td>40</td>
<td>0</td>
<td>AFM</td>
</tr>
<tr>
<td>Ulvospinel ($\text{Fe}_2\text{TiO}_4$)</td>
<td>120</td>
<td>0</td>
<td>AFM</td>
</tr>
<tr>
<td>Hematite ($\alpha$-$\text{Fe}_2\text{O}_3$)</td>
<td>948</td>
<td>0.4</td>
<td>canted</td>
</tr>
<tr>
<td>Goethite ($\alpha$-$\text{FeOOH}$)</td>
<td>393</td>
<td>~0.5</td>
<td>defect</td>
</tr>
<tr>
<td>Lepidocrocite ($\gamma$-$\text{FeOOH}$)</td>
<td>52</td>
<td>~0.1</td>
<td>defect</td>
</tr>
<tr>
<td>Siderite ($\text{FeCO}_3$)</td>
<td>37</td>
<td>0.38</td>
<td>canted</td>
</tr>
<tr>
<td>Rhodocrosite ($\text{MnCO}_3$)</td>
<td>34</td>
<td>0.46</td>
<td>canted</td>
</tr>
<tr>
<td>Vivianite ($\text{Fe}_3[\text{PO}_4]_2\text{H}_2\text{O}$)</td>
<td>~12</td>
<td>0.06 (?)</td>
<td>defect?</td>
</tr>
<tr>
<td>Ferrihydrite ($\text{Fe}_5\text{HO}_8\text{H}_2\text{O}$)</td>
<td>~500</td>
<td>6-12</td>
<td>non-compensated</td>
</tr>
</tbody>
</table>

Data from various sources
# Ferrimagnetic Minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>$T_N$ (K)</th>
<th>$M_s$ (Am$^2$/kg) at 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite ($\text{Fe}_3\text{O}_4$)</td>
<td>853</td>
<td>92</td>
</tr>
<tr>
<td>Maghemite ($\gamma\text{-Fe}_2\text{O}_3$)</td>
<td>863-948</td>
<td>73</td>
</tr>
<tr>
<td>Greigite ($\text{Fe}_3\text{S}_4$)</td>
<td>Unknown, &gt;593</td>
<td>59</td>
</tr>
<tr>
<td>Pyrrhotite ($\text{Fe}_7\text{S}_8$)</td>
<td>593</td>
<td>20</td>
</tr>
<tr>
<td>Jacobsite ($\text{MnFe}_2\text{O}_4$)</td>
<td>673</td>
<td>77</td>
</tr>
<tr>
<td>Trevorite ($\text{NiFe}_2\text{O}_4$)</td>
<td>713</td>
<td>51</td>
</tr>
<tr>
<td>Daubreelite ($\text{FeCr}_2\text{S}_4$)</td>
<td>~170</td>
<td>~30 (at 70 K)</td>
</tr>
<tr>
<td>$\varepsilon\text{-Fe}_2\text{O}_3$</td>
<td>~510</td>
<td>~15</td>
</tr>
<tr>
<td>Feroxyhyte ($\delta\text{-FeOOH}$)</td>
<td>440-460</td>
<td>~12</td>
</tr>
</tbody>
</table>

Data from various source
Nonuniform Magnetization in Bulk Ferro- and Ferrimagnetic Materials: Domains

(110) Fe_3O_4

(100) Fe_3O_4

(100)-oriented silicon iron crystal

(100) Titanomagnetite

(subdivision into domains reduces total magnetic moment, lower-energy state)

http://www.ifwdresden.de/institutes/imw/sections/24/members/schaefer/magnetic-domains/5
Magnetization process in SD Grains
Rotation of Moments
Response of a random assemblage of uniaxial single domain (SD) particles during hysteresis cycle

Single Domain Behavior
SD particles produced by magnetotactic bacterium strain MV-1
d ~ 30-100 nm

Frankel and Moskowitz, 2003

Tauxe, 2008
Magnetization process in MD grains
Translation of domain walls

a) Demagnetized state
b) In the presence of a saturating field,
c) Field lowered to +3 mT
d) Remanent state, e) back field of -3 mT,

Inset shows detail of domain walls moving by small increments called Barkhausen jumps.

(Domain wall observations from Halgedahl and Fuller, J. Geophys. Res., 88, 6505-6522, 1983)
Room temperature saturation remanence ($M_{rs}$) and coercivity ($H_c$) as a function of grain size for magnetite (Dunlop and Özdemir 2007)
Magnetic Mineralogy

Magnetite and Titanomagnetites \( (\text{Fe}_{3-x}\text{Ti}_x\text{O}_4) \)
Hematite and Titanohematites \( (\text{Fe}_{2-y}\text{Ti}_y\text{O}_3) \)
Maghemite and Titanomaghemites

Chemical Change
- Exsolution
  - High temperature oxidation, \( T>600 \, \text{C} \) (oxy-exsolution)
  - Low temperature oxidation (titanomaghemites)

Magnetic Oxyhydroxides, Sulfides, and Fe-Ni

Exsolved titanomagnetite grain (width of image =320\( \mu \text{m} \))

Bacterial Magnetite (Sicily Strait, Dinares-Turell et al., 2003)
Ternary diagram for iron-oxides

Most Important Magnetic Phases

Titanomagnetites \( (\text{Fe}_{3-x}\text{Ti}_x\text{O}_4) \)
Titanohematites \( (\text{Fe}_{2-y}\text{Ti}_y\text{O}_3) \)
oxidized forms \((z)\)
Magnetite

Curie Temperature: 853 K (580 °C)
Saturation Magnetization at 23° C
92 Am²/kg
480 kA/m

Crystallographic (Verwey) transition
\[ T_V = 122 \text{ K (-151 °C)} \]

\[ M_s(T) = (T_c - T)^{\gamma} \]
\[ \gamma = 0.36 \]
\[ \gamma = 0.39 \]

\[ T < T_V \text{ Monoclinic} \]
\[ T > T_V \text{ Cubic} \]

Photo by Rob Lavinsky, iRocks.com
Hematite: $\text{Fe}_2\text{O}_3$

Curie Temperature: $953 \text{ K (680 }^\circ \text{C)}$
Saturation Magnetization at 300 K
  - Pure AF: $0.5 \text{ Am}^2/\text{kg}$
  - Canted AF: $2 \text{ kA/m}$

SEM image of hematite. Image is $\sim 800 \mu m$ across.

Wikipedia Commons

Dunlop and Özdemir, 1997; Butler, 1
Other Common Magnetic Phases

Goethite (\(\alpha\)-FeOOH)

Common weathering product and precursor to hematite in sediments and soils.

Saturation Magnetization
~0.1 Am\(^2\)/kg
1-2 kA/m

\(T_N = 393\) K

Özdemir and Dunlop (1996)
Iron-Sulfides: Pyrrhotite

**Monoclinic pyrrhotite** (Fe$_7$S$_8$):
- Ferrimagnetic
- $T_c$=593 K (320°C)
- $M_s$=~20 Am$^2$/kg (80 kA/m)

**Hexagonal pyrrhotite** (Fe$_{10}$S$_{11}$, Fe$_9$S$_{10}$):
- Structural transition from an (imperfect) antiferromagnet to ferrimagnet at about 200°C.

Fe$^{2+}$ cations are FM coupled within c-planes and AF coupled between layers via S$^{2-}$ ions.
Iron-Sulfides: Greigite ($\text{Fe}_3\text{S}_4$)

Crystal Structure: Cubic, Inverse spinel
Magnetic Structure: Ferrimagnetic

$M_s = 125 \text{ kA/m, } 59 \text{ Am}^2/\text{kg}$

Low-temperature measurements of $M_s$

Chang et al., 2008
Greigite and Pyrrhotite occur in reducing environments and both tend to oxidize to various iron oxides leaving paramagnetic pyrite as the sulfide component.