Magnetic Remanences

TRM (Thermoremanent Magnetization)
pTRM (Partial Thermoremanent Magnetization)
SR-TRM (self-reverse TRM)
VRM (Viscous Remanent Magnetization)
TVMR (Thermoviscous Remanent Magnetization)
CRM (Chemical Remanent Magnetization)
DRM (Detrital Remanent Magnetization)

Types of NRM

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<td>pTRM</td>
<td>Reheating below ( T_c )</td>
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Natural Remanent Magnetization (NRM)

\[ J = J_{\text{induced}} + J_{\text{remanent}} \]
\[ J_{\text{induced}} = x_0 H_a \]

NRM is a function of several important parameters

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NRM = Primary + Secondary

Component formed during initial rock formation
Component(s) formed at some later time

Thermoremanent Magnetization

TRM is the magnetization produced by cooling from above the Curie temperature \( T_c \) in the presence of a magnetic field without any physical or chemical changes.

TRM is a thermally-activated magnetization and is the form of remanent magnetism acquired by most igneous rocks.

I lava flows, welded tuff deposits (ignimbrites), dikes, gabbros, anorthosites, granites
TRM

Let’s do the following experiments on identical samples containing SD grains:

1. Give a sample a TRM by cooling from \( T_c \) to room temperature in \( B_a = 50 \mu T \)
2. Give a sample an isothermal remanent magnetization (IRM) in the same field at room temperature without any heating.

**Observations**

Intensity of Magnetization: \( J_{TRM} > J_{IRM} \)

Field needed to reduce \( J \) to zero:

\[
\begin{align*}
J_{IRM}: B &= B_a (50 \mu T) \\
J_{TRM}: B &= B_a > B_a \\
B_a (coercivity of remanence) &\sim 50-100 \text{ mT}
\end{align*}
\]

At surface temperatures, TRM can be stable over geologic time and resistant to remagnetization by the geomagnetic field (\( B_a > B_a \)).

**Some Experimental Properties of TRM**

Weak-Field TRM: \( B_0 < B_a \)

- \( J_{TRM} \) is parallel to \( B_0 \)
- \( |J_{TRM}| \propto |B_0| \)
- \( |J_{TRM}| \) decreases with particle size
- Equivalence of blocking and unblocking temperatures in heating and cooling (\( T_B = T_U \))

\( B_a (coercivity of remanence) \)

\( \sim 50-100 \text{ mT} \)

At surface temperatures, TRM can be stable over geologic time and resistant to remagnetization by the geomagnetic field (\( B_a > B_a \)).

**Theoretical Model of TRM for SD grains**

Néel (1949) established the theoretical basis for understanding thermally-activated magnetization.

Very small changes in \( v, T, \) or \( H \) can produce very large changes in relaxation times.

**Starting Assumptions:**

Consider an assemblage of identical, non-interacting, SD grains.

The magnetic moment of an SD grain can point in one of two equal and opposite directions (uniaxial anisotropy).

Above \( T_B \), the magnetic moment will flip rapidly between these two antiparallel directions.

\( J_{TRM} \) is parallel to \( B_0 \).

Agreement of directions of thermoremanent magnetization in a basaltic lava flow on Mt. Etna (Sicily) with the direction of the geomagnetic field during eruption of the lava (based upon data from Chevallier, 1925).

\[ \text{Mt. Etna lavas (Chevallier, 1925)} \]
**Néel Model for SD Thermoremanent Magnetization**

Two-state particle (parallel or antiparallel to $H_0$)

$$E_x = +\mu_0 v M_i H_0, n_+$$
$$E_y = -\mu_0 v M_i H_0, n_-$$

The energy difference between these two states will create a preference for occupying the state where $m$ is parallel to $H$.

**But**, thermal energy ($kT$) acts as a randomizing influence.

Energy partition function

$$n_+ = \frac{e^{-E_x/4kT}}{e^{-E_x/4kT} + e^{-E_y/4kT}}$$
$$n_- = \frac{e^{-E_y/4kT}}{e^{-E_x/4kT} + e^{-E_y/4kT}}$$

$$n_1 = e^{2\mu_0 v M_i H_0/kT}$$

TRM = frozen high-temperature partition between micromagnetic states

**Néel Model for SD TRM**

Néel made a critical assumption

$T > T_B$ grain assembly in equilibrium with $T, H$ $M = M_{eq}$

$T < T_B$ magnetization is blocked (frozen) at $T_B$ no further redistribution Bias is fixed at $T_B$

Weak-field TRM (acquired in $B_0$)

$T = T_B$

TRM($T_B$) = $M_s(T_B) \tanh \left( \frac{\nu M_s(T_B) B_0}{kT_B} \right)$

$T = T_0$

TRM($T_0$) = $M_s(T_0) \tanh \left( \frac{\nu M_s(T_0) B_0}{kT_0} \right)$

Cartoon of TRM blocking in SD Grains

**Néel Model for SD Thermoremanent Magnetization**

Magnetization

$$M(T) = \frac{n_+ - n_-}{n_+ + n_-} = \frac{1 - e^{-E_x/4kT}}{1 + e^{-E_x/4kT}} = \tanh(b), \quad b = \frac{\mu_0 v M_i H_0}{kT}$$

Equilibrium Magnetization for a given $v, T$, and $H$

$$M(T) = M_s(T) \tanh(b)$$

Maximum Magnetization

The bias of magnetic moments (degree of alignment) along $H_0$

$$\tanh(b) = \begin{cases} b & b << 1 \\ 1 & b >> 1 \end{cases}$$

$-1 \leq \tanh(b) \leq 1$

$-\infty \leq b \leq \infty$

At blocking temperature

Direction is frozen in (bias) Only magnitude changes with $T$

This bias will be "locked" in as the assemblage cools through its blocking temperature to $T_B$

The only variable that will change during cooling is the saturation magnetization.

$T = T_B$

TRM($T_B$) = $M_s(T_B) \tanh \left( \frac{\nu M_s(T_B) B_0}{kT_B} \right)$

$T = T_0$

TRM($T_0$) = $M_s(T_0) \tanh \left( \frac{\nu M_s(T_0) B_0}{kT_0} \right)$
**Néel Model for SD Thermoremanent Magnetization**

**Degree of Alignment at \( T_B \)**

Let's work through an example:

- Spherical particle with diameter=40 nm
- \( T_B = 550^\circ C \) (823 K)
- \( H = 100 \mu T \) (This is ~2x the modern field)
- \( M_s \) of magnetite at 550°C = 140 kA/m
- \( v = 3.35 \times 10^{-21} m^3 \)

Use these values here:

\[
b = \frac{\sqrt{M_s} B}{kT}
\]

\[
b = 0.041 \quad \tanh(0.041) = 0.041
\]

This is an incredibly small degree of alignment!

\[
\tanh(b) = \frac{n - n}{N} \approx 4\%
\]

---

**Theoretical Model of TRM for SD grains**

\[
\text{TRM}(T_B) = M_s(T_B) \tanh \left( \frac{\sqrt{M_s} (T_B) B}{kT_B} \right)
\]

This model also assumes that all the SD grains in the assemblage are identical with only one blocking temperature.

Real rocks have a wide variety of sizes and shapes that produce a range of \( T_B \).

To visualize TRM acquisition for distributions of \( T_B \), we can use \( v-H_c \) diagram.
Generalizing the Model

OK, so this model is pretty good in that it explains the essentials of TRM acquisition, but it assumes uniaxial anisotropy axes are all aligned. (In real rocks, ferromagnetic grains and their easy axes are distributed randomly).

To deal with this reality, we can set the aligning energy for an individual particle as:

\[ E = m \cdot B = m B \cos \theta \]

where \( \theta \) is the angle between the easy axis and \( B \).

Final TRM intensity if found by integrating over all orientations

\[ TRM = M \int_0^{\pi/2} \tan \theta \cos \theta \sin \theta d\theta \]

\[ TRM(T_e) = M_e(T_e) \frac{\sqrt{M_e(T_e)} B_0}{3kT_s} \]

This leads to a more complicated expression, but the essence of the physics is the same.

We can actually “see” the distribution of Ti’s in a sample during thermal demagnetization.

![Partial Thermoremanent Magnetization](image)

A rock’s total TRM can be viewed as portions acquired in distinct temperature intervals, or windows of blocking temperatures.

\[ pTRM(T_1, T_2, 0) = 0 \]
\[ \tanh(0) = 0 \]

\[ B_{p0} = 0 \]
\[ B_{p0} \neq 0 \]
\[ pTRM(T_0, T_1, 0) = 0 \]
\[ \tanh(0) = 0 \]

Only those SD grains with \( T_1 < T_2 < T_3 \) will acquire a TRM.

Thellier (1938) demonstrated 3 experimental laws governing pTRMs:

- Law of Additivity
- Law of Independence
- Law of Reciprocity
**Partial Thermoremanent Magnetization**

**Law of Additivity**

PTRMs are only influenced by the magnetic field that is present during cooling through their respective $T_B$ interval.

If you add up each of the PTRMs you should arrive at the total TRM.

$$\text{Total TRM} = p\text{TRM}_1 + p\text{TRM}_2 + p\text{TRM}_3 + \ldots$$

Blocking temperature spectrum can be decomposed into non-overlapping fractions


**Law of Independence**

A particular $p\text{TRM}$ is independent in direction & intensity from any other $p\text{TRM}$ produced over a different temperature interval.

While this may seem like an obvious statement, it is only true for SD grains.

This “Law” fails spectacularly for MD grains and certain kinds of PSD grains.

Tauxe, 2008.

**Law of Reciprocity**

The grains that define a particular $p\text{TRM}$ have unblocking temperatures ($T_u$) that are identical to their blocking temperature ($T_B$).

$$p\text{TRM}(T_u, T_B, B_0)$$ is thermally demagnetized over precisely the $(T_u, T_B)$ interval when heated in zero field

While this may seem like an obvious statement, it is only true for SD grains.

This “Law” fails spectacularly for MD grains and certain kinds of PSD grains.

Tauxe, 2008.

**Thermal Demagnetization**

Heating samples to elevated temperatures ($T>T_c$)

Cooling to room-temperature in zero magnetic field

All grains $T<T_{demag}$ become unblocked

(Acquires a $p\text{TRM}=0$ upon cooling in $H=0$)

Grains with short relaxation times (low $T_c$) are likely to pick up secondary NRM’s (unstable NRM)

These grains get demagnetized first before grains with long relaxation times (stable NRM)
**Partial Thermoremanent Magnetization**

**Thermal demagnetization**

(a) Room temperature microscopic coercive force, $H_c$.

**pTRM acquisition**

(b) pTRM(400,500, $B_0$) acquisition.

![Figure](image)

**Grain Size Dependence of TRM**

$$\text{TRM}(T_e) = M_e(T_e) \tanh \left( \frac{vM_e(T_e)B}{kT_e} \right)$$

This model also assumes that all grains in the assemblage are SD.

Real rocks have a wide variety of sizes and shapes, and usually only a small fraction are truly SD.

Most grains are PSD or MD.

What do we know about how PSD and MD acquire TRM?

![Graph](image)

**PSD Grains**

TRM efficiency starts to decrease relative to SD grains.

PSD grains do acquire TRMs that are stable in time and resistant to demagnetization by later magnetic fields.

The physics of PSD TRM acquisition is not well understood, but the basic concept seems to be the same.

NOTE! PSD grains do not always follow the Law of Additivity, Independence, and Reciprocity.

![Image](image)
Grain Size Dependence of TRM

MD
TRM efficiency is very low relative to SD grains.
TRM acquired by MD tends to decay rapidly with time (viscous magnetization).

SD and PSD grains typically carry stable TRM, while MD grains carry a component acquired long after cooling.

Grain Size Effects: Extrusive vs. Intrusive Rocks

Extrusive Igneous: Rapidly cooled volcanic rocks have a grain size distributions peaking at $d < 10 \mu m$, mainly in the SD and PSD size range.

Thus volcanic rocks are often possess strong and stable TRMs. Typical intensities for a basalt flow are $1 \text{ A m}^{-1}$
There is a small fraction of MD grains, but their effect is minimized.

Intrusive igneous: Grain size distributions peak at larger diameters and a majority of grains are MD.

The intensity of stable TRM in intrusive igneous rocks is usually much smaller than in extrusive volcanic rocks.
Secondary components carried by the MD grains can dominate the magnetization.

Grain Size Effects: Intrusive Rocks: Felsic vs. Mafic
Mafic rocks (gabbros, anorthosites) are more likely to carry a stable TRM than felsic rocks (granites, diorites).
Mafic melts have higher Fe and Ti contents and titanomagnetite grains in these rocks frequently undergo high temperature exsolution yields an effective magnetic grain size less than that of the original FeTi oxide grain.
Mafic rocks are also more likely to contain silicate minerals with exsolved grains of magnetite and/or hematite/ilmenite.

Grain Size Dependence of pTRM

SD grains
- sharp $T_S$ and $T_T=T_{UB}$

PSD and MD grains
- individual walls can have different $T_S$'s
- Set of $T_S$'s can change when a wall moves because of changes in $H_D$
- One MD grain can have a distribution of $T_S$'s

Thermal demagnetization spectrum broadens with increasing grain size

PSD and MD grains
- demagnetization starts below $T_S$ extend beyond $T_E$ up to $T_C$
  - low-T and high-T pTRM tails

Stepwise thermal demagnetization of pTRM (acquired by heating at $T_D$ for 3.5 hr) produced over narrow $T_B$ ranges in magnetites for SD (405°C), PSD(375°C), and MD (350°C) grain sizes

Dunlop and Özdemir, 2000
Field Dependence of TRM

$$TRM(T_c) = M_s(T_c) \tanh \left( \frac{vM_s(T_c)B_0}{kT} \right), \quad T < T_c$$

TRM intensity reaches saturation when $B_0 > 4kT/vM_s$

For 50 nm cubes of magnetite at $T_F = 500^\circ$C

$B_{sat} = 1.5$ mT

The intensity of a TRM acquired in a weak field is proportional to the field strength.

There is a linear relationship.

$$TRM(T_c) = M_s(T_c) \frac{vM_s(T_c)}{kT} B_0$$

"constant"

Dunlop & Özdemir, 1997

Paleointensity

The linearity of TRM acquisition in weak fields and pTRM Laws of Additivity, Independence, and Reciprocity also serve as the foundation of most paleointensity methods.

How is the Intensity of the Earth’s Ancient Field Determined?

Given:

$$M_{NRM} = \alpha_{int} B_{arc}$$

$$M_{lab} = \alpha_{lab} B_{lab}$$

Assuming that $\alpha_{int} = \alpha_{lab}$ then

$$B_{anc} = \frac{M_{NRM}}{M_{lab}} B_{lab}$$

Acquisition of TRM in 2D Grain Schmidt Model (1973)

$$E_r(x) = E_c + E_a + E_m = E_c - 2 \mu_o M x + \mu_o NAM^2 x^2 / a$$

Increasing Fields: parabolas are tilted to the right by the field energy, moving wall from one LEM state to another

Decreasing Fields: wall is pinned in a different set of LEM states

$H_0 \rightarrow 0$: wall is trapped away from center of grain (x=0) producing a net remanence (IRM)

$$E_r(x) = E_c + E_a = E_c - 2 \mu_o AM_x H x + \mu_o NAM^2 x^2 / a$$

Total energy $E_r(x)$ as a function of wall displacement in increasing (down arrows) and decreasing (up arrows) fields

For small $H_0$: walls are pinned near local energy minima (A,C)

For larger $H_0$: wall is displaced towards max. slope in $E_r$ (D,E)
MD TRM

Experimental and theoretical (dashed) dependences of TRM intensity on applied magnetic field \( H_0 \) for SD and MD magnetite and hematite.

Hematite

Small demagnetizing fields in hematite (low \( M_s \)) allow large wall displacements towards saturation (\( M_s \)).

When \( H_0 \) is removed walls remain displaced (\( H_d \approx 0 \)), \( M_s \approx M_s \).

Magnetite

Self demagnetization (due to high \( M_s \)) drive walls back from saturation.

When \( H_0 \) is removed, \( M_s \approx M_s \).

Surprisingly, in hematite, TRM intensity is larger in coarse grained MD particles (> 1-1000 µm) than in fine grained SD particles.

TRM grain size relationship that is exactly opposite to that found in magnetite and titanomagnetite.

Summary of TRM Properties

Weak-Field TRM: \( B_0 << B_{cr} \)

- Remanence of an assemblage of randomly oriented SD/PSD particles
  - \( J_{TRM} \) is parallel to \( B_0 \)
  - \( |J_{TRM}| \propto |B_0| \)
- pTRM laws of Additivity, Independence, and Reciprocity
  - Equivalence of blocking and unblocking temperatures in heating and cooling (\( T_B = T_U \))
  - Sharpness of blocking temperature responsible for simplicity of laws

- \( |J_{TRM}| \) decreases with particle size
- MD grains
  - TRM efficiency is very low relative to SD grains.
  - One \( T_B \) produces a spectrum of \( T_U \)'s
  - pTRM produced at \( T_x < T_B \) needs to be heated to \( T_B \) to fully remove it

Dependence of TRM intensity on grain size for magnetite and hematite

Viscous Remanent Magnetization

VRM is the magnetization that is gradually acquired during prolonged exposure to magnetic fields.

VRM is typically acquired long after a rock is formed.

It is often viewed as a secondary, unwanted magnetization that is a source of noise.

VRMs can effect igneous, sedimentary, and metamorphic rocks...
**Single Domain VRM**

As time increases unblocking window moves across the grain distribution

The initial magnetization is gradually replaced by a viscous remanent magnetization (VRM) in the direction of $H_0$

$$\ln (f_{VRM}) = \frac{\mu_0 v H_0 M}{2 k T} \left(1 - \frac{H_{av}}{H_c}\right)^2$$

Butler, 1992

The viscosity coefficient is strong function of temperature

**Magnetic Relaxation and VRM**

$$M(t) = M_{eq} - (M_{eq} - M_0)e^{-t/\tau}$$

Tauxe, 2007

Commonly observed that VRM does not follow a simple exponential dependence but instead a logarithmic dependence

$$VRM = S \log(t)$$

$S=$Viscosity Coefficient

Logarithmic dependence comes from a distribution of grain sizes and shapes $f(v,H_k)$ producing a distribution of relaxation times

**Examples of VRM acquisition**

Experiments also show that VRM can be acquired in a non-log fashion.

VRM for a ocean floor basalt showing non-log time behavior (Moskowitz, 1985).

VRM in pelagic limestone samples (Lowrie and Heller, 1982).

Dunlop and Ozdemir, 2007
Acquisition of Thermoviscous Remanent Magnetization (TVRM)

Rocks are often reheated by a variety of geologic processes:

Local metamorphism (nearby dike or sill), regional metamorphism (large-scale igneous intrusions), burial metamorphism, tectonic metamorphism, etc...

How do prolonged periods of reheating below a mineral's Curie temperature effect a rock's ability to retain a primary magnetization?

How do prolonged periods of reheating below a mineral's Curie temperature effect a rock's ability to acquire a VRM?

To explore these questions, let's imagine a population of identical SD grains. Their relaxation time (as a function of temperature) is given by the classic Néel equation:

\[ \tau = \frac{1}{f_s} \exp \left[ \frac{\mu_0 V M_s(T) H_k(T)}{2kT} \right] \]

<table>
<thead>
<tr>
<th>State</th>
<th>(\tau)</th>
<th>(M)</th>
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<tr>
<td>superparamagnetic</td>
<td>(&lt;\tau_s)</td>
<td>(M_{m\text{eq}})</td>
</tr>
<tr>
<td>viscous</td>
<td>(\approx\tau_s)</td>
<td>(M_{\text{Slog}(t)})</td>
</tr>
<tr>
<td>Stable SD</td>
<td>(&gt;\tau_s)</td>
<td>(0.5M_s)</td>
</tr>
</tbody>
</table>

VRM acquisition for PSD & MD grains

VRM is acquired through thermal activation of domain walls.

Thermal energy allows domain walls (or wall sections) to overcome local energy barriers.

This thermal energy augments the interaction energy between the applied field and the magnetization of the grain, resulting in increased magnetization in the direction of the applied field.

MD grains

Grains with low coercivity rapidly acquire VRM and often dominate the overall VRM. This relationship between coercivity and VRM is exploited by paleomagnetists during demagnetization, in an effort to remove VRM components.

Acquisition of TVRM

Assemblage of identical SD grains (\(v=\text{constant}\))

\[ \frac{\mu_0 V}{2k} = \text{constant} = \frac{T \ln(\tau(T)f_s)}{M_s(T)H_k(T)} \]

The population of SD grains will have a relaxation time \(\tau_1\) at temperature \(T_1\) and \(\tau_2\) at temperature \(T_2\).

Because the left side of the equation is constant, the relationships between parameters \(\tau_1\), \(\tau_2\) and \(T_1\), \(T_2\) can be written as:

\[ \frac{T_1 \ln(\tau_1 f_s)}{M_s(T_1)H_k(T_1)} = \frac{T_2 \ln(\tau_2 f_s)}{M_s(T_2)H_k(T_2)} \]

Time-temperature relationship
Acquisition of TVRM

**Magnetite**: \( H_k \) values for SD particles are dominated by shape anisotropy:
\[
H_k (T) = \Delta N M_s (T)
\]
\( \Delta N \) is the difference in the internal demagnetizing factor between short and long axes of the SD grain.

**Hematite**: \( H_k \) values for SD particles are dominated by magnetocrystalline anisotropy, which are more sensitive to temperature:
\[
H_k (T) = D M_s^a (T)
\]
where \( D \) is a proportionality constant that is independent of temperature.

General Case \((n=1,2,3,..., a=constant)\):
\[
H_k (T) = a M_s^a (T)
\]

Acquisition of TVRM

*\( \tau-T \) diagrams*, are useful ways to visualize this relationship.
\[
\frac{T_1 \ln(r_{f_1})}{M_s^4(T_1)} = \frac{T_2 \ln(r_{f_2})}{M_s^4(T_2)}
\]
for magnetite.

Each one of these lines is a locus of points in \( \tau-T \) space that activate the same grain.

**Point 1** shows a population of SD grains in \( \tau-T \) space that has a relaxation time of 10 Ma at 260°C.

Translation: after 10 Ma, these SD grains would acquire a significant VRM.

Acquisition of TVRM

*\( \tau-T \) diagrams*, are useful ways to visualize this relationship.
\[
\frac{T_1 \ln(r_{f_1})}{M_s^4(T_1)} = \frac{T_2 \ln(r_{f_2})}{M_s^4(T_2)}
\]
for magnetite.

**Point 2** shows a population of SD grains in \( \tau-T \) space that has a relaxation time of 30 minutes at 400°C.

Point 1 and 2 lie on the same nomogram.

After 30 minutes at 400°C, these grains would acquire the same VRM acquired over 10 Ma at 260°C.

Acquisition of TVRM

Using the definition of \( H_k (T) \times M_s^a (T) \) in the blocking equation above:
\[
\frac{T_1 \ln(r_{f_1})}{M_s^4(T_1)} = \frac{T_2 \ln(r_{f_2})}{M_s^4(T_2)}
\]
which gives
\[
\frac{T_1 \ln(r_{f_1})}{M_s^4(T_1)} = \frac{T_2 \ln(r_{f_2})}{M_s^4(T_2)}
\]

**Magnetite** \((n=1)\)  **Hematite** \((n=3)\).

Note: \( \Delta N \) and \( D \) are constants and cancel out in these calculations.

Normalized \( Ms(T) \) dependences for five common magnetic minerals

\[
\frac{T_1 \ln(r_{f_1})}{M_s^4(T_1)} = \frac{T_2 \ln(r_{f_2})}{M_s^4(T_2)}
\]
Acquisition of TVRM: Paleothermometry

- \( T \), are useful ways to visualize this relationship.

\[
\frac{T_u \ln(r_u f_u)}{M_u'(T_u)} = \frac{T_b \ln(r_b f_b)}{M_b'(T_b)}
\]

This has BIG implications!

TVRM acquired by a rock during a 10 Ma interval can be unblocked by heating a sample in a lab for 30 minutes in zero magnetic field.

This heating would reset the grains’ magnetization to zero, even though we didn’t heat to the Curie temperature.

The \( T-T \) diagram is broadly split into A and B regions.

Grains in region A have laboratory blocking temperatures within 100°C of the Curie temperature, \( T_c \).

These grains are resistant to resetting of magnetization, except by heating to temperatures near \( T_c \).

Grains in region B have laboratory blocking temperatures distributed over wide intervals below \( T_c \).

These grains are more susceptible to VRM or TVRM acquisition, and are generally too unstable to retain a primary NRM.

Acquisition of TVRM

- \( T \) diagrams, are useful ways to visualize this relationship.

\[
\frac{T_u \ln(r_u f_u)}{M_u'(T_u)} = \frac{T_b \ln(r_b f_b)}{M_b'(T_b)}
\]

Now look at points 3 and 4.

The size and shape of these SD grains are different from the SD grains at points 1 and 2. But both populations of grains have the same value of \( \nu/2k \).

Point 3 shows a population of SD grains in \( \tau-T_b \) space that has \( \tau = 10 \) Ma at \( T_b = 520 \)°C.

Point 4 shows a population of SD grains in \( \tau-T_b \) space that has \( \tau = 30 \) min at \( T_b = 550 \)°C.

This is another way of showing the rapid increase in relaxation time with decreasing temperature for grains with \( T_b \) close to the Curie temperature.

There are differences between the unblocking diagrams for magnetite and hematite.
Acquisition of TVRM

These diagrams indicate that primary NRM's should survive heating through the greenschist metamorphic facies (300-500°C), but not through the amphibolite facies (550-750°C).

Grains in region A should have magnetizations that are blocked at approximately the same time as radiogenic argon is trapped in hornblende (~525°C).

These blocking diagrams cover only time-temperature effects, and do not incorporate the chemical changes that often occur to magnetic minerals during heating (oxidation, reduction, exsolution, dissolution, growth, etc...)

Caveats on the theory of VRM

Theory works well for SD grains (T_u= T_d).

Theory seems to work better for hematite-dominated assemblages than for magnetite assemblages.

Hematite has a wider range of SD grain sizes, while magnetite-bearing rocks have a significant portion of their grains in the PSD range

PSD and MD grains (T_c=f(T_u))

High-T tails on thermal demagnetization curves complicates TVRM separation

These blocking diagrams cover only time-temperature effects, and do not incorporate the chemical changes that often occur to magnetic minerals during heating (oxidation, reduction, exsolution, dissolution, growth, etc...)

Chemical Remanent Magnetization

CRM acquisition by Grain Growth

Precipitation of a ferromagnetic mineral from solution. Nucleation and growth through blocking volume

CRM acquisition by recrystallization

Alteration of a preexisting mineral (possibly ferrimagnetic) to a ferrimagnetic mineral Two-phase or phase-coupled CRM

Chemical reactions producing CRMs

low-temperature oxidation hydrothermal alteration exsolution below T_c diagenesis microbially-mediated reactions

Dunlop, 2002


Magnetite and Pyrrhotite


Lowrie, 1998
**Grain-Growth CRM**

During CRM acquisition temperature stays constant (usually room temp), and consequently, $M_r(T)$ and $H_c(T)$ are also constant.

During CRM, grains start with an initial volume of zero. Small grains have short relaxation times and are superparamagnetic (SP).

As the grains continue to grow, they experience a dramatic increase in relaxation time and change from being SP to SD.

The grain volume at which this transition occurs is called the **blocking volume**.

$$T = \text{constant}$$

$$v_s = \frac{2kT}{\mu_0 M_r H_c} \ln(f_{ij})$$

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Red sandstones (like the ones that make up Pillsbury Hall) owe their color to pigmentary hematite, which may have formed long after the sand grains were initially deposited.

A variety of dehydration reactions generate hematite as a final product. For example, goethite dehydrates to form hematite:

$$2(\alpha \text{FeOOH}) \rightarrow \alpha \text{Fe}_2\text{O}_3 + \text{H}_2\text{O} \text{ (evaporates)}$$

A CRM is acquired during growth of the resulting hematite grains.

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The timing of these dehydration reactions is important to the interpretation of the sandstone’s magnetization.

If the hematite formed soon after deposition, then the magnetization is regarded as primary.

If the hematite formed at some later time, then its magnetization is secondary.

Thus, there’s a lot of controversy around whether or not such “redbeds” accurately preserve a recording of the Earth’s magnetic field at the time of sedimentation.
**CRM acquisition by recrystallization**

Alteration of a preexisting mineral (possibly ferrimagnetic) to a ferrimagnetic mineral
Two-phase or phase-coupled CRM

What controls the CRM direction?
- External field ($B_e$) during crystallization
- Preexisting TRM of parent phase

Recrystallization without a change in crystal structure
- titanomagnetite $\rightarrow$ titanomaghemite controlled (in part) by the magnetization (TRM) of the starting mineral.
- Exchange or magnetostatic coupling between phases

Recrystallization with a change in crystal structure
- magnetite $\rightarrow$ hematite controlled by external field

**Recrystallization without a change in crystal structure**

Example: Source Rocks of Marine Magnetic Anomalies
Primary TM60 in pillow lavas produced at mid-ocean ridges is soon oxidized in seawater to titanomaghemite

Direction of CRM formed by maghemitization of single-domain TM60 in a field applied perpendicular to the initial TRM direction.

CRM direction ‘remembers’ parent TRM.

CRM forms parallel to initial TRM until multiphase oxidation products begin to appear around $z \sim 0.6$.

For $z < 0.6$, only when exchange coupling is broken does external field becomes important.

CRM direction is deflected towards $B_e$.

Ödemir and Dunlop (1985)

**Recrystallization without a change in crystal structure**

Example: Source Rocks of Marine Magnetic Anomalies
Primary TM60 in pillow lavas produced at mid-ocean ridges is soon oxidized in seawater to titanomaghemite

A magnetite crystal (≈ 30 μm) undergoing maghemitization. Because of the change in volume, the crystal begins to crack. [From Gapeyev and Tsel'movich, 1988.]

**Magnetic Characterization of Minerals**

High-field thermomagnetic ($M_s$) and NRM unblocking Temperature curves

Young Oceanic Crust East-Pacific Rise

Why discrepancy between High-field results and NRM results?

High-Field Results: $T_c \sim 150$ C, unoxidized TM60, coarse grained, MD
NRM unblocking: $T_b > 300$ C, oxidized TM60, fine grained SD/PSD

Kent and Gee, Science, 1994
Authigenic formation of fine-grained magnetite (SSD and SPM) is responsible for widespread chemical remagnetization of many carbonate rocks.

CRM

CRM can heavily influenced by the magnetization of the parent mineral.

Sometimes it is parallel.
Sometimes it is antiparallel (SELF-REVERSAL)
Sometimes it is oriented at an intermediate angle to both the parent mineral's magnetization and the field at the time of alteration.

CRMs can be acquired sporadically through time, depending on the chemical environment of a rock.

It is difficult to ascribe an age to the minerals holding a CRM and consequently, paleomagnetists strive to remove CRM components from their samples during demagnetization.

Grains carrying CRM may have similar rock magnetic properties (Coercivity, relaxation time), which can be difficult to disentangle during demagnetization.

In general paleomagnetists like to steer clear of rocks that may have CRM components.

Extra Slides

Field Reversal vs. Self-Reversal

Field Reversal: Geomagnetic Field behavior due to internal geodynamo

Self-Reversal: Mineralogy or magnetic recording process unrelated to geomagnetic field

Minerals become magnetized antiparallel to an applied magnetic field
Early Results

David and Brunhes (France), 1904-1906:
- Clays baked in lavas, Massif Central, France
- Same direction of TRM as lava
- Changes in magnetization direction => polarity change

Matuyama (Japan), 1929:
- Quaternary lava = normal polarity
- Pleistocene lava = opposite polarity
- Miocene = 3 different polarities
- Link between polarity and age

Paleomagnetic results from lava flow at Pontfarein, with some representative diagrams: new results (circles) by Laj et al. [2002], and Brunhes' and David's original results (triangles)

Mechanisms for Self-Revered Remanent Magnetization

Néel Classification of Ms-T curves

N-type ferrimagnetism

Different combinations of AB, AA, BB interactions give rise different types of M_s-T curves

N-type: M_s=M_A-M_B changes sign during heating

Early Pleistocene age or older

Matuyama (1929)

100 Tertiary basalts coming from 38 sites in Japan

Many lavas were reversely magnetized

Polarity was correlated to stratigraphic position. He clearly identified the most recent field reversal (Brunhes-Matuyama chron)

Stated that the polarity of the Earth's magnetic field depended on time in an organized way.

First study to show that the Earth's field reversed polarity in the past

Mechanisms for Self-Revered Remanent Magnetization

Ionic re-ordering during extreme low-temperature oxidation of titanomagnetites

Inversion of initial A-site moment to a B-site moment due to decomposition and ionic reordering

Pavel V. Doubrovine and John A. Tarduno, On the compositional field of self-reversing titanomaghemite: Constraints from Deep Sea Drilling Project Site 307, JGR, 110, 2005

Non-reversible Self-Reversal
Mechanisms for Self-Revered Remanent Magnetization

**Magnetostatic or Exchange Coupling between two magnetic phases**

Phase B sees $H_B = H_A$ if $H_B > H_A$ then $M_B$ is reversed.

(a) $T_C > T_C^B$

(b) $M_{B0} > M_{A0}$

$V_B > V_A$

Fig. 6.1 Model for a self-reversal mechanism in rocks with two magnetic phases $A$ and $B$. $A$ has the higher Curie temperature but $B$ has the higher remanent value of saturation magnetization ($M_S$). (a) On cooling, $A$ becomes magnetized first in a direction parallel to the external field $H$, and on further cooling, phase $B$ becomes magnetized in the total field $H + H_B$, where $H_B$ is the field in phase $B$ causing the magnetization of $B$ and $H_A$ is applied to $H$. The relative magnetizations of $B$ and $H_B$ determine the direction of the total field in which $B$ becomes magnetized. (b) If $H_B$ is larger than $H$, then phase $B$ will acquire a magnetization antiparallel to $H$ on further cooling. Because $B$ has the higher remanent moment $M_C$, the sample will then have a self-reversed magnetization. McElhinny and McFadden

Mechanisms for Self-Revered Remanent Magnetization

**Negative Exchange Coupling across a phase boundary**

Figure 14.06 (a) Self-reversing TRM as a function of applied field for randomly oriented synthetic titanohematite, synthesized at $1300^\circ$C and reduced. Hanada (1983) supplied powdered synthetic titanohematite (TRM) for the Hanada furnace. (After Sato et al. 1973) The sample was annealed at $900^\circ$C, with the permission of the authors. Maruzen Co., Ltd., and Crawford Preservation and Geosciences, Tokyo, Japan. Dunlop and Özdemir, 1997

Mechanisms for Self-Revered Remanent Magnetization

**Negative Exchange Coupling**

Variation of properties with Ti substitution in the titanohematite series.

Compositions around $y=0.5$ have the property of self-reversal thermoremanence. Applied a field in the positive direction and cool through Curie temperature an negative remanence is produced. Butler, 1992

Fine-scale microstructure, chemical disorder, and exchange coupling in ferrimagnetic titanohematites

Transmission electron microscope image of antiphase domains and antiphase domain boundaries in the llm70Hem30 sample synthesized at 1300°C and subsequently annealed at 900°C

Lawson et al., 1981
Aeromagnetic anomalies caused by nanoscale lamellae structures in hemo-ilmenite intergrowths

3D image of Heskestad magnetic anomaly (southern Norway) from nearly 1 billion years old rocks.

TEM image of the ilmenite host containing fine-scale hematite precipitates. Scale bar = 100 nm.

It is estimated that lamellar magnetism can result in saturation magnetization values of ~55 kA m⁻¹ (22 times larger than hematite and 11% of the moment in magnetite) and remanent magnetization up to 30 A/m.

McEnroe et al. (2002), McEnroe et al. 2004, Robinson et al., 2002