Magnetic property characterisation focusing on soil and archaeological materials.

Training school TS3
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- *Properties of some magnetic minerals*
- *Formation of magnetic minerals*
- *Magnetic characterisation methods*
- *Examples*

Magnetic minerals

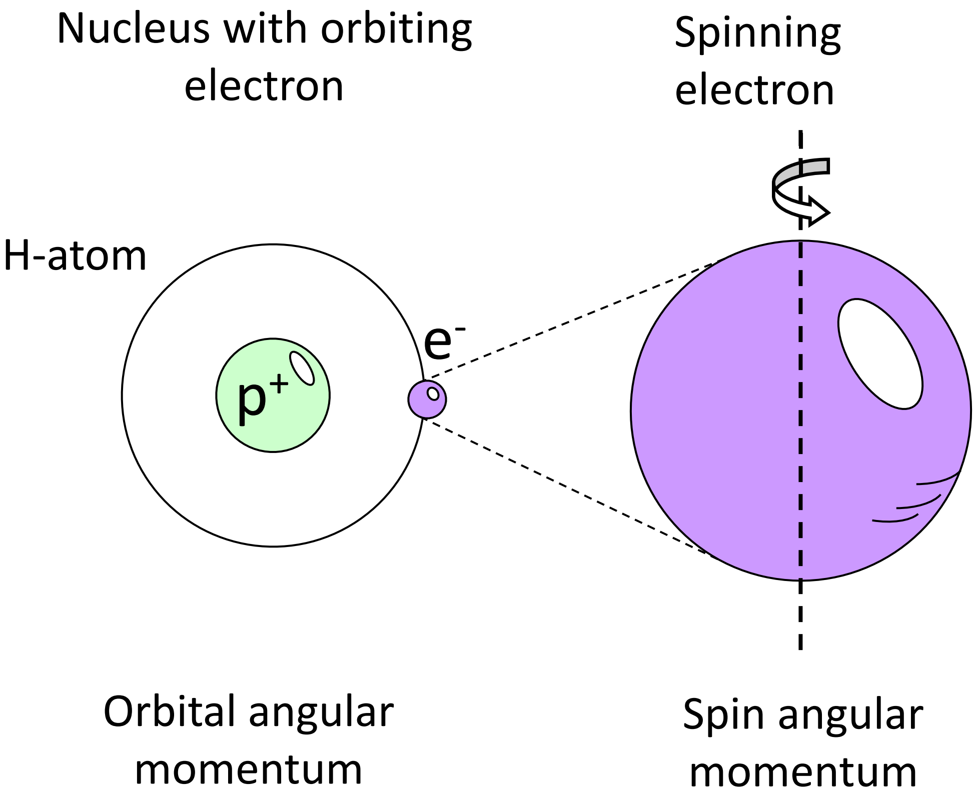
Element	Abundance (wt %)* in Earth's crust
Oxygen	**46.6**
Silicon	27.7
Aluminum	8.1
Iron	**5.0**
Calcium	3.6
Sodium	2.8
Potassium	2.6
Magnesium	2.1
All other	1.5

*Lutgens & Tarbuck 2000

Magnetite	Fe_3O_4
Maghaemite	γ–Fe_2O_3
Haematite	α–Fe_2O_3
Goethite	α–FeOOH
Pyrrhotite	mon. Fe_7S_8 hex. Fe_9S_{10}
Greigite	Fe_3S_4

Iron resides amongst the most abundant elements in the Earth's crust and forms in combination with oxygen and sulphur magnetic minerals which are omnipresent in our environment.

Electrons = moving electric charges



$$\mu_{orbit} = -\frac{e\, n\, \hbar}{2m}$$

$$\mu_{spin} = -\frac{e\, S\, \hbar}{m}$$

Free atoms

orbit + spin momenta

Solids

often only spin momenta

Ferromagnetic s.l. minerals

uncompensated spin momenta in overlapping orbits

n – main quantum number of Hydrogen, s – spin quantum number of e^-, m – mass of e^-, e – elementary charge, $\hbar$ – reduced Planck constant

Magnetite

ferrimagnetic

- Fe_3O_4

$$\overbrace{\left(Fe^{3+}\right)_A}^{\text{tetra}} \overbrace{\left[Fe^{3+}Fe^{2+}\right]_B}^{\text{octa}} O_4$$

$M_S = 480\ kA/m$

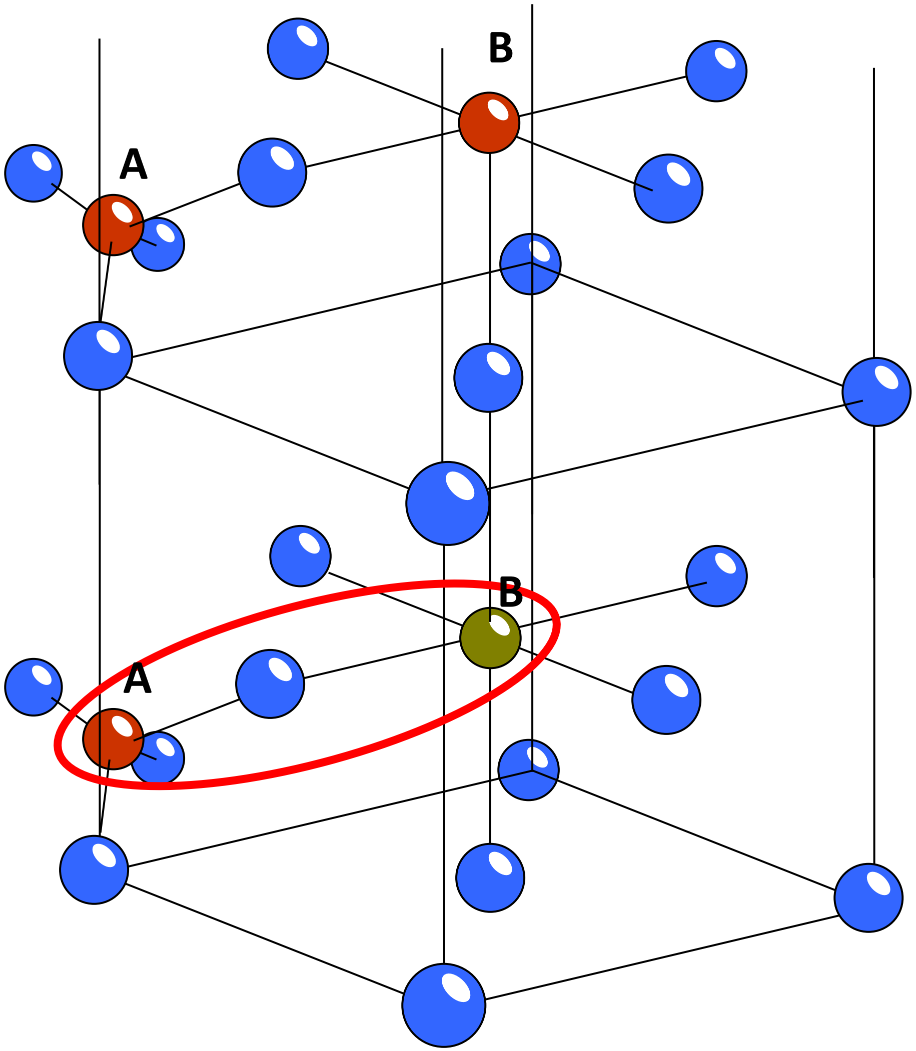
$T_C = 585\ °C$

$T_V =$ between -163 and -153 °C

$H_c =$ between 10 and 80 mT
(size dependent)

- (Soils)
- Inside bacteria
- Baked clays
- Combustion product
- Lacustrine/marine sediments

Magnetic minerals



ferric iron Fe^{3+} at tetrahedral (A) and octahedral (B) sites

ferrous iron Fe^{2+} at octahedral site

oxygen anions

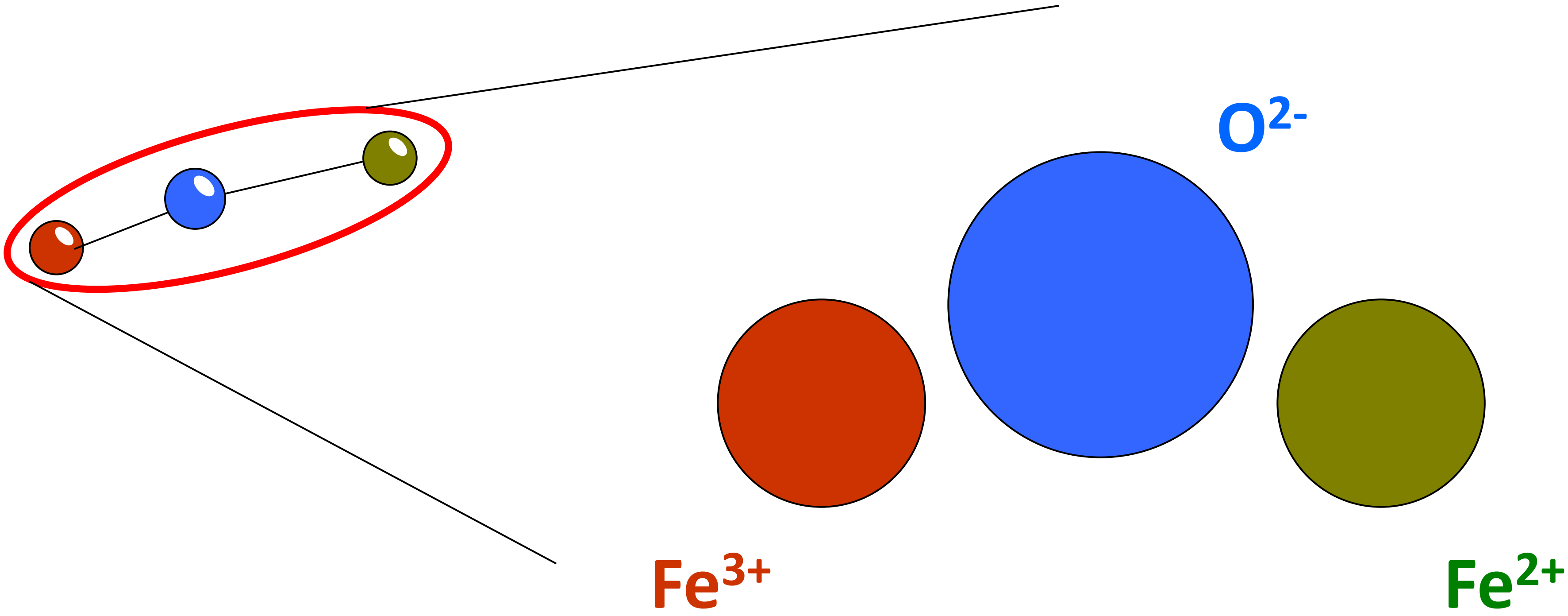
Magnetite Fe_3O_4

tetra **octa**

$$\underbrace{(Fe^{3+})_A}_{\text{tetra}} \; \underbrace{[Fe^{3+}Fe^{2+}]_B}_{\text{octa}} \; O_4$$

Superexchange

Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$

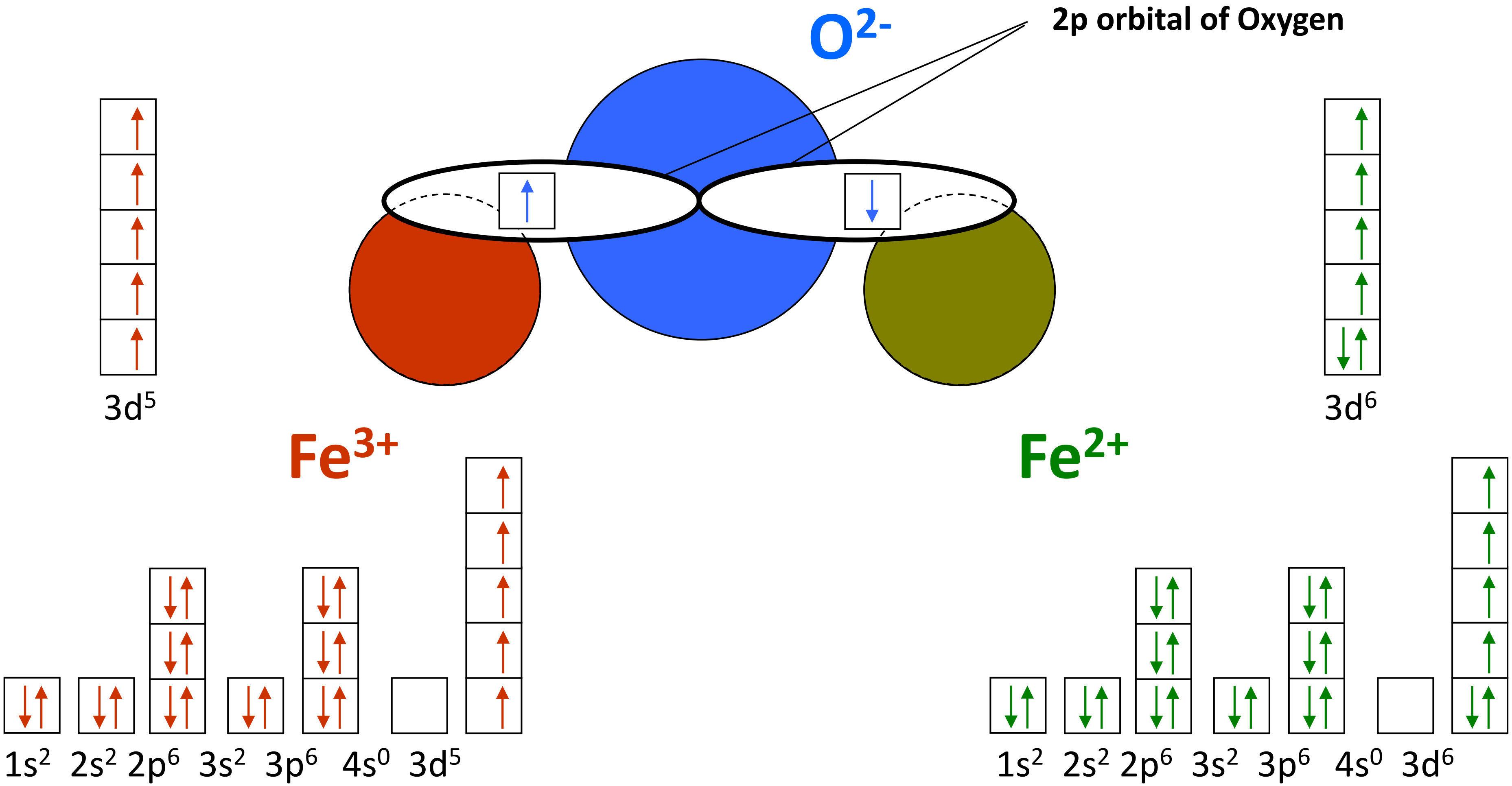


Close packing of oxygen & iron

Superexchange

Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$

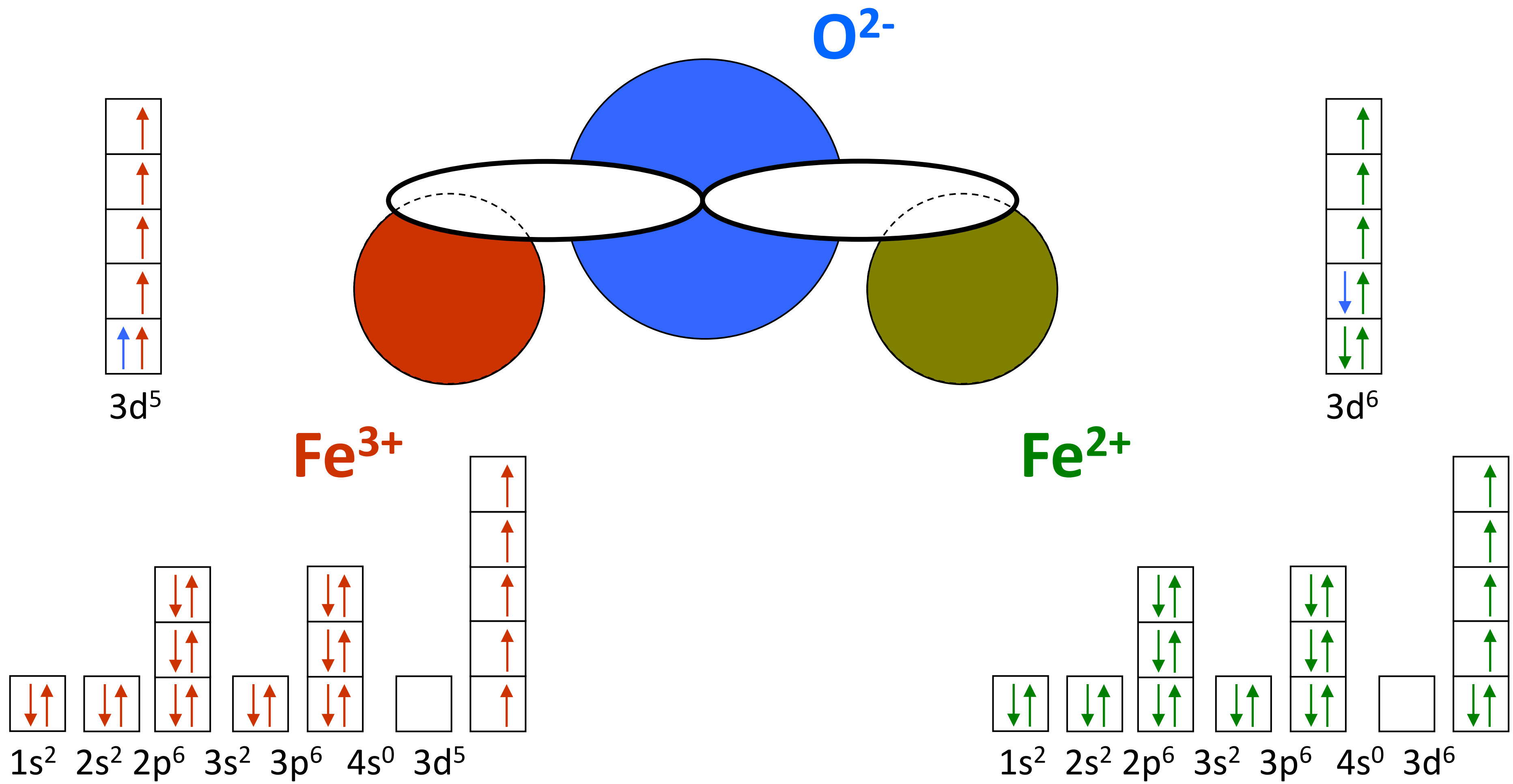
Oxygen 2p orbital overlaps with both 3d orbitals of Fe^{3+} and Fe^{2+}



Superexchange

Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$

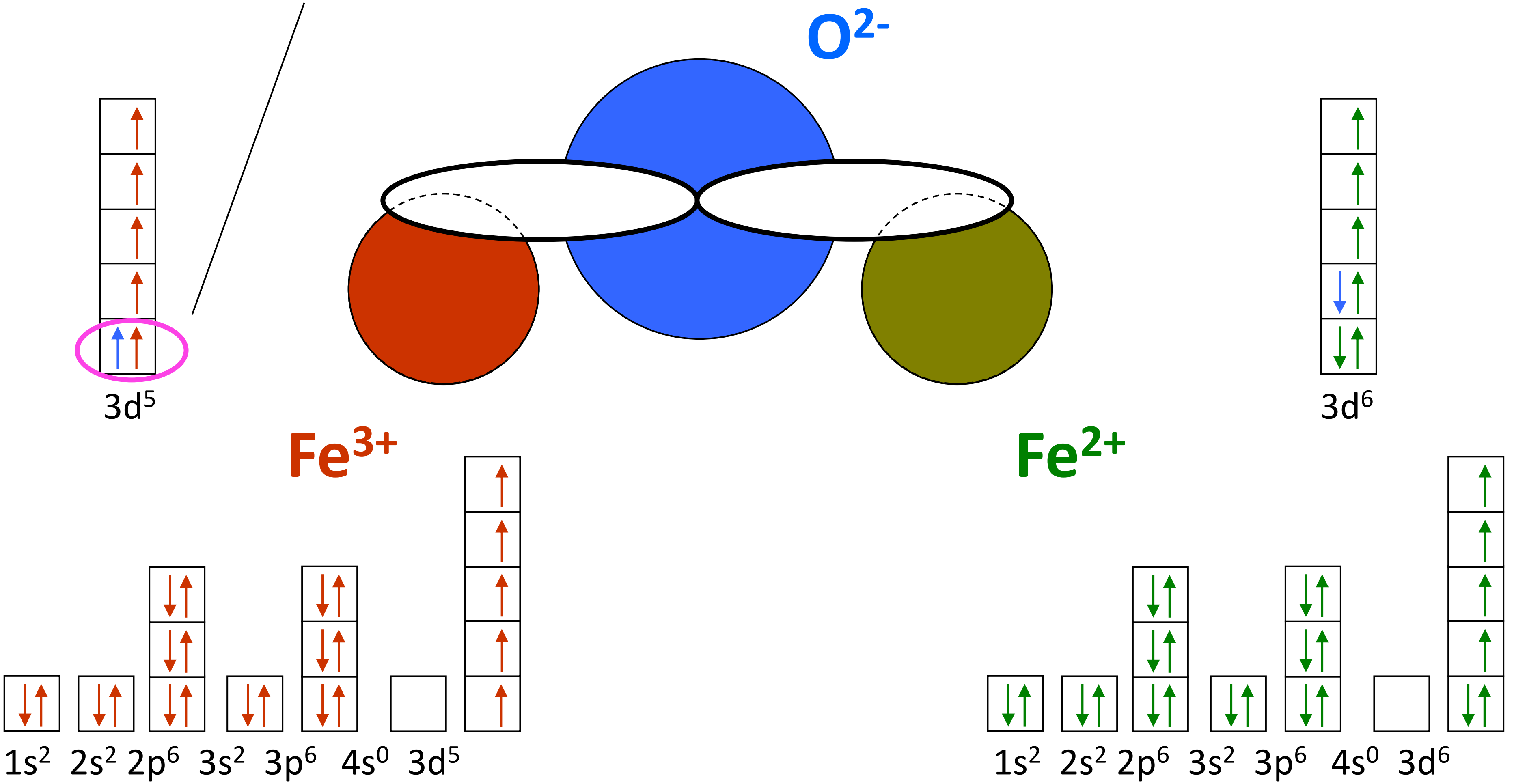
Oxygen exchanges both outer 2p electrons with the iron ions



Superexchange

Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$

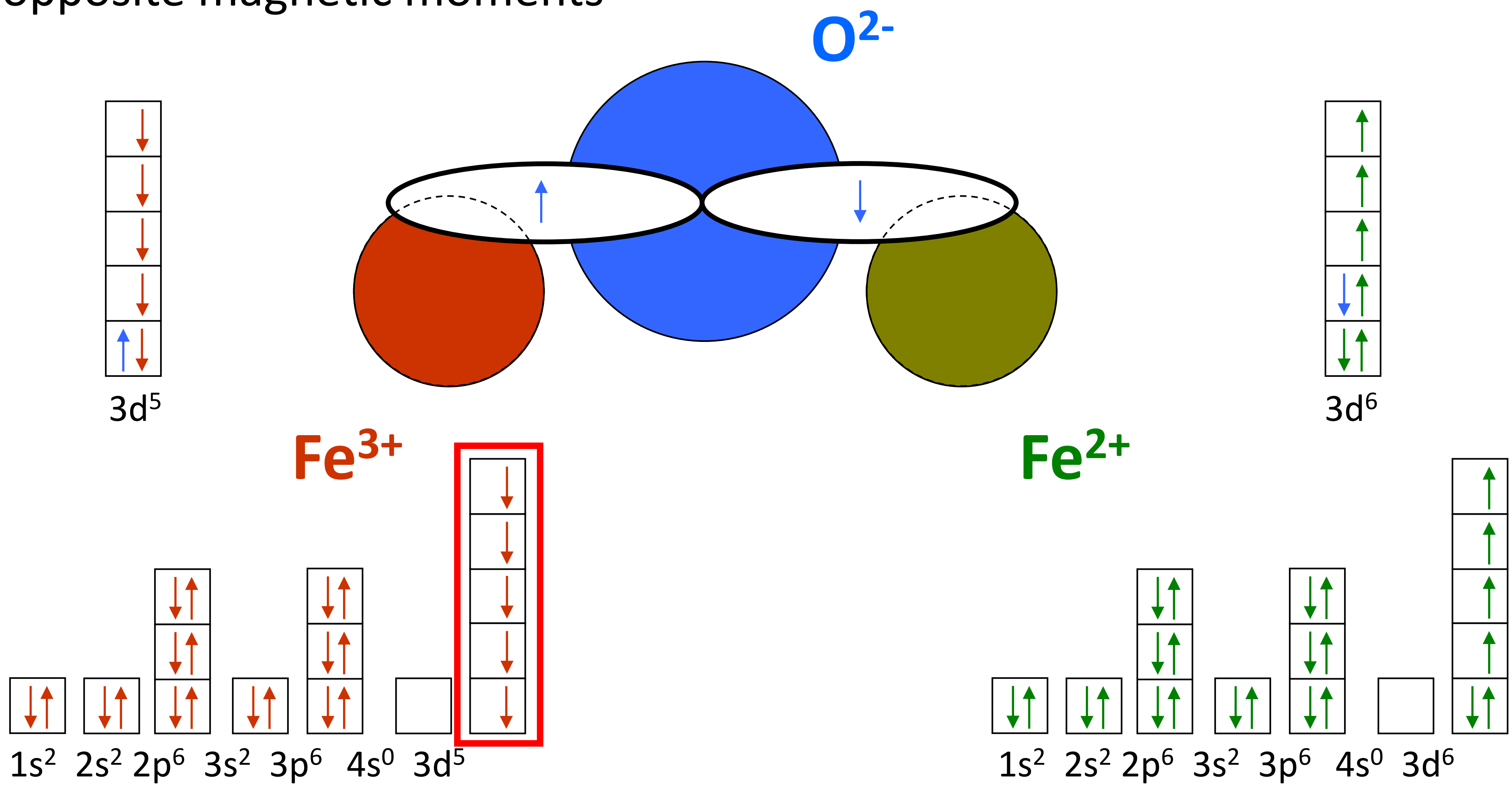
2 parallel spins → violation of Pauli principle



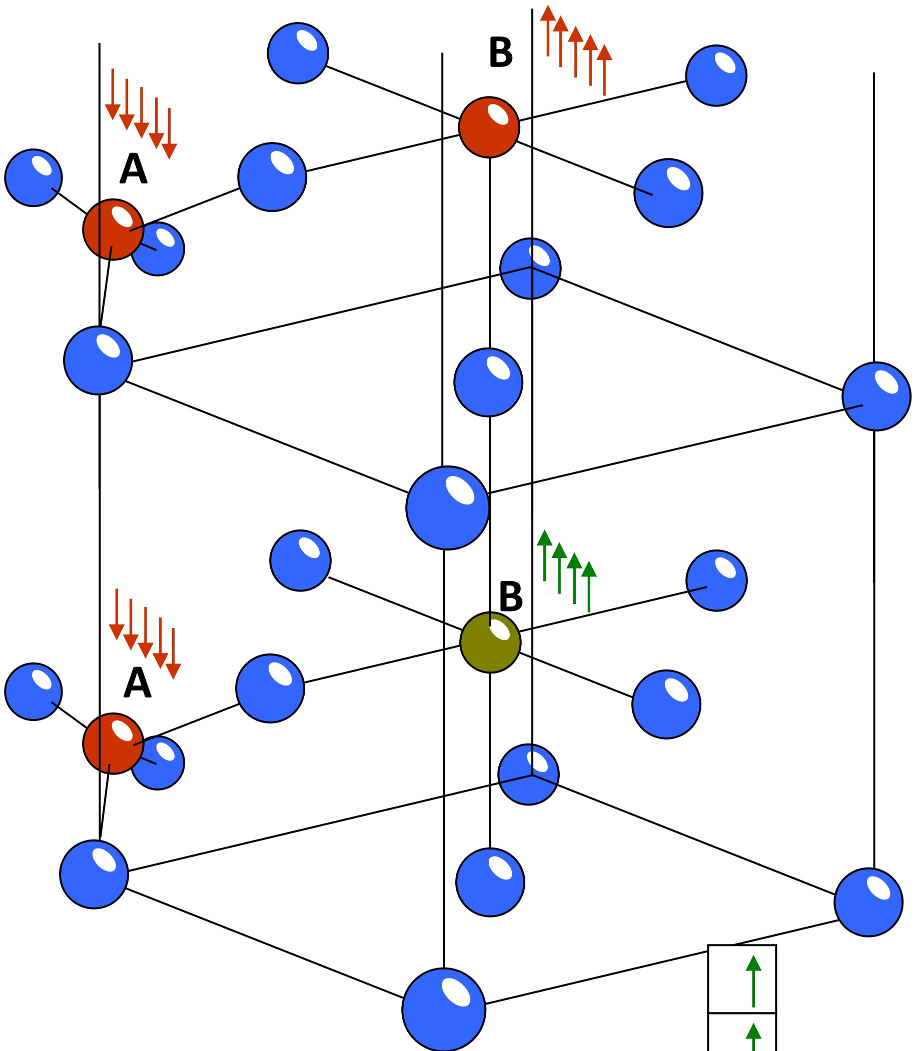
Superexchange

Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$

Solution: opposite spins of Fe- ions → lattices with opposite magnetic moments



Magnetic minerals



Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$

- ferric iron Fe^{3+} at tetrahedral (A) and octahedral (B) sites
- ferrous iron Fe^{2+} at octahedral site
- oxygen anions

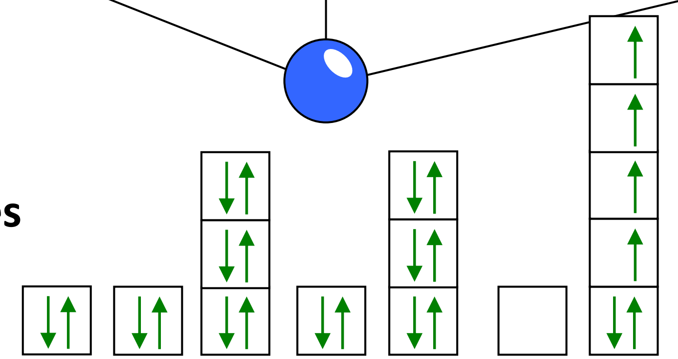
at tetrahedral sites, Fe^{3+} occurs only

at octahedral sites occur both, Fe^{3+} and Fe^{2+}

whole crystal: spins of Fe^{3+} at A sites equal spins of Fe^{3+} at B sites -> resulting moment only from Fe^{2+}

magnetic moments at A and B sites are unequal and antiparallel -> ferrimagnetism

B sites



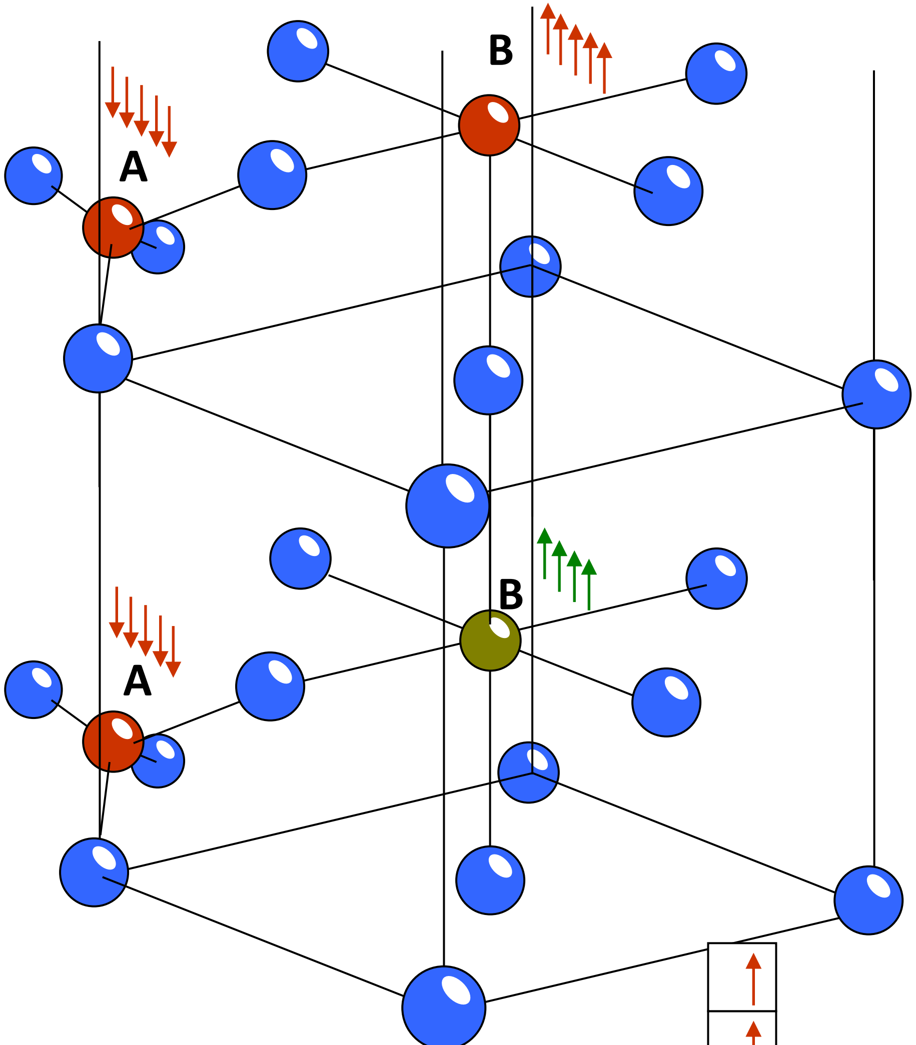
Fe^{2+} $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $4s^0$ $3d^6$

4 uncompensated moments

$4\,\mu_B$

Magnetic minerals

Magnetite $Fe^{3+}[Fe^{3+}Fe^{2+}]O_4$



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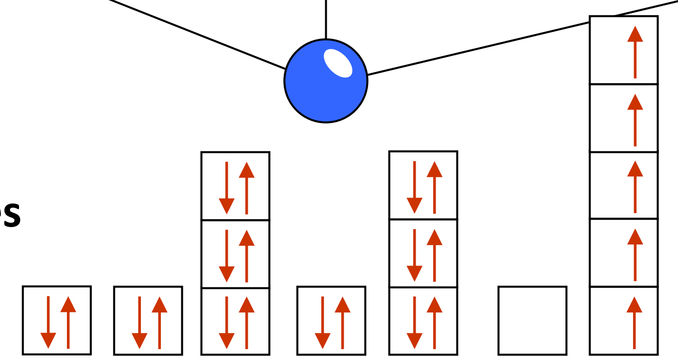
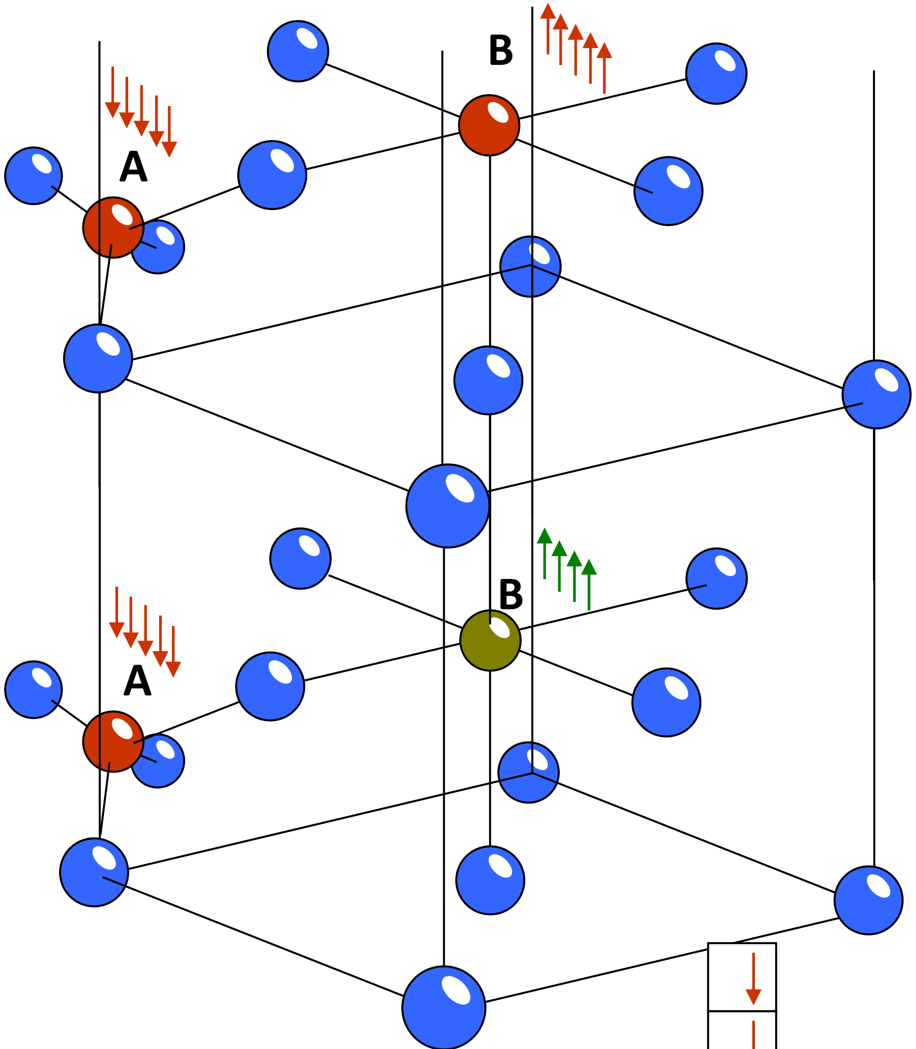


Fe^{3+} $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $4s^0$ $3d^5$

5 uncompensated moments

$4\ \mu_B$

Magnetic minerals



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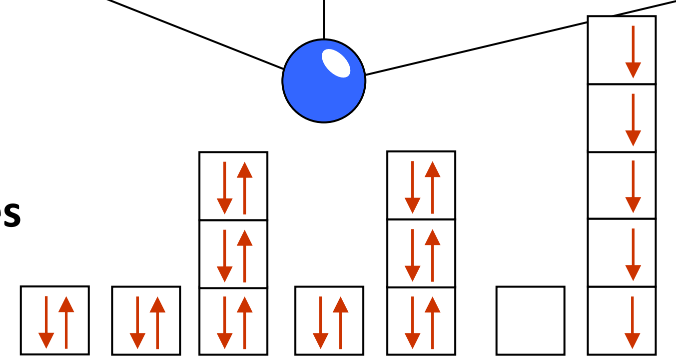
A sites



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5 uncompensated moments

$4\ \mu_B$

Magnetite

- Fe_3O_4

$$\overbrace{\left(Fe^{3+}\right)_A}^{\textbf{tetra}} \ \overbrace{\left[Fe^{3+}Fe^{2+}\right]_B}^{\textbf{octa}} \ O_4$$

loss of magnetic ordering due to high thermal energy

characteristic temperature for each mineral
but depends on substitution degree

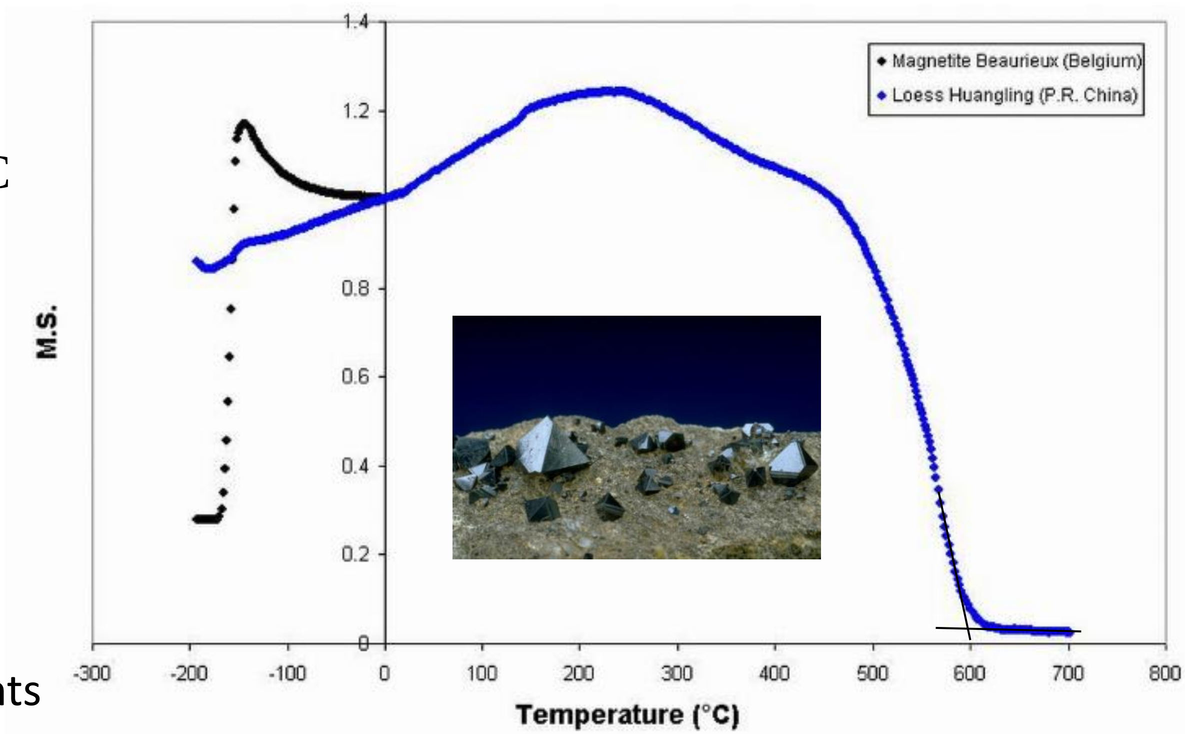
$M_S = 480\ kA/m$

$T_C = 585\ °C$

$T_V =$ between -163 and -153 °C

$H_c =$ between 10 and 80 mT
(size dependent)

- (Soils)
- Inside bacteria
- Baked clays
- Combustion product
- Lacustrine/marine sediments



Maghaemite

- γ-Fe_2O_3

tetra octa

$$\underbrace{\left(Fe^{3+}\right)_A}_{\text{tetra}} \underbrace{\left[Fe^{3+}_{5/3}\,\square_{1/3}\right]_B}_{\text{octa}} O_4$$

$3.33\ \mu_B$

ferrimagnetic

Oxidised magnetite

$M_S = 380\ kA/m$

$T_C = 645$ °C (depends on substitution)

$T_V =$ depending on oxidation degree

Metastable 250 – 750 °C
Converts to haematite

- Soils
- Soil bacteria excretion
- Baked clays
- Lacustrine/marine sediments

Maghaemite

- γ-Fe_2O_3

Oxidation of 44 *nm* magnetite

at 30° and variable p_{O_2}

M_S = 380 *kA/m*

T_C = 645 °C (depends on substitution)

T_V = depending on oxidation degree

Metastable 250 – 750 °C
Converts to haematite

- Soils
- Soil bacteria excretion
- Baked clays
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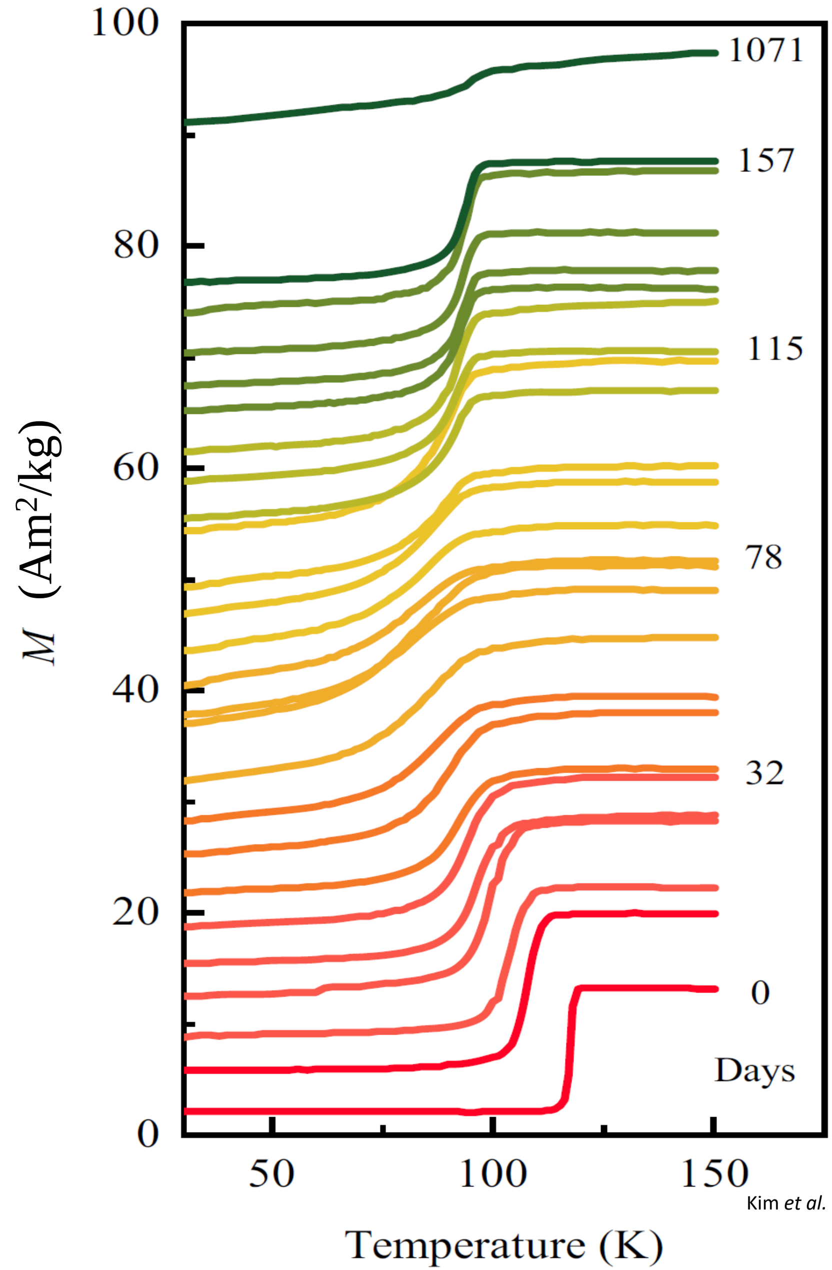

Kim *et al.* 2021

Haematite

- α-Fe_2O_3

"antiferromagnetic"

$M_S = 2.5\ kA/m$

$T_N = 680 - 690\ °C$

T_M = between -100 and - 13 °C
(size dependent)

H_c size dependent

- Soils
- Baked clay
- Sediments

Haematite

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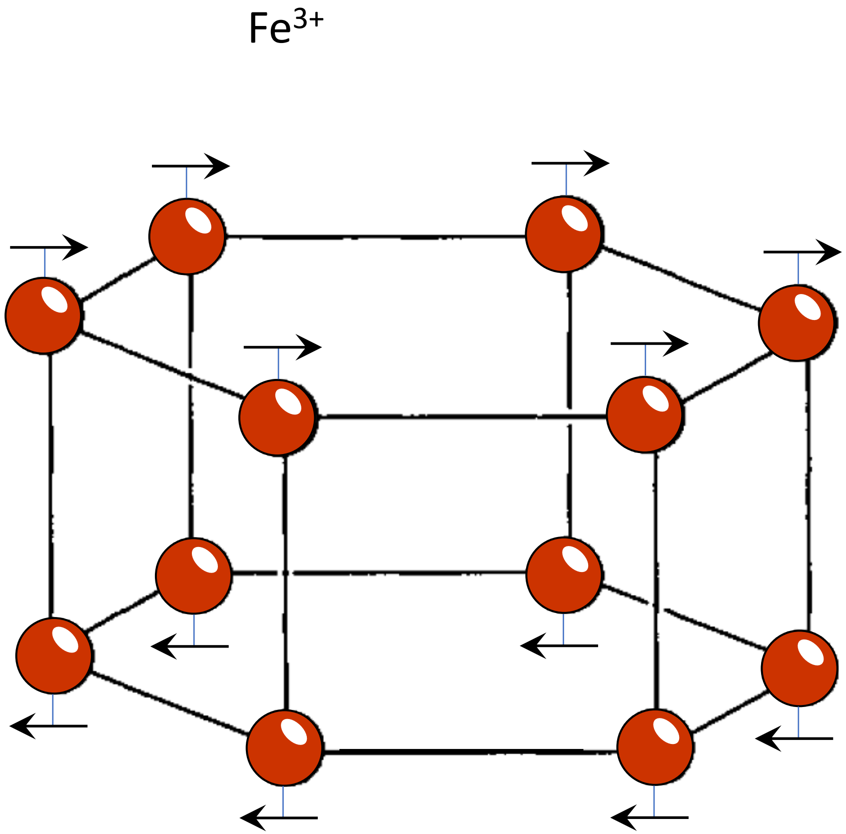
H_c size dependent

- Soils
- Baked clay
- Sediments

- apparent antiparallel alignment of spins



Modified from Evans & Heller 2003

Haematite

- α-Fe_2O_3

- Imperfect antiparallel alignment of spins

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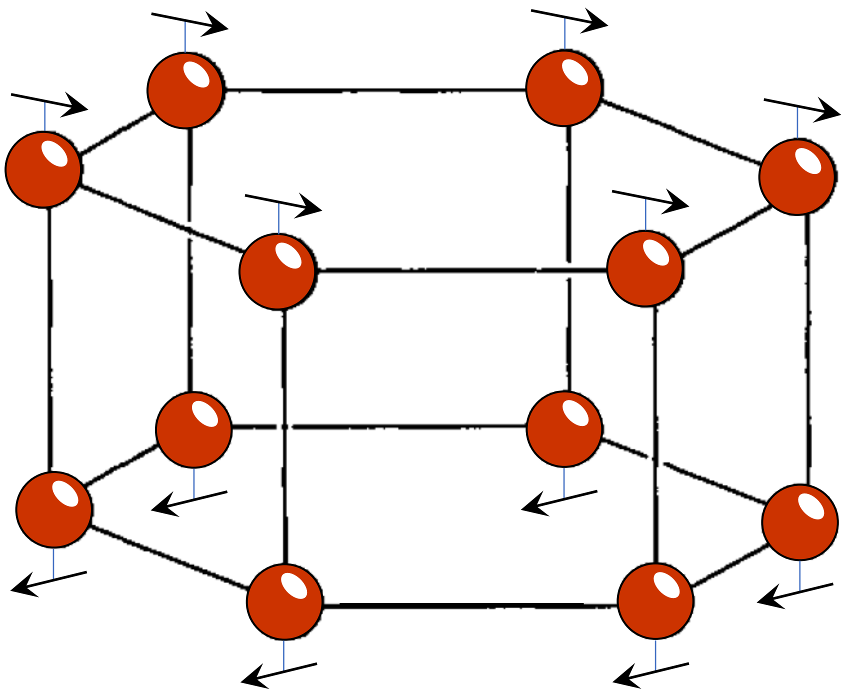

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Haematite

- α-Fe_2O_3

Fe^{3+}

- Imperfect antiparallel alignment of spins

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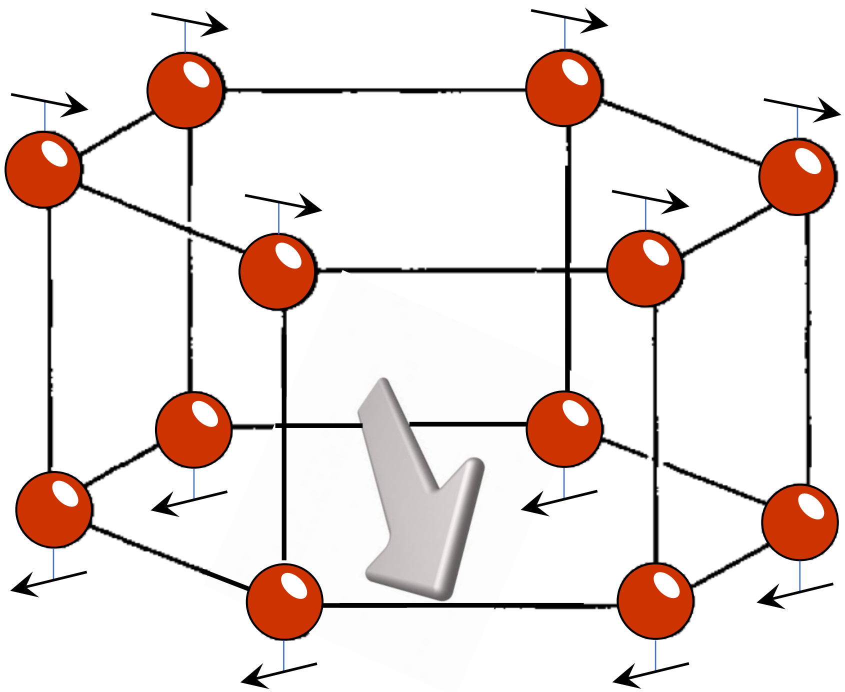

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Haematite

- α-Fe_2O_3

- Imperfect antiparallel alignment of spins
- Holes in crystal lattice (defects)

→ weakly ferromagnetic behaviour

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H_c size dependent

- Soils
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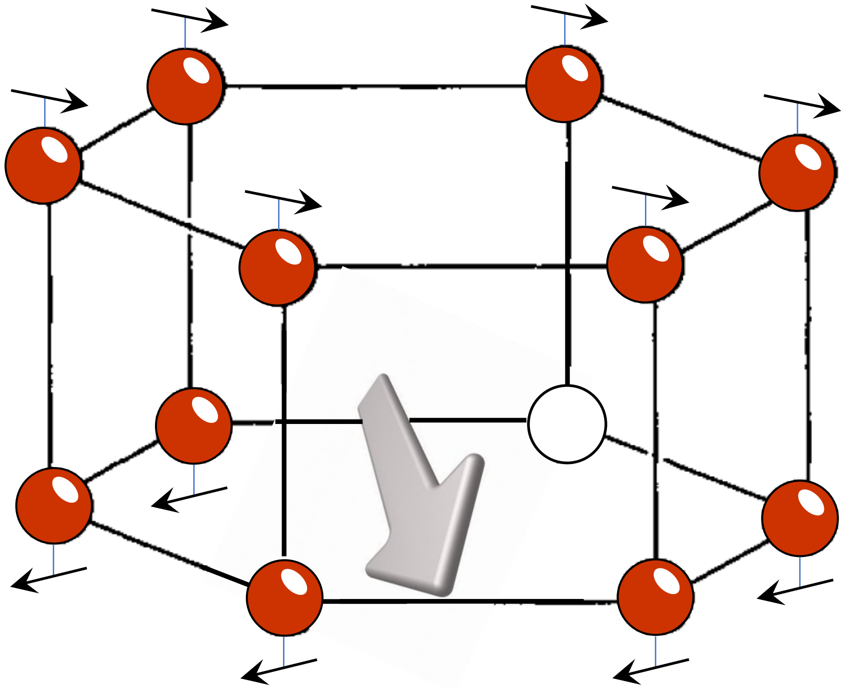

Modified from Evans & Heller 2003

Magnetic minerals

Haematite

- α-Fe_2O_3

- Imperfect antiparallel alignment of spins
- Holes in crystal lattice (defects)

→ weakly ferromagnetic behaviour

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- Soils
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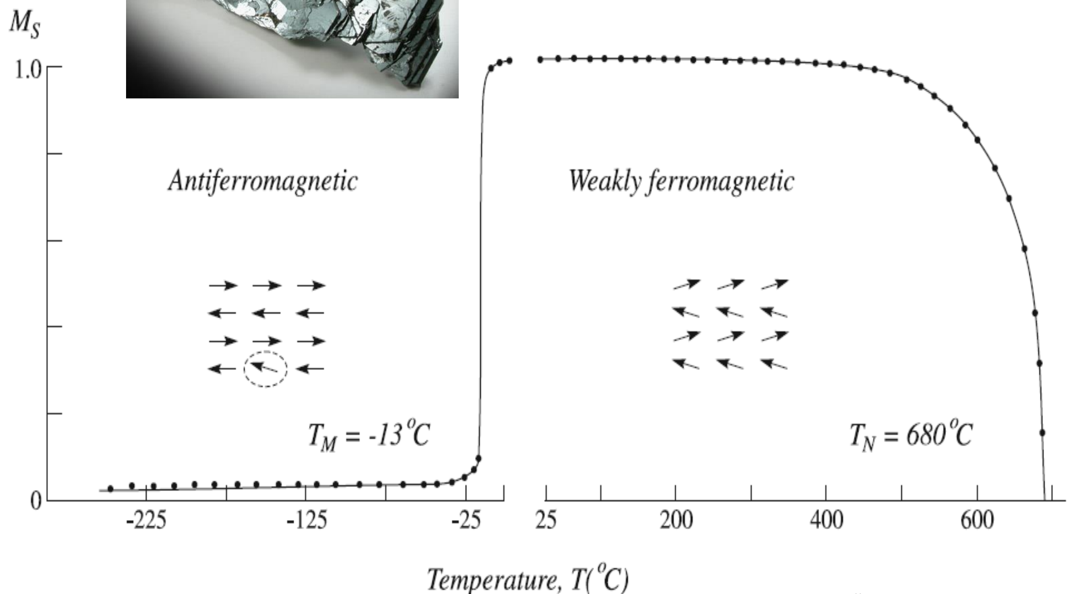

Özdemir & Dunlop 2006

Haematite

- α-Fe_2O_3

- Imperfect antiparallel alignment of spins
- Holes in crystal lattice (defects)

→ weakly ferromagnetic behaviour

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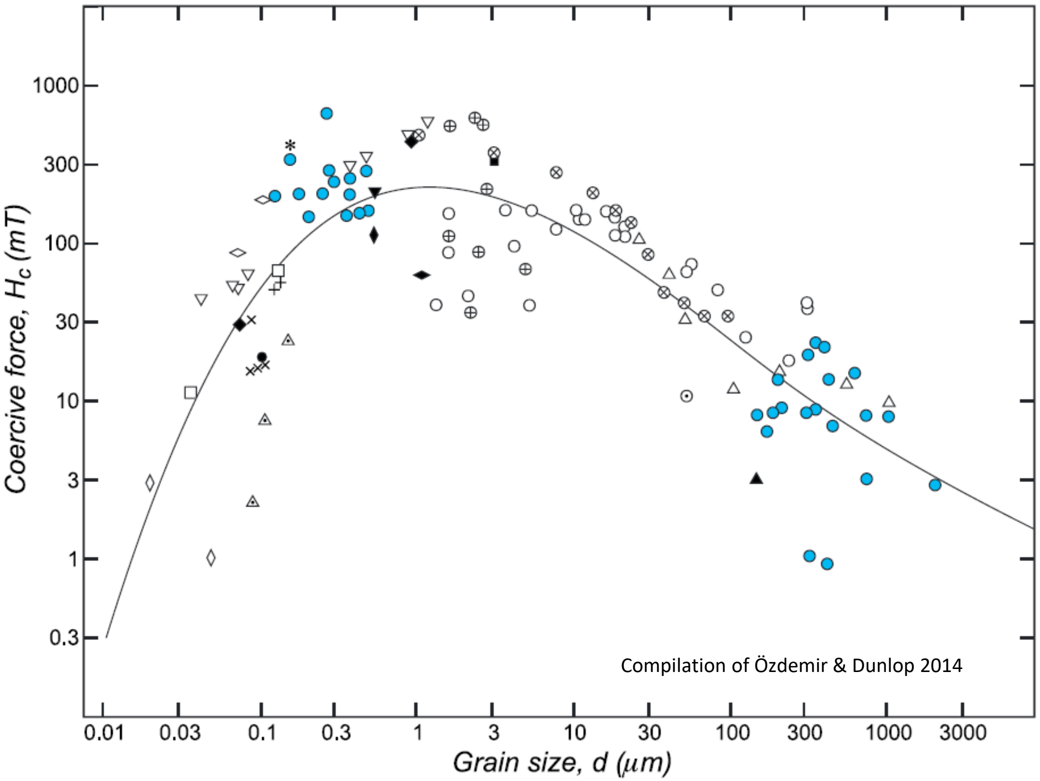
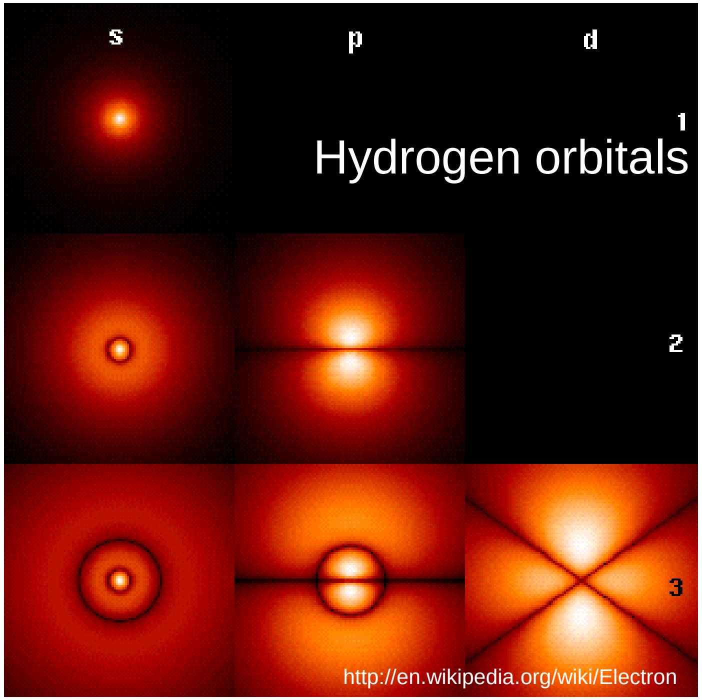


Summary

Origin of magnetism

- Electrons carry a spin magnetic moment
- In crystals with uncompensated spins
- Ordering requires energy gain by spin coordination of electrons in overlapping orbitals.
- Only ions with uncompensated spins in highly eccentric orbitals (*e.g.* 3d for Fe^{3+}) are possible sources of ferro-, ferri- or antiferromagnetism.



Summary

Diamagnetism ($\kappa < 0$)

- external magnetic field H causes distortion of electron-orbit (*Lorentz force*)

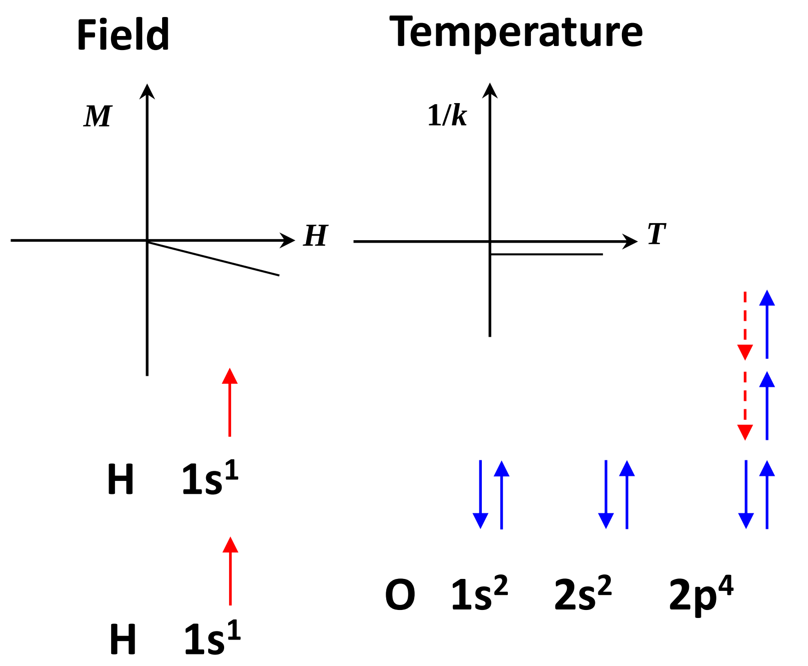
- precession of orbital plane around H direction (*Larmor-precession*)

- a second magnetic moment is created but opposite to H (*Lenz rule*)

- precession frequency depends on H

- in all materials

- weak, best observed in materials without a resulting spin momentum

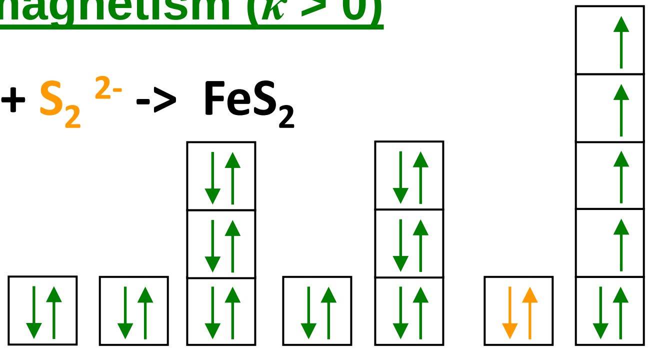


Calcite	$CaCO_3$	-0.48×10^{-8} m³/kg
Quartz	SiO_2	-0.62×10^{-8} m³/kg
Water	H_2O	-0.90×10^{-8} m³/kg

Paramagnetism ($\kappa > 0$)

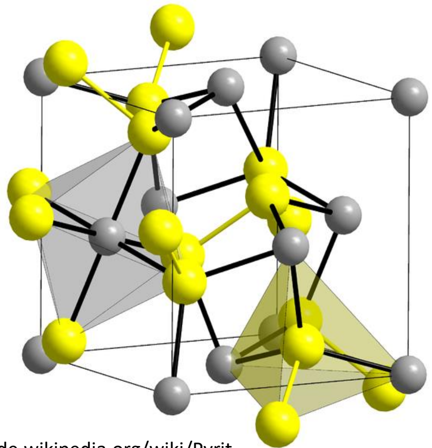
Fe^{2+} + $S_2^{\ 2-}$ -> FeS_2

Pyrite



FeS_2 $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $4s^2$ $3d^6$

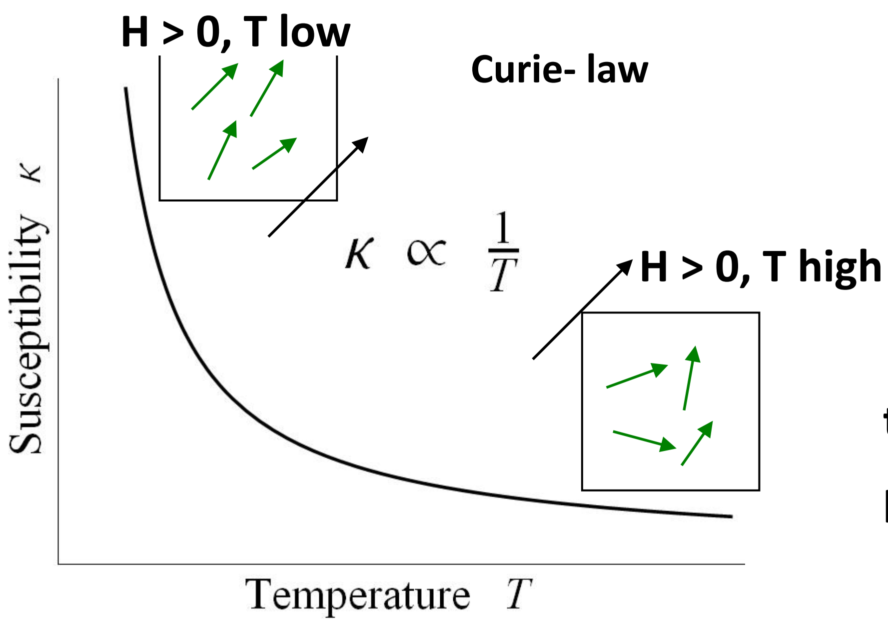
4 uncompensated moments



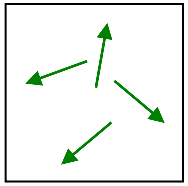
de.wikipedia.org/wiki/Pyrit

de.wikipedia.org/wiki/Kubisches_Kristallsystem

non-overlapping atomic orbitals



H = 0



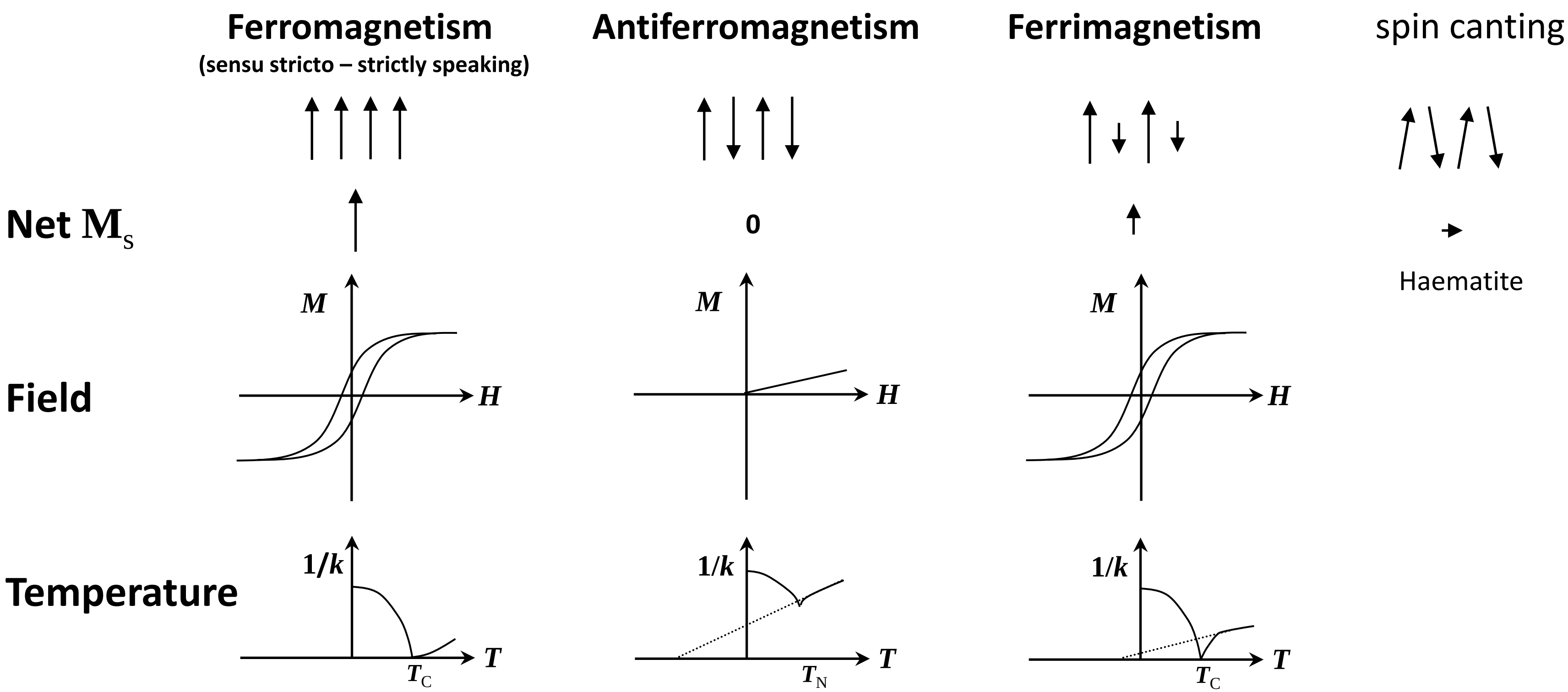
random spin alignment

thermal energy randomises spin alignment

hence spin alignment depends on temperature

Ferromagnetism (κ >> 0)

- in materials with unpaired spins and overlapping atom orbits (close packing)
- electrons are exchanged between iron atoms either directly (ferromagnetism) or indirectly via interjacent oxygen atoms (superexchange – *e.g.* antiferromagnetism, ferrimagnetism)
- materials exhibit a spontaneous magnetisation M_S after field removal, due to uncompensated spin moments



Materials

Iron (α-Fe)
Nickel

Pyrrhotite Fe_9S_{10}
(@ room temperature)

Magnetite Fe_3O_4
Maghaemite γ-Fe_2O_3
Pyrrhotite Fe_7S_8
Greigite Fe_3S_4

parasitic ferromagnetism ->

Haematite α-Fe_2O_3
Goethite α-FeOOH

Magnetic iron minerals

Magnetite (Fe_3O_4): M_s = 480 kA/m, T_c = 580 °C, T_v = -150 °C

ferrimagnetic, in soils, bacteria, lacustrine/marine sediments, often partly oxidised, also in human and animal tissue, combustion product

Maghaemite (γ-Fe_2O_3): M_s = 380 kA/m, (T_c = 590-675 °C)

ferrimagnetic weathering product (fully oxidised magnetite, no Fe^{2+} in lattice), common in soils and sedimentary rocks, combustion product

Haematite (α-Fe_2O_3): M_s = ~2.5 kA/m, T_c = 675 °C, T_M = -15 °C,

imperfect antiferromagnet (weakly ferromagnetic) common in soils and sediments, red beds

Pyrrhotite (Fe_7S_8): M_s = ~ 80 kA/m, T_c = 320 °C

Pyrrhotite (Fe_9S_{10}): ferrimagnetic above 200 °C, T_c = 265 °C

in sedimentary metamorphic rocks, sulfide ores

Greigite (Fe_3S_4): M_s = ~ 125 kA/m, T_c = ~330 °C

forms in aquatic enivronments (and soils) under unoxic conditions, in bacteria

Goethite (α-FeOOH): M_s = ~ 2 kA/m, T_c = 120 °C

imperfect antiferromagnet (weakly ferromagnetic), in soils and acquatic environments, lateritic weathering product

Siderite ($FeCO_3$): T_N = - 235 °C (antiferromagnetic, but paramagnetic @ room temperature) marine lacustrine, in soils probably

- *Properties of some magnetic minerals*
- *Formation of magnetic minerals*
- *Magnetic characterisation methods*
- *Examples*

Soils

Dead vegetable and animal matter is decomposed by soil animals and microorganisms (such as worms, mollusca, bacteria, fungi), altered and incorporated into the soil. -> humification of organic matter.

Source material and products of weathering/humification are transported on and in the soil, either as solid particles or in solutions.

The soil constituents are then connected by cementing material, which is partly of biologic origin. This causes a new texture and granularity.

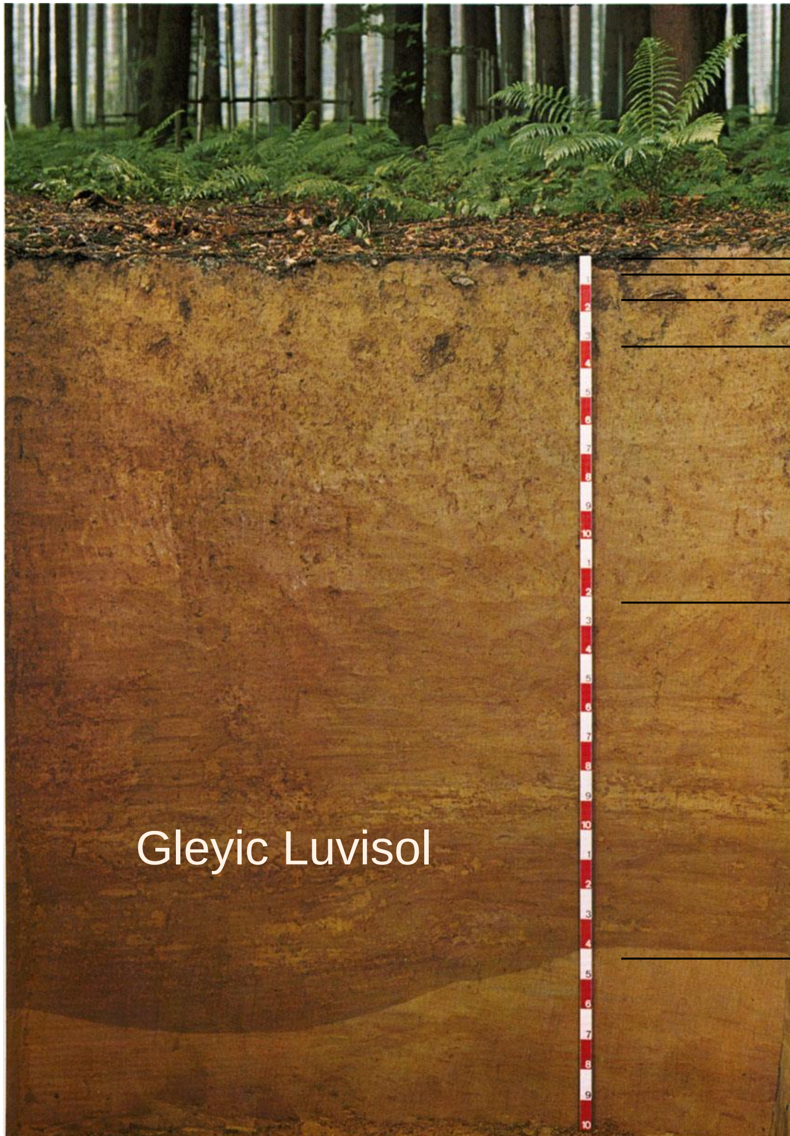
Woodlouses (Armadillidium)

Mites (Acari)

Fungi

Earthworms

Pedogenesis = progressive transformation of bed rock into a soil



O – organic horizon (organic matter)

A_h – mineral horizon (humified organic matter)

E – eluvial horizon (with lighter colour)

B_{tg} – argillic horizon, partly gleyic

B_g – horizon with manganese concretions

C – loess

Bed rock subjected to

Physical processes
- temperature differences
- dilatation shrinking

Chemical processes
- hydrolysis,
- dissolution,
- oxidation, hydration/dehydration

Ionic iron supply from bedrock

Soils

Formation

I. Hydrolysis

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH_4) + 2Na^+ + 2HCO_3^- + 4H_4SiO_4$$

albite — carbon dioxide — water — kaolinite — sodium ions — bicarbonate ions — silicic acid

Destruction of silicates

II. Oxidation

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \text{ (partial reaction)}$$

ferrous ion — ferric ion — electron to other element

$$2Fe^{2+} + 4HCO_3^- + 1/2O_2 + 4H_2O \rightarrow Fe_2O_3 + 4CO_2 + 6H_2O$$

ferrous ions — bicarbonate ions — oxygen — water — hematite — carbon dioxide — water

Fe^{2+} from pyroxene/olivine
To Fe^{3+} in hematite
goethite

III. Hydration and dehydration

$$2FeOOH \Leftrightarrow Fe_2O_3 + H_2O$$

goethite — hematite — water

$$CaSO_4 \cdot 2H_2O \Leftrightarrow CaSO_4 + 2H_2O$$

gypsum — anhydrite — water

Water bound/released in crystal lattice

IV. Dissolution

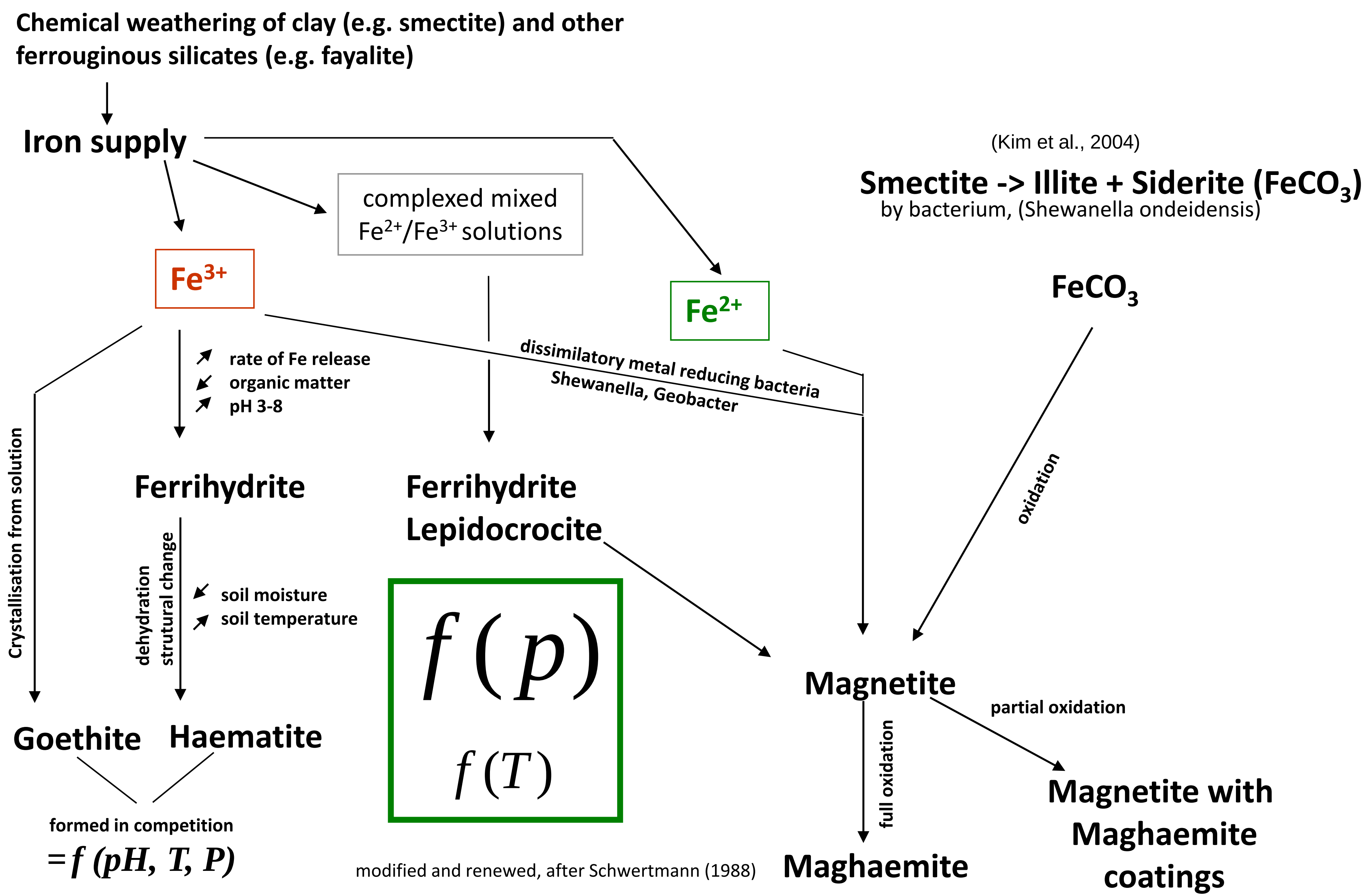
$$CaCO_3 + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^-$$

calcite — carbon dioxide — water — calcium ion — bicarbonate ions

Carbonate dissolution and precipitation

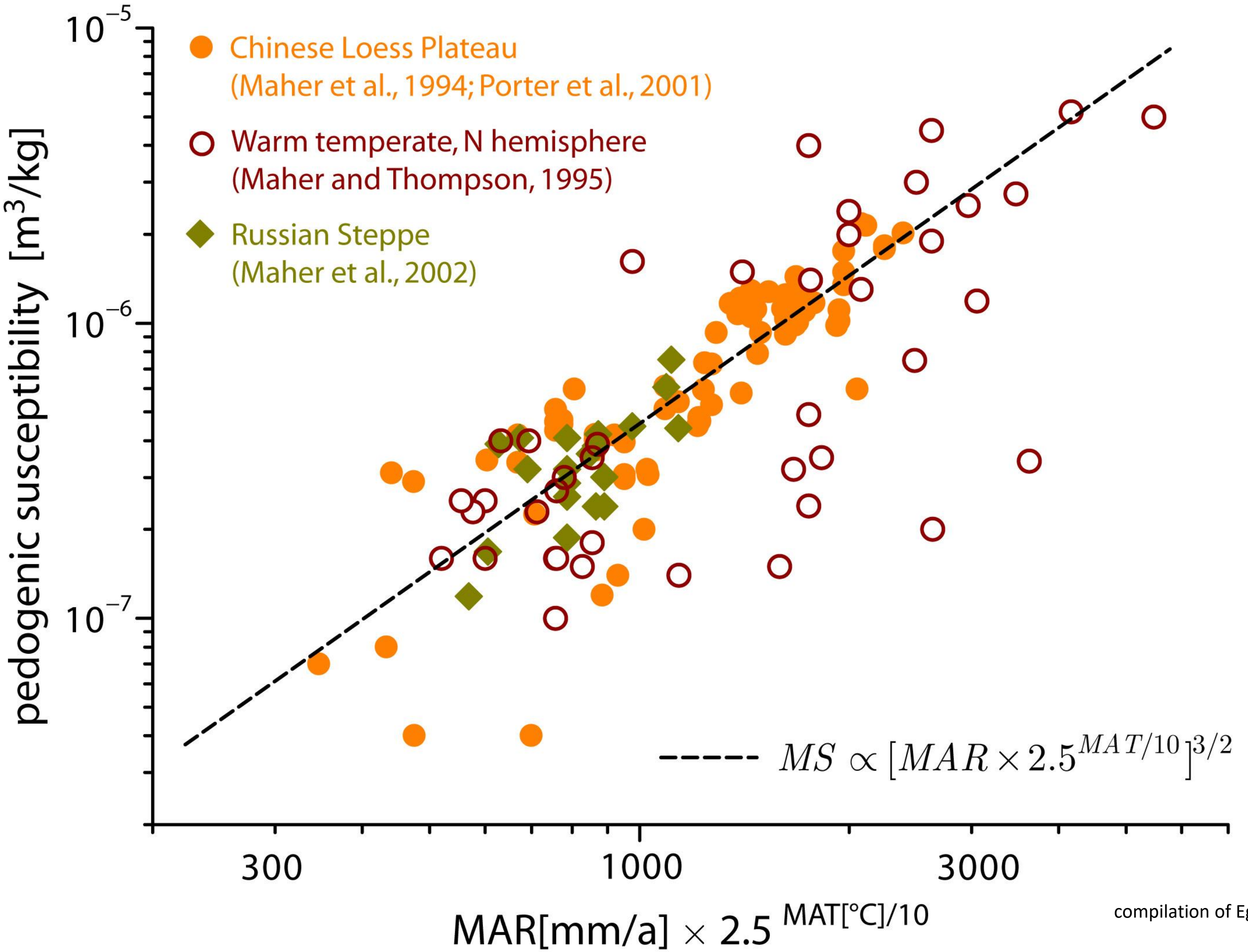
From Garrels and Mackenzie, 1971; compiled by Retallack, 1990 (© Kluwer Academic Publishers, with kind permission of Kluwer Academic Publishers and the author).

Soils


Chemical weathering of clay (e.g. smectite) and other ferrouginous silicates (e.g. fayalite)
Iron supply
complexed mixed Fe^{2+}/Fe^{3+} solutions
Fe^{3+}
Fe^{2+}
(Kim et al., 2004)
Smectite -> Illite + Siderite ($FeCO_3$)
by bacterium, (Shewanella ondeidensis)
$FeCO_3$
rate of Fe release
organic matter
pH 3-8
dissimilatory metal reducing bacteria
Shewanella, Geobacter
Crystallisation from solution
Ferrihydrite
Ferrihydrite
Lepidocrocite
oxidation
dehydration
strutural change
soil moisture
soil temperature
$f(p)$
$f(T)$
Magnetite
partial oxidation
full oxidation
Goethite
Haematite
formed in competition
$= f\ (pH, T, P)$
modified and renewed, after Schwertmann (1988)
Maghaemite
Magnetite with Maghaemite coatings

Soils

Formation



compilation of Egli 2006

Baked materials

Baked materials

Source material contains “non”-magnetic iron

Magnetic minerals are generated during prolonged heat exposure at different p_{O_2}


Muskovit


Phlogopit


Apophyllit


Talk

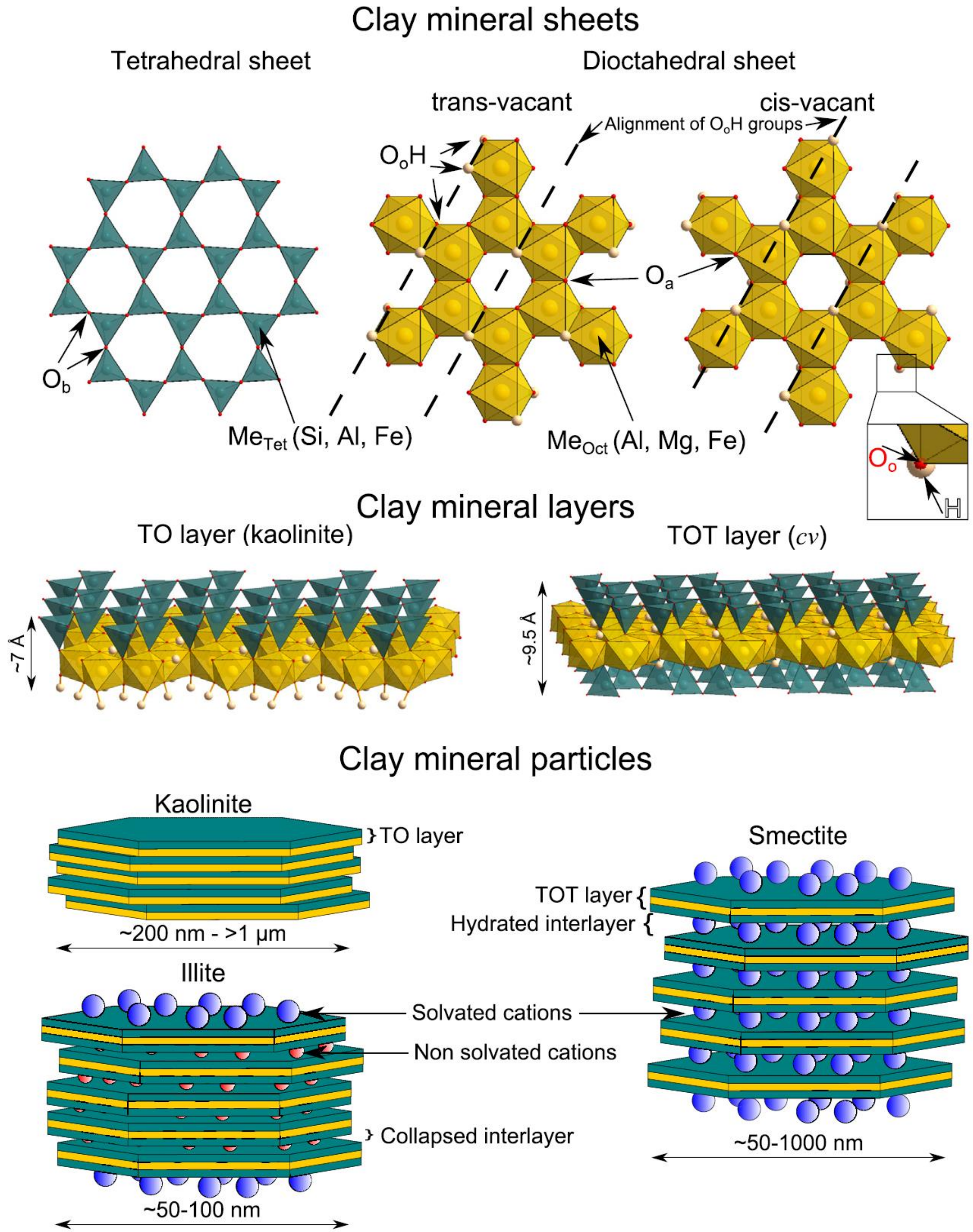

Carletonit

Phylloscilicates (e.g. clays, micas, chlorites)

Murad & Wagner 1998

1. Loss of physically adsorbed or intercalated water at 100–200 °C
2. Oxidation, where applicable, of divalent iron
3. Loss of structural hydroxyl at intermediate higher temperatures
4. Final structural breakdown combined with the formation of new phases close to 1000 °C
5. Vitrification.

Formation



Tournassat *et al.* 2015

FIGURE 1.1 From top to bottom: tetrahedral and octahedral sheets, TO (Kaol) and TOT layers (*cv*-Mt), and clay mineral particles. The Kaol layer structure was taken from the COD database (Gražulis et al., 2012). The *cv*-Mt structure was taken from Tsipursky and Drits (1984).

Baked materials

Source material contains “non”-magnetic iron

Magnetic minerals are generated during prolonged heat exposure at different p_{O_2}

Iron minerals

Murad & Wagner 1998 (and references therein)

Dehydroxylation under | **200 - 320°C** | **310-485°C**

oxidising conditions $2\ (\alpha,\gamma)\text{-}FeOOH \rightarrow \gamma\text{-}Fe_2O_3 + H_2O \rightarrow \alpha\text{-}Fe_2O_3$

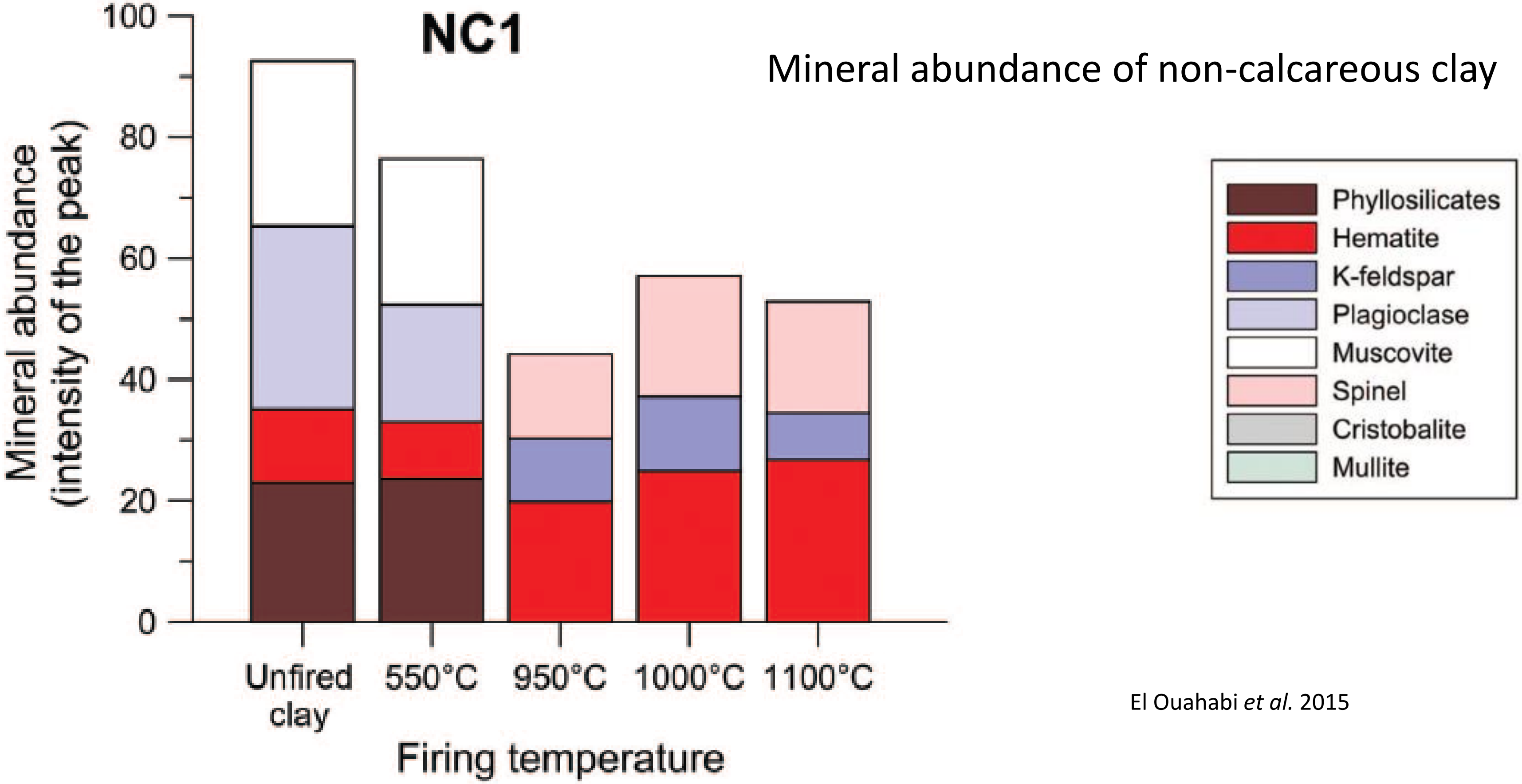
reducing conditions $Fe^{3+} + e^- \rightarrow Fe^{2+} \rightarrow Fe_3O_4$

Presence of *Al* and *Ti* in clay can result in substituted maghaemite and haematite.

Baked materials

Source material contains “non”-magnetic iron

Magnetic minerals are generated during prolonged heat exposure at different p_{O_2}



Mineral abundance of non-calcareous clay

El Ouahabi *et al.* 2015

Baked materials


Roman pottery kiln at Bruyelle (Belgium)

- Properties of some magnetic minerals
- Formation of magnetic minerals
- **Magnetic characterisation methods**
- Examples

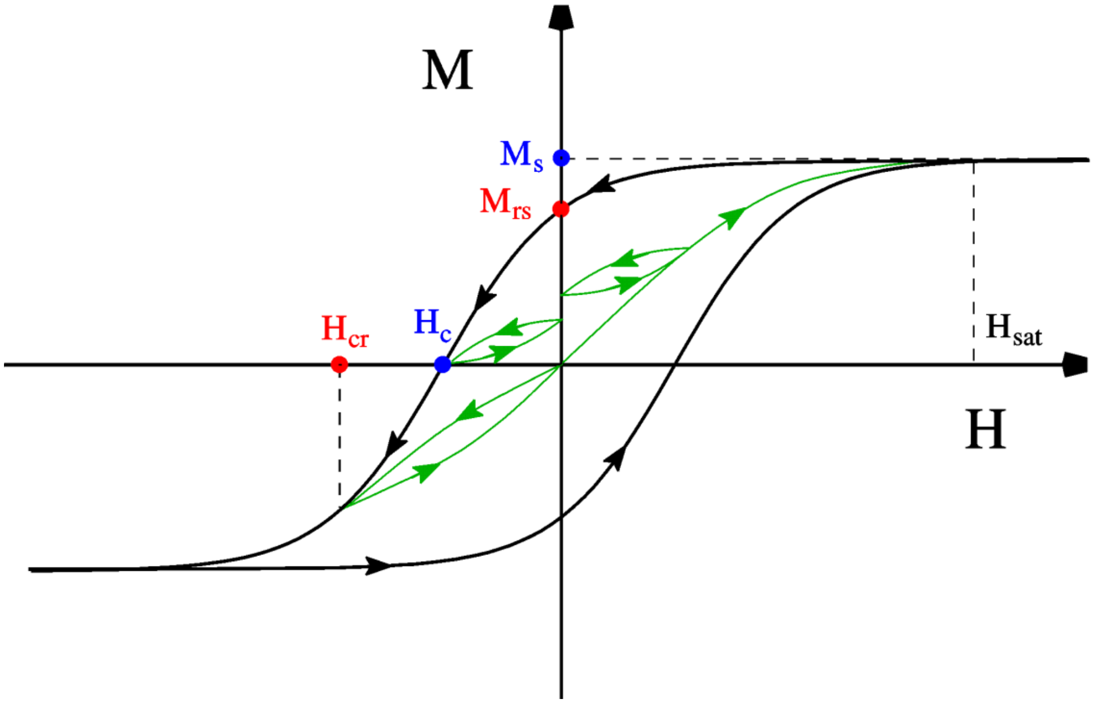
Hysteresis

Loops RT LT, Day, exchange bias, Pasha,
FORC nur am rande
Coercivity spectra analysis nur am rande

Magnetic hysteresis

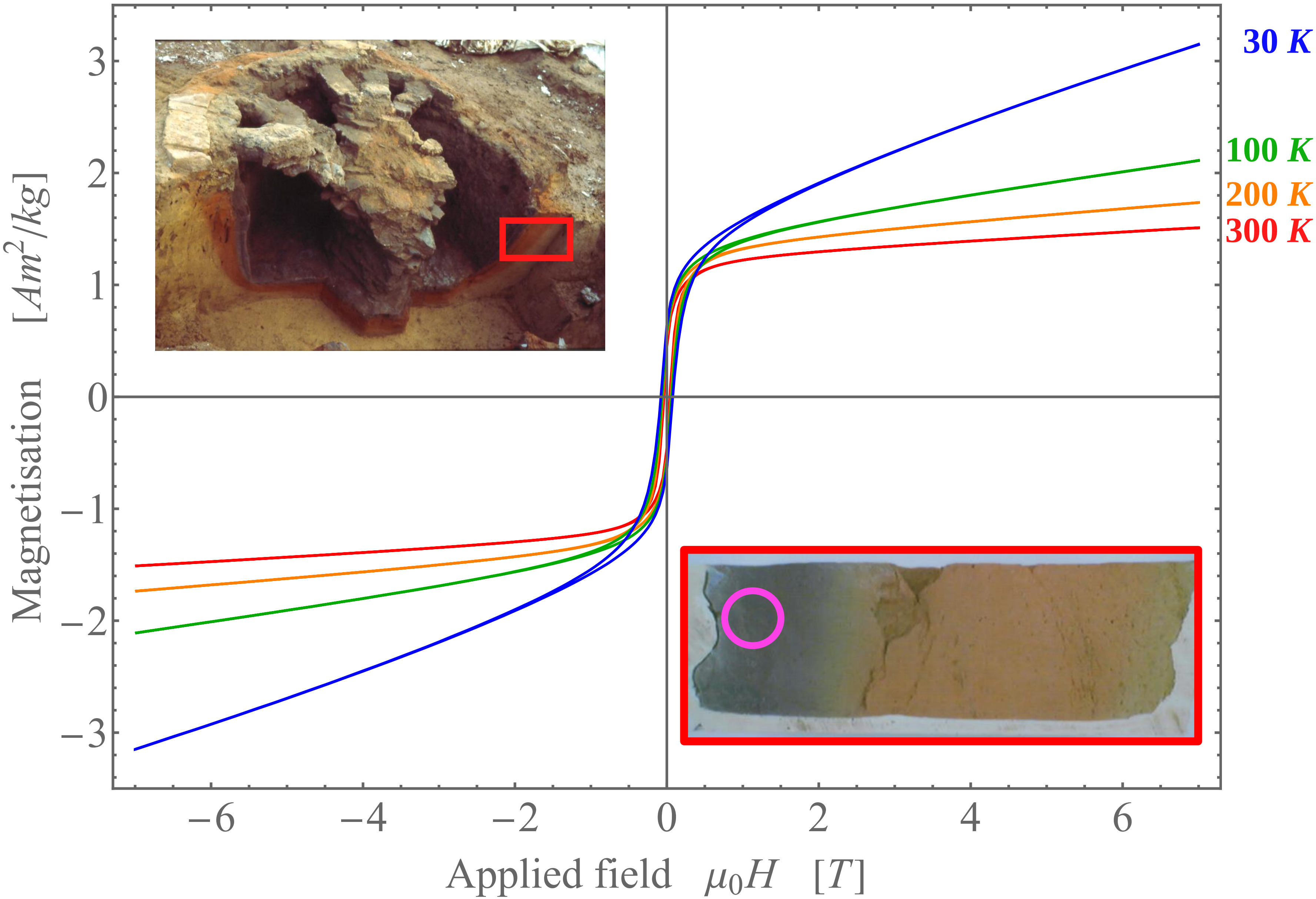
H_c – coercive force
H_{cr} – remanent coercive force
M_s – saturation magnetisation
M_{rs} – saturation remanence

Ratios M_{rs}/M_s and H_{cr}/H_c are indicators of the magnetic grain size

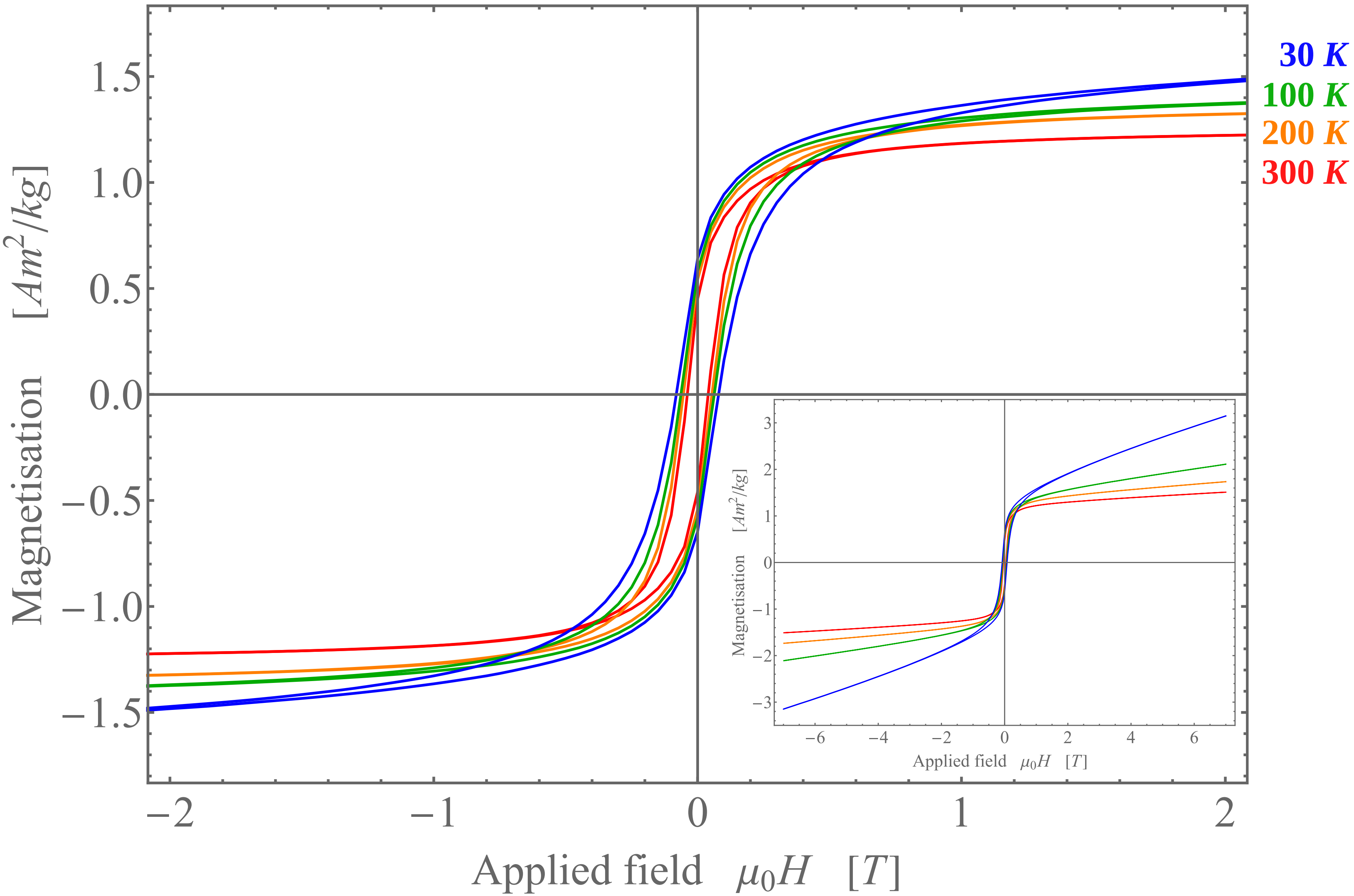


Hysteresis

Characterisation

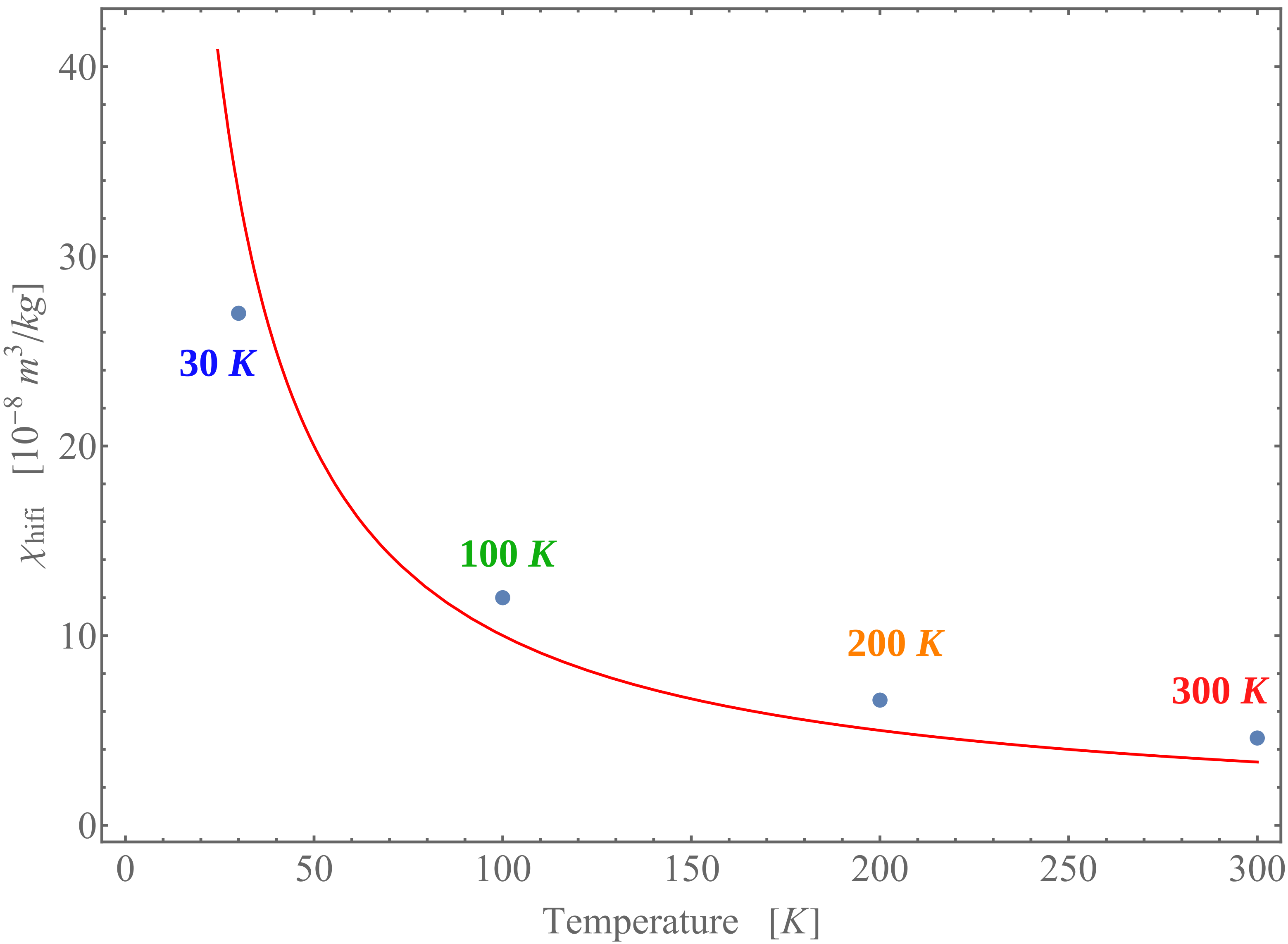


Hysteresis


1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Magnetisation [Am^2/kg]
−2
−1
0
1
2
Applied field $\mu_0 H$ [T]
30 K
100 K
200 K
300 K
3
2
1
0
−1
−2
−3
Magnetisation [Am^2/kg]
−6
−4
−2
0
2
4
6
Applied field $\mu_0 H$ [T]

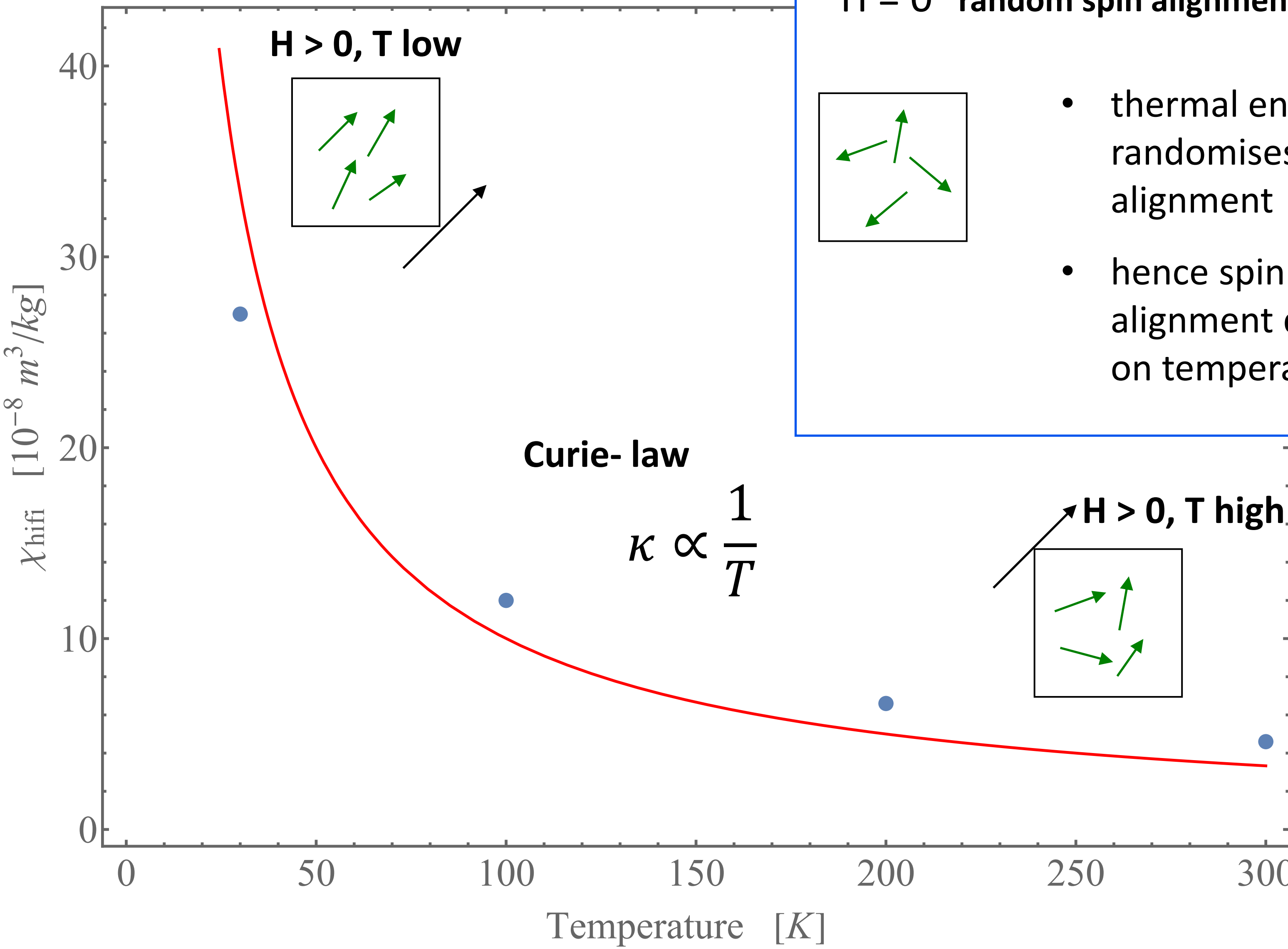
Hysteresis

Characterisation



Hysteresis

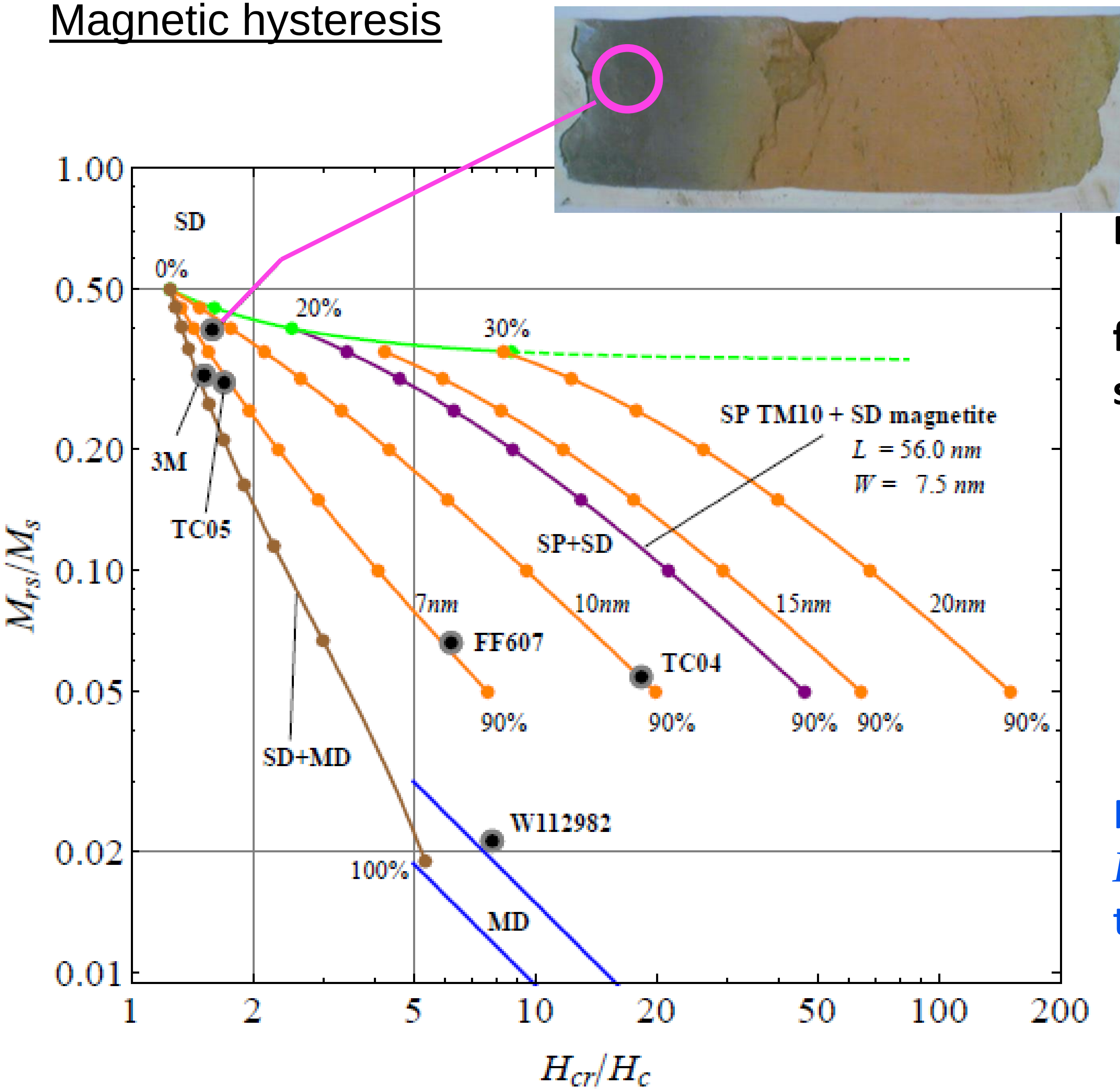
Characterisation



H = 0 **random spin alignment**

- thermal energy randomises spin alignment
- hence spin alignment depends on temperature

Magnetic hysteresis



Day-Dunlop plot

for magnetite samples

Ratios M_{rs}/M_s and H_{cr}/H_c are indicators of the magnetic grain size

Definition & Units

$\vec{M} = \kappa \vec{H}$ H [A/m] and M [A/m] $\rightarrow \kappa$ dimensionless, refers to volume

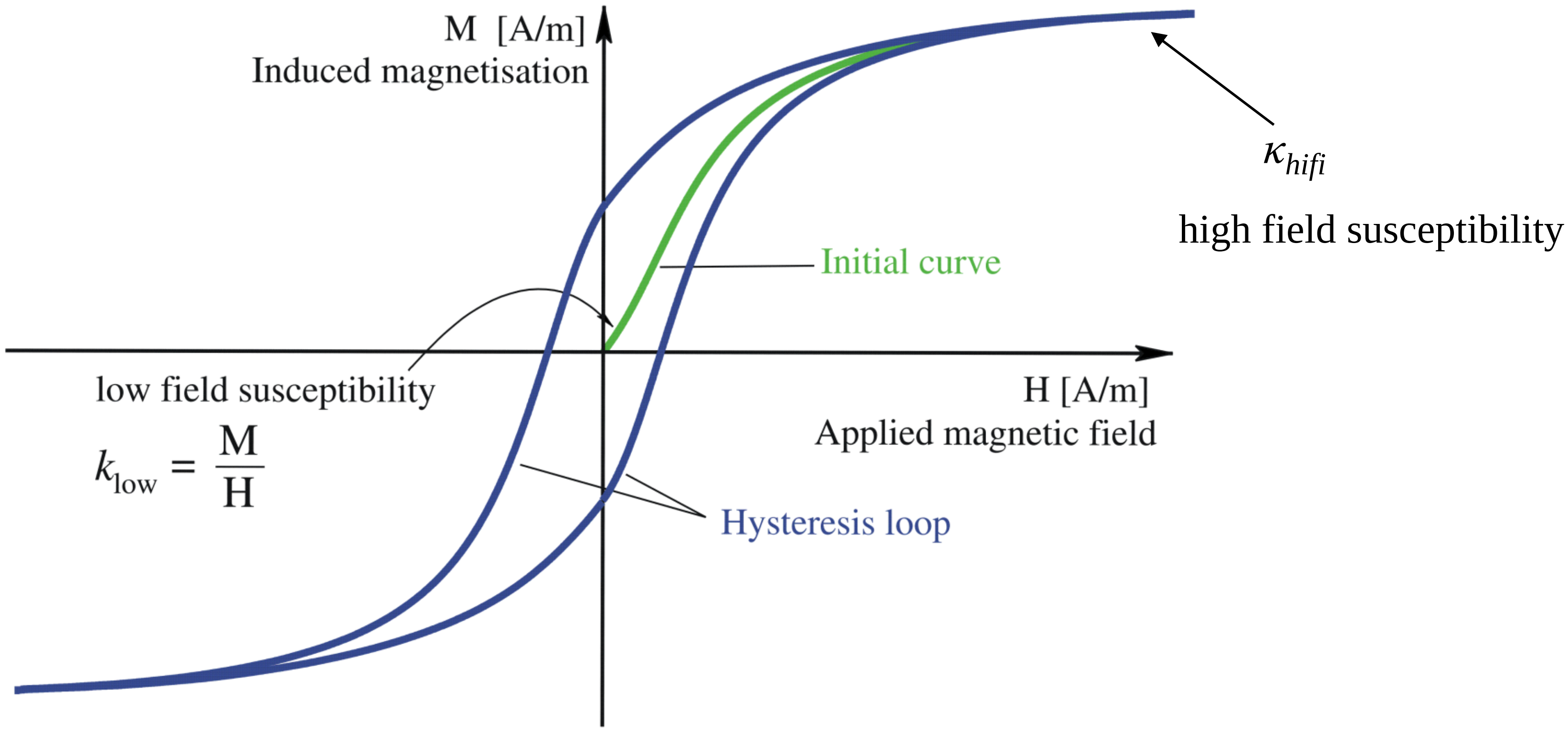
$M_i = \kappa_{ij} H_j$ 2nd degree Tensor

For practical use

Mass susceptibility $\chi_{mass} = \frac{\kappa}{\rho} = \frac{\kappa}{m_{sample}} V_{measurement}$ $[m^3/kg]$

Molar susceptibility $\chi_{molar} = M \cdot \chi_{mass}$ $[m^3/mol]$

DC susceptibility



Initial and high-field susceptibility are determined by fitting the $M(H)$ curve.

General practice κ_{low} obtained from AC measurements, only κ_{hifi} used for interpretations.

AC susceptibility

$$\vec{M} = \kappa \vec{H} \qquad H_{ac} = H(t) = H_0 \cos(\omega t)$$

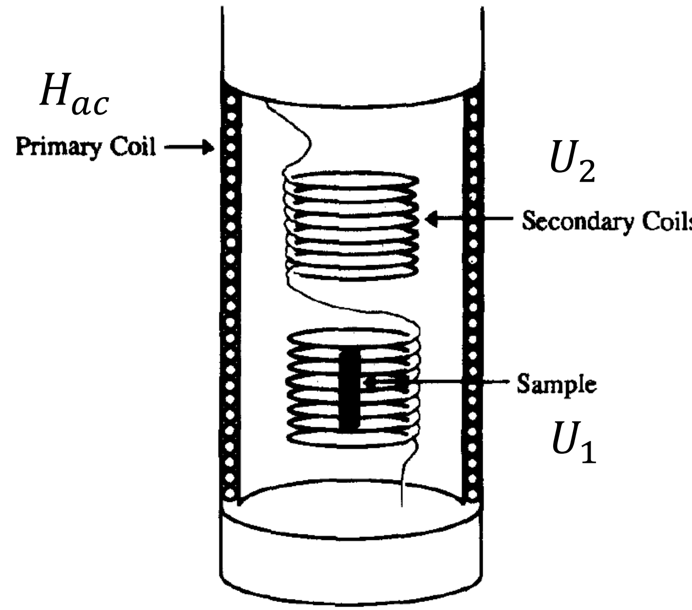
$$\kappa_{ac} = \frac{\partial M}{\partial H_{ac}} \qquad \kappa_{ac} = \kappa' - i\kappa''$$

$$U(t) = -c \cdot \frac{dM(t)}{dt}$$

$$M(t) = \sum_{n=1}^{\infty} H_0^n \left(\kappa_n' \cos n\omega t + \kappa_n'' \sin n\omega t\right)$$

for $n = 1$

$$U(t) = c\, n\omega H_0 (\kappa_1' \sin \omega t - \kappa_1'' \cos \omega t)$$



from Nikolo, *Am. J. Phys. 63*, 1995

U measured with a phase separating lock-in amplifier $\rightarrow$ κ' and κ'' can be separated.

AC susceptibility

Real part

χ'

- Related to reversible magnetisation processes.
- Absorption of energy during magnetisation.
- Stays in phase with the driving oscillating field,
- Reflects the sensitivity of material to applied magnetising field H. “Magnetisability”
- is positive for antiferro-, ferro-, ferri-, paramagnetics
- is negative for diamagnetics

AC susceptibility

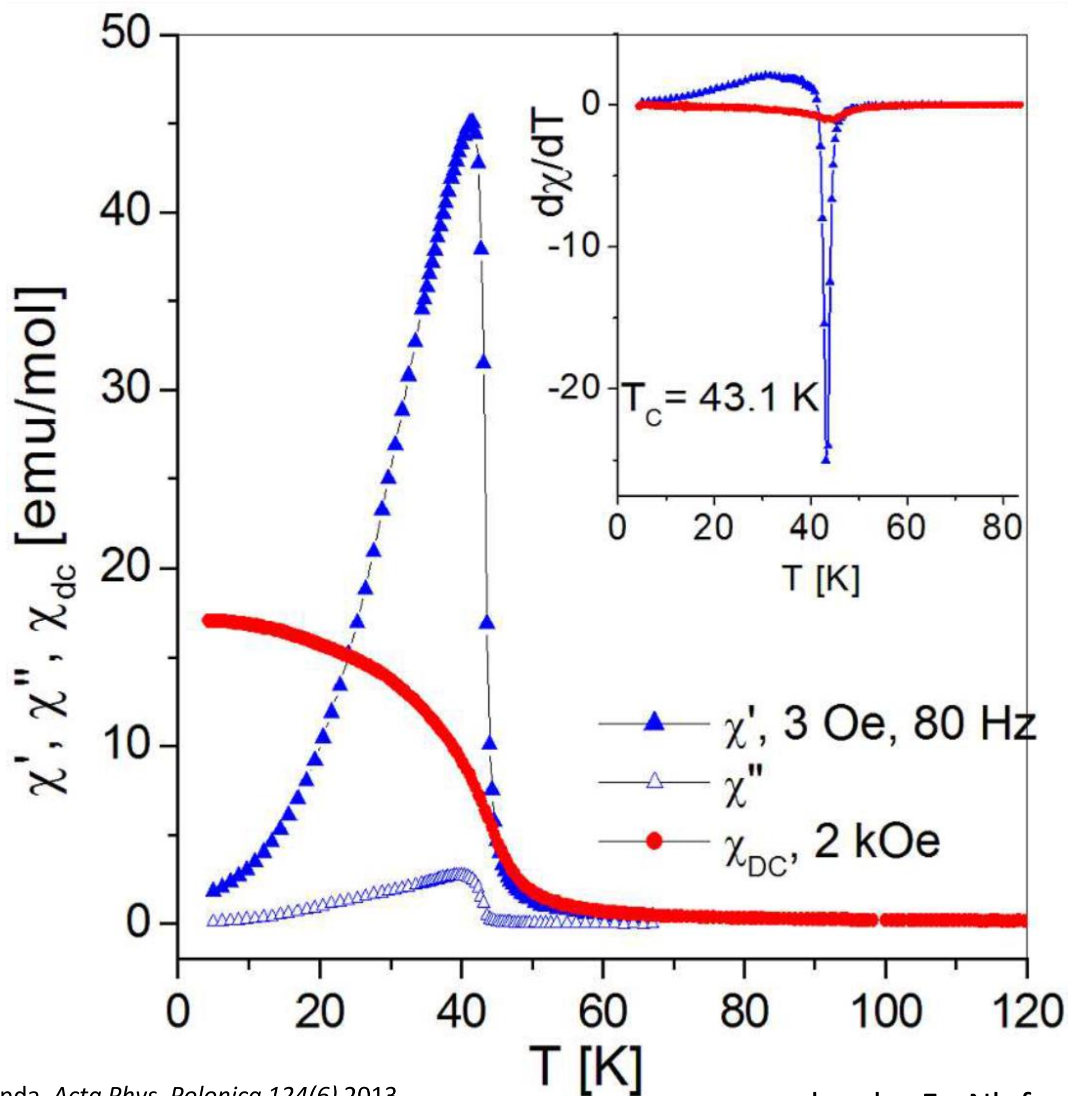
Imaginary part

χ''

- Due to irreversible magnetisation changes
- Dissipation of energy during magnetisation, e.g. due to:
  - irreversible domain wall movements
  - relaxation of SP grains
  - Spin lattice relaxation in paramagnets
  - eddy currents in conducting materials
- May be zero or positive, but never negative.
- $\chi'' < \chi'$
- If $\chi'' = 0 \rightarrow \chi_{ac} = \chi_{dc}$

Susceptibility

AC vs. DC susceptibility

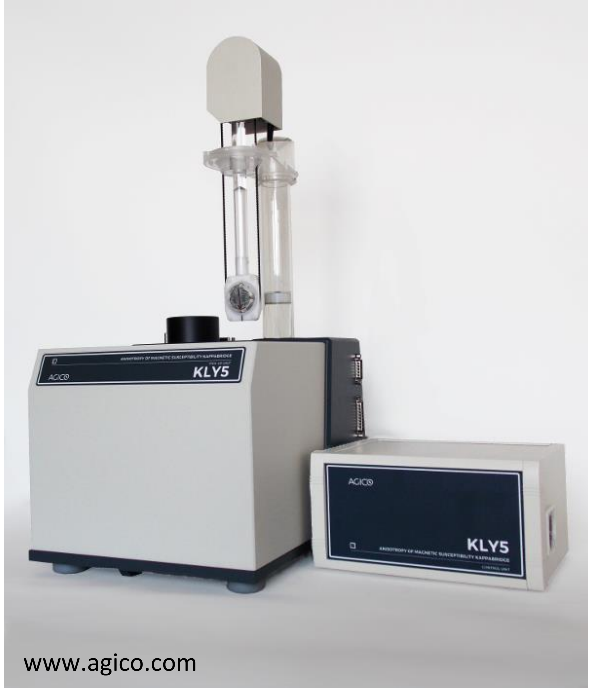


Balanda, *Acta Phys. Polonica 124(6)* 2013,
Pinkowicz et al., *Dalton Trans.*, 2009,

molecular Fe-Nb ferromagnet with a Curie temperature well below room temperature

Instruments measuring κ_{AC}

Producer	T [K]	H_{ac} [A/m]	f [kHz]	$H_{DC\text{-}bias}$ [mT]
Bartington	73-1123	0.2	0.456 & 4.56	-
Agico	81-973	5-750	0.976, 3.904, 15.6	-
QD	0.5-1000	8-800	0.0001-1	0.5-7000



→ Bulk, anisotropy, $\chi(T)$, $\chi(f)$, $\chi(H)$

Susceptibility

Instruments measuring κ_{AC}

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www.bartington.com

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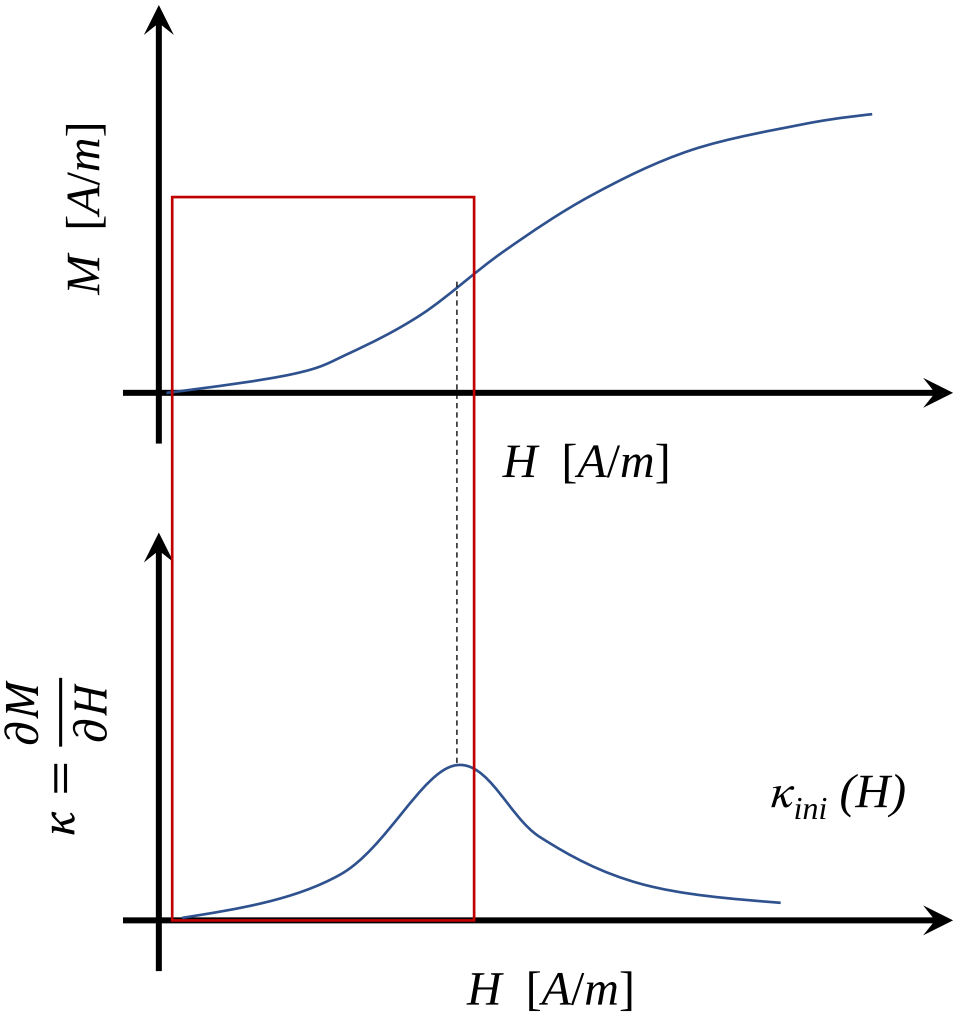
DC in function of T, H,
Anisotropy in function of H
AC χ', χ'' in function of T, H, f

Susceptibility

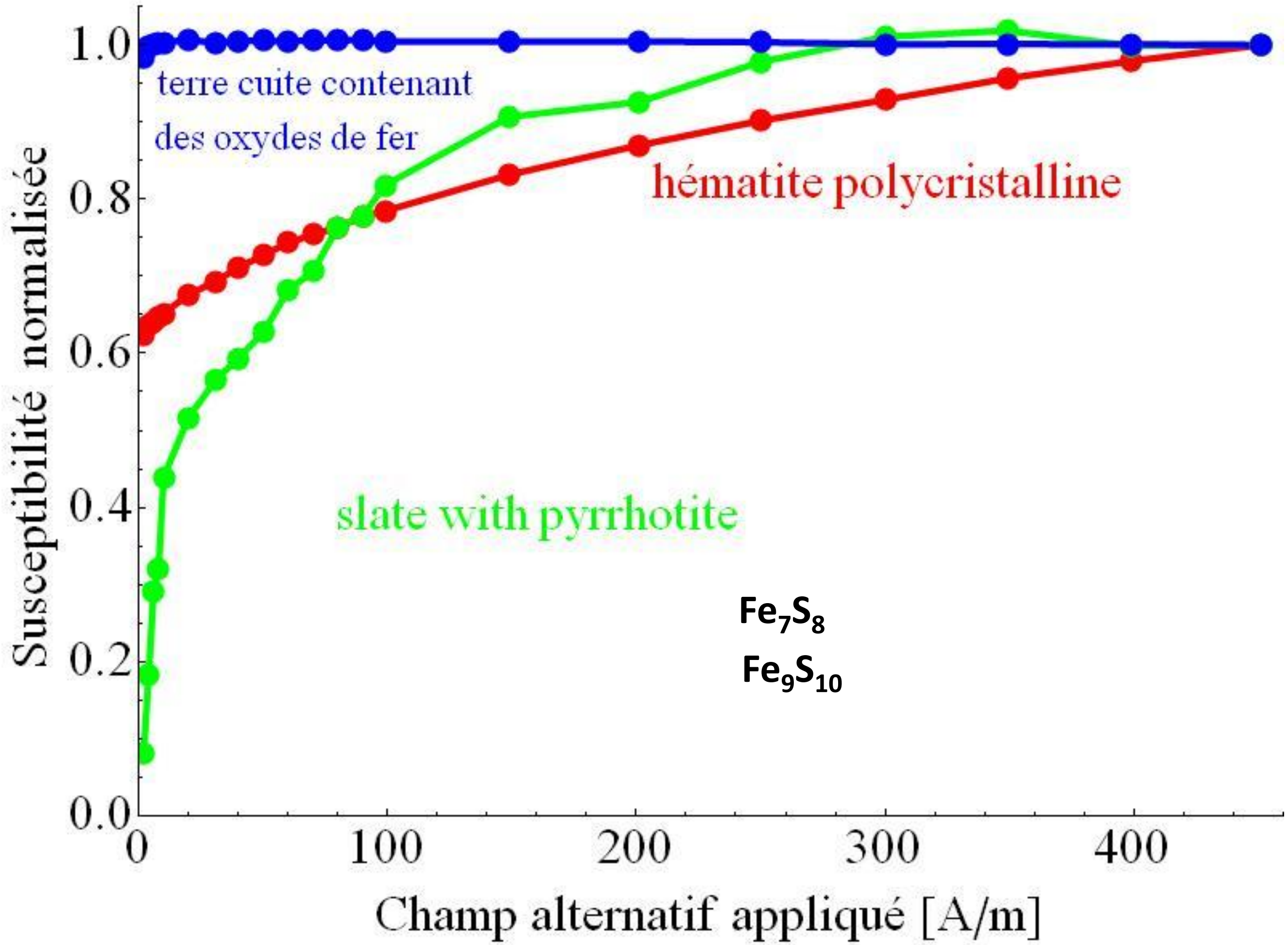
Field dependence



magnetic mineral identification

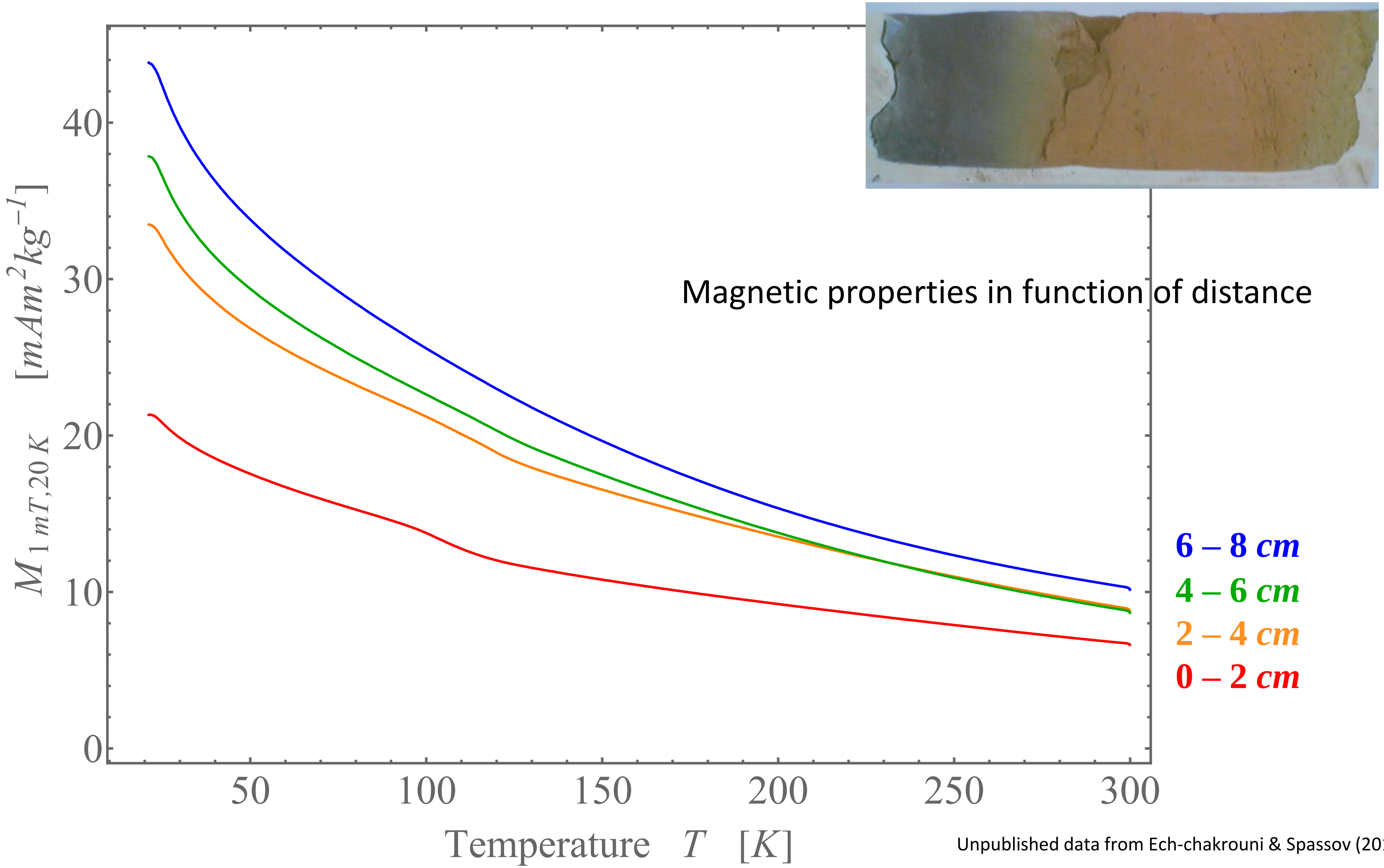
- small fields < 800 A/m
  (in reversible region of hysteresis loop)
- Initial slope changes are different for different magnetic minerals

Field dependence



Unpublished data Hus & Spassov (2006)

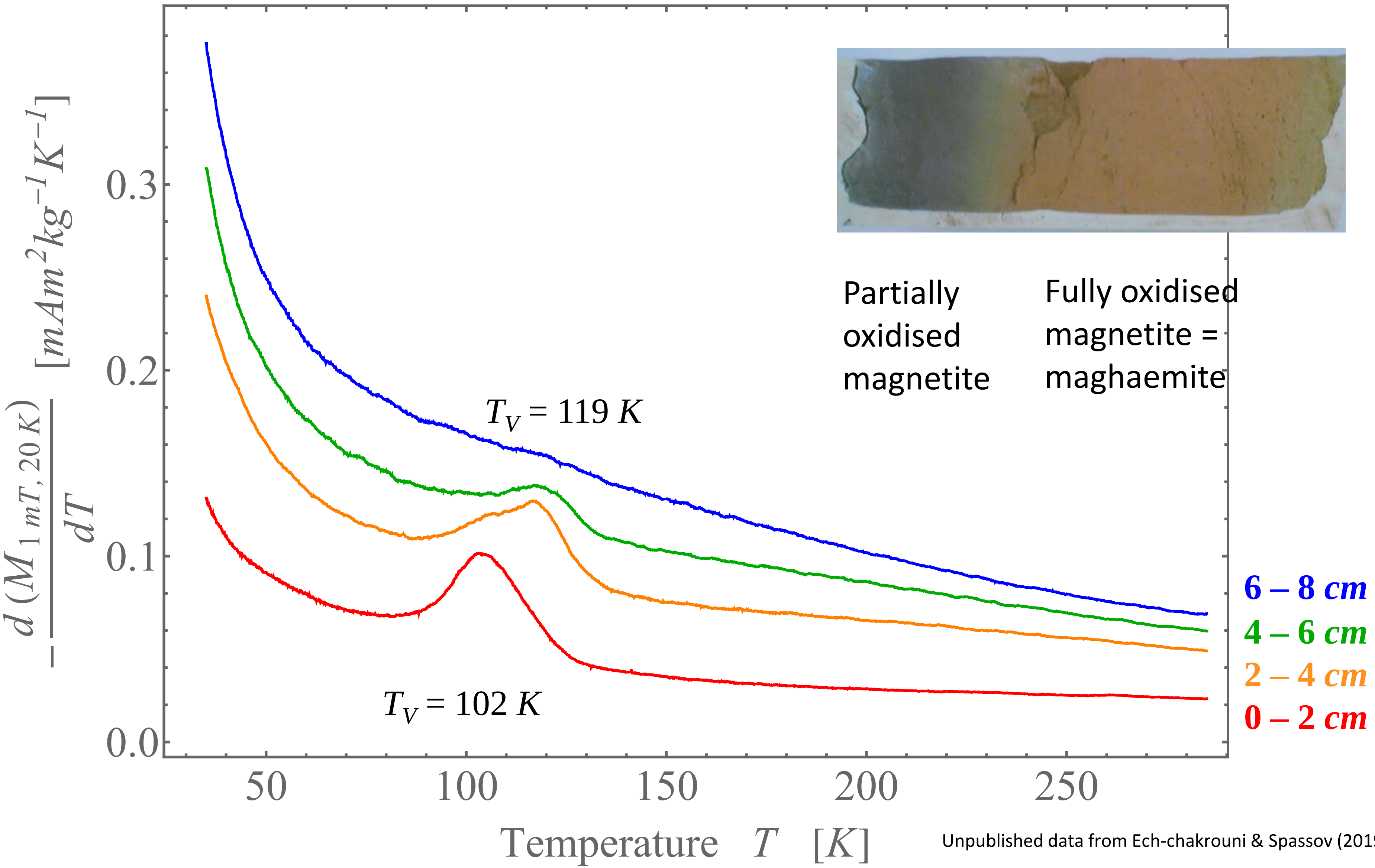
Low temperature magnetisation



Magnetic properties in function of distance

Unpublished data from Ech-chakrouni & Spassov (2019)

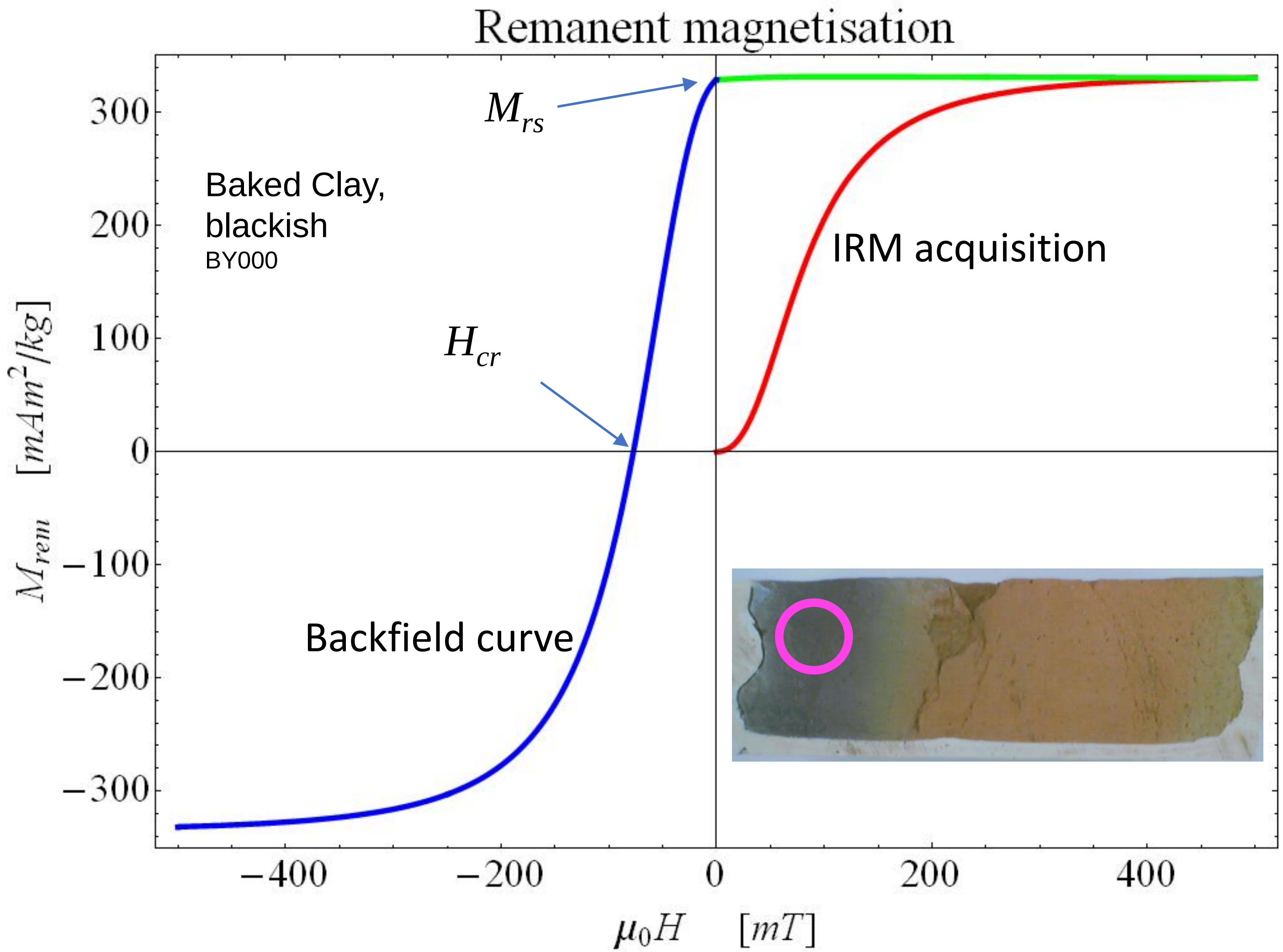
Low temperature magnetisation



Unpublished data from Ech-chakrouni & Spassov (2019)

Isothermal remanent magnetisation

Steady field magnetisation



S-ratio

$$\frac{|IRM_{-300mT}|}{M_{rs}}$$

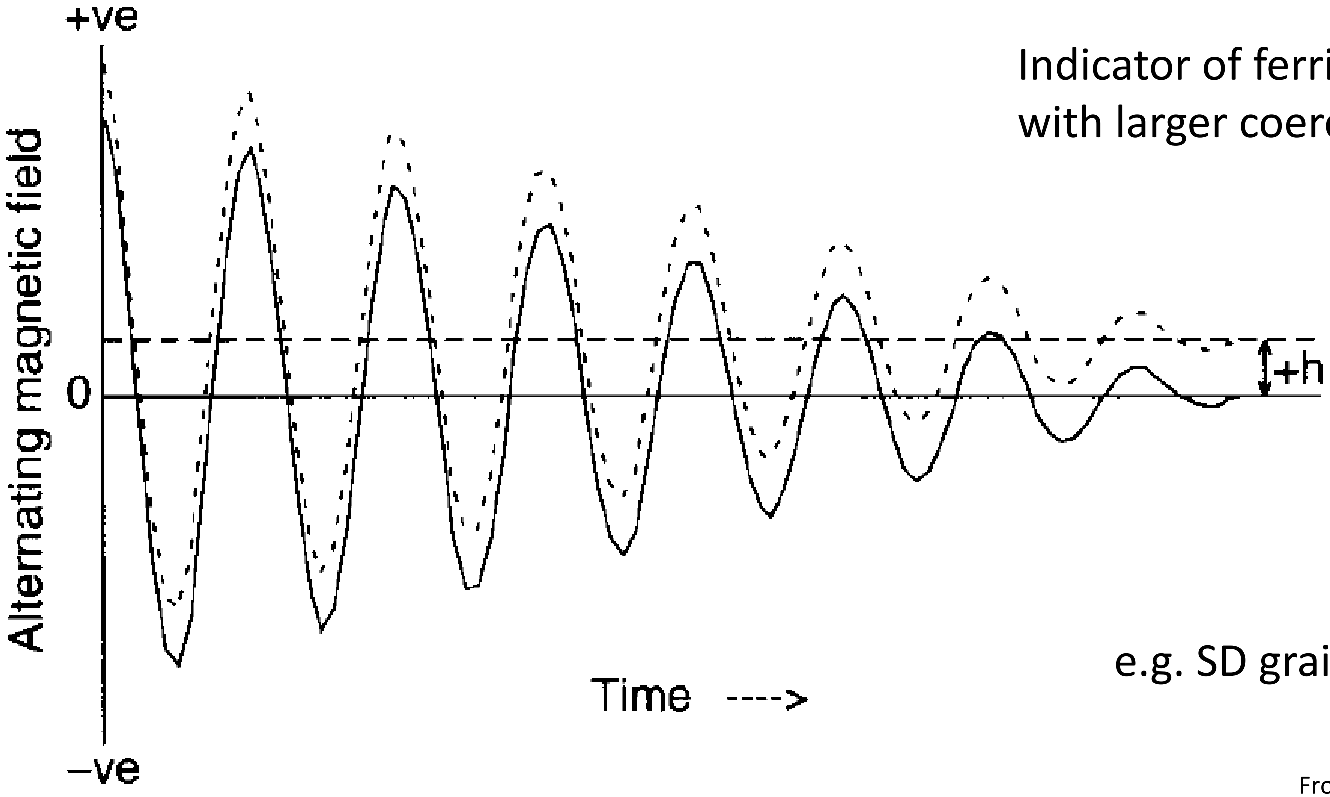
Ratios < 1 indicative for presence of high-coervivity minerals

ARM

Anhysteretic remanent magnetisation

Steady field magnetisation and alternating field demagnetisation at once

Indicator of ferrimagnetic grains with larger coercive forces



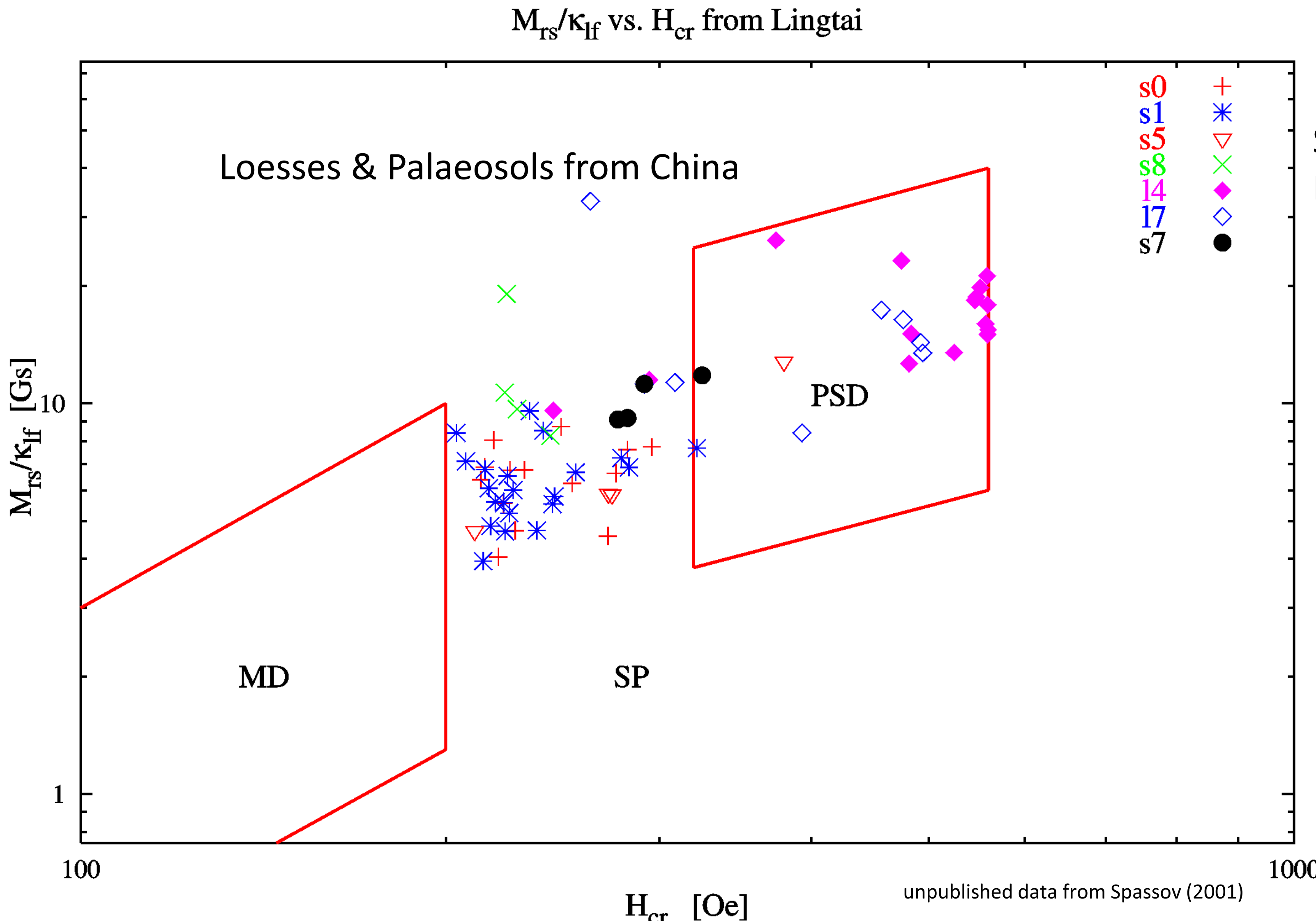
e.g. SD grains of magnetite

From Evans & Heller (2003)

Normalised SIRM vs remanent coercive force

Characterisation

grain size



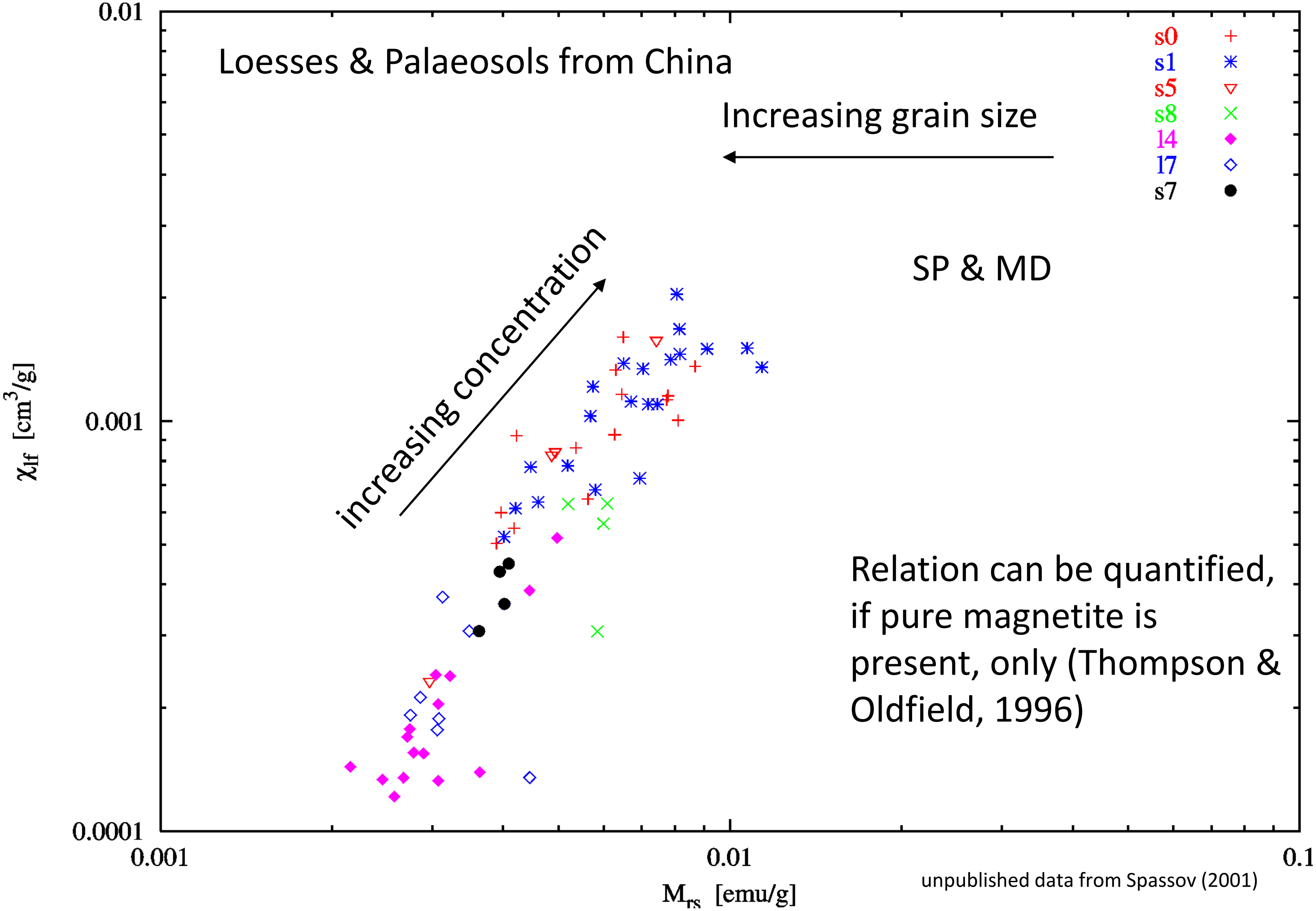
unpublished data from Spassov (2001)

S - Palaeosol
L - loess

Saturation remanence vs. susceptibility

Characterisation

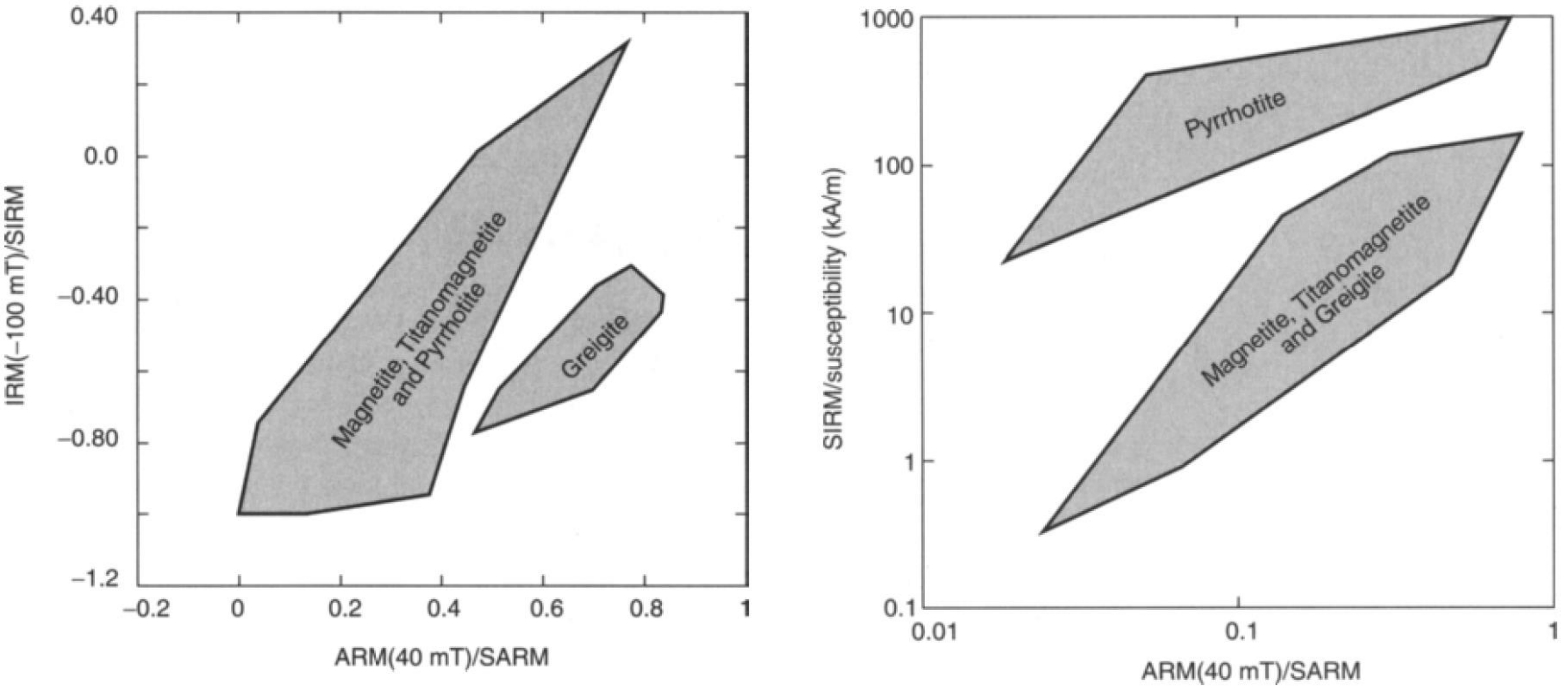
Grain size & concentration



unpublished data from Spassov (2001)

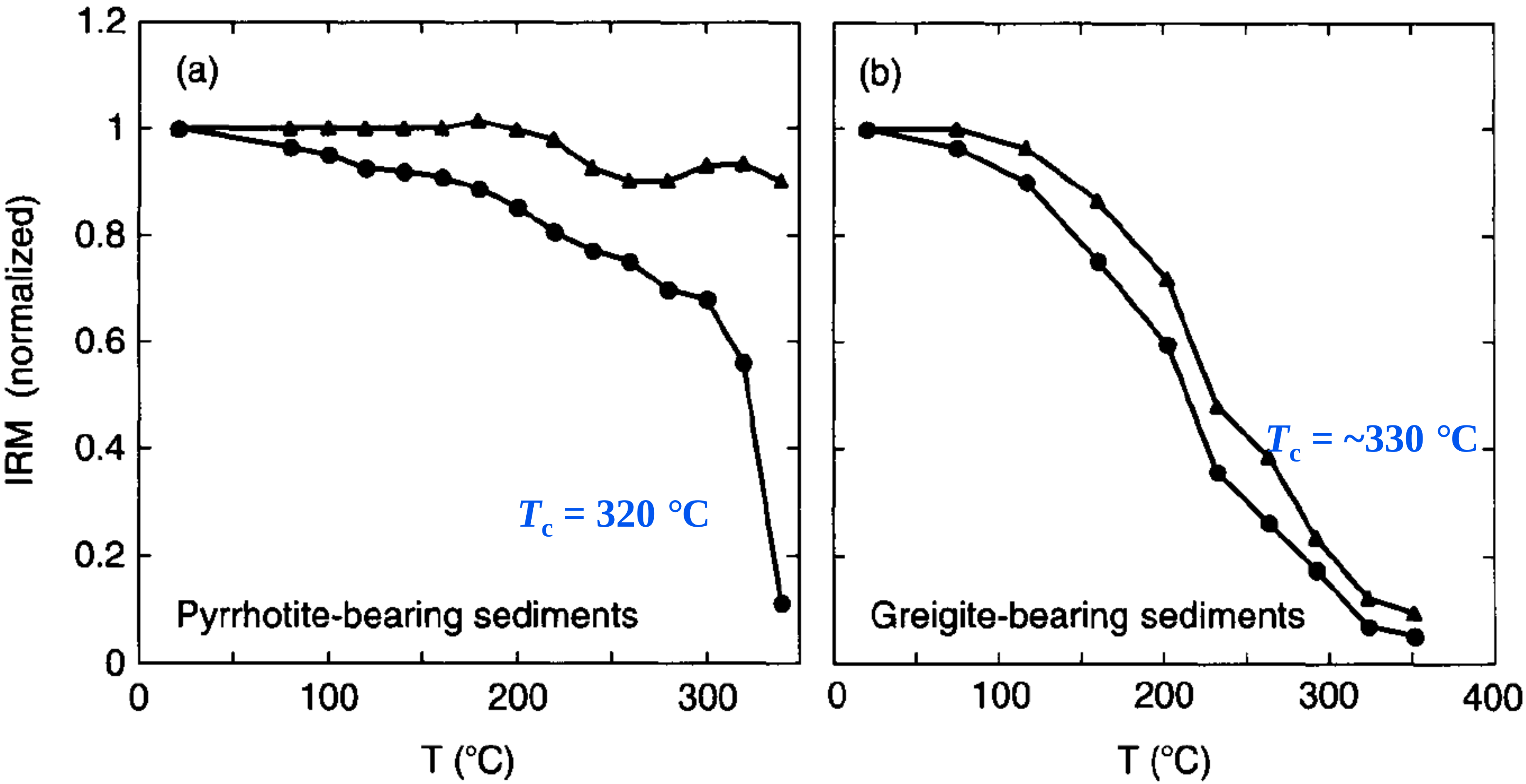
Backfield IRM vs ARM

Characterisation



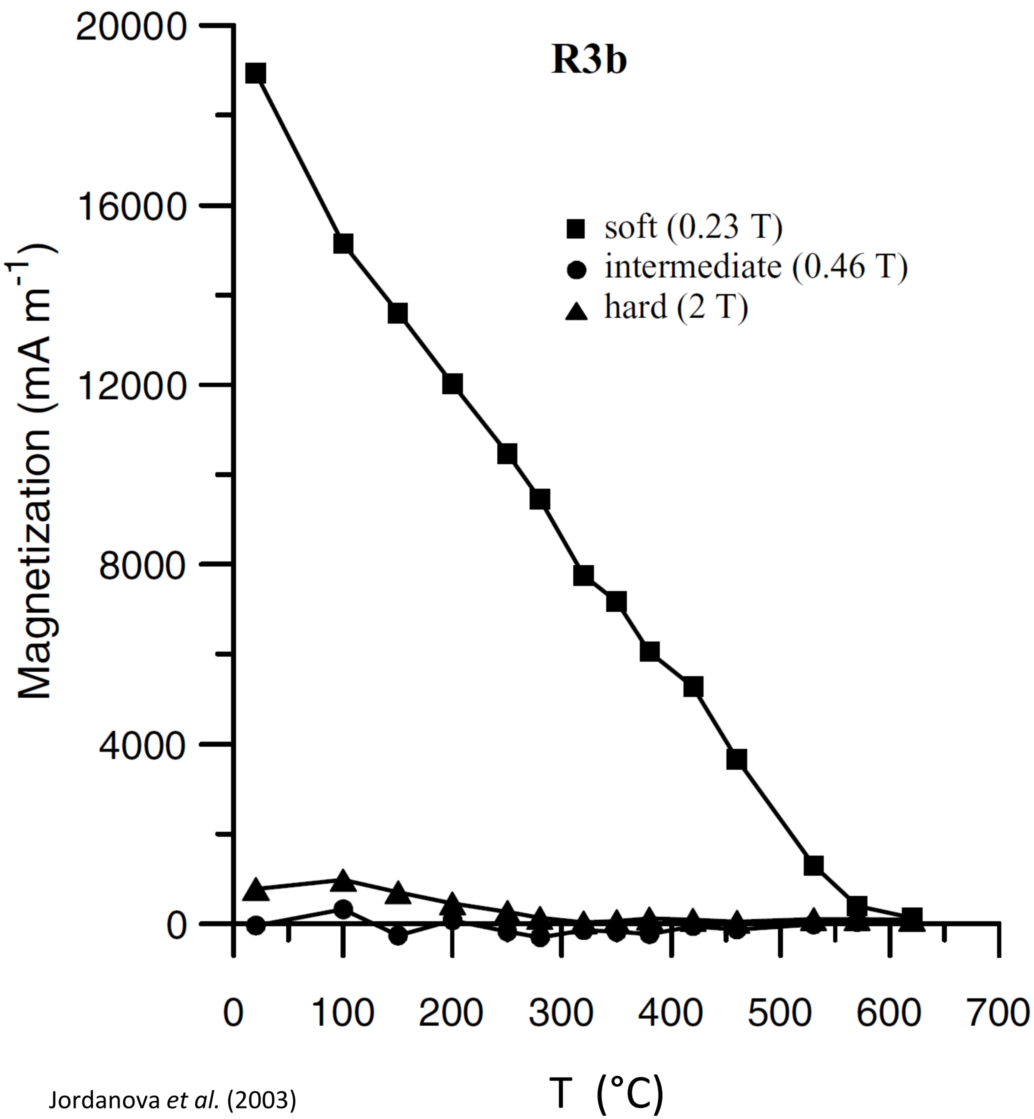
From Evans & Heller (2003)

Thermal demagnetisation of IRM



From Evans & Heller (2003)

Thermal demagnetisation of IRM



Jordanova *et al.* (2003)

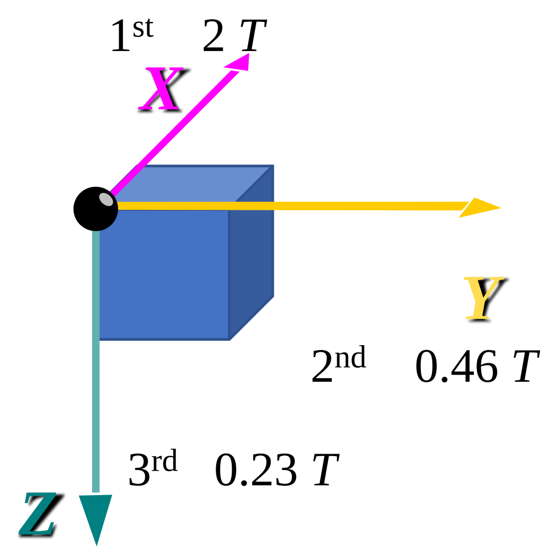
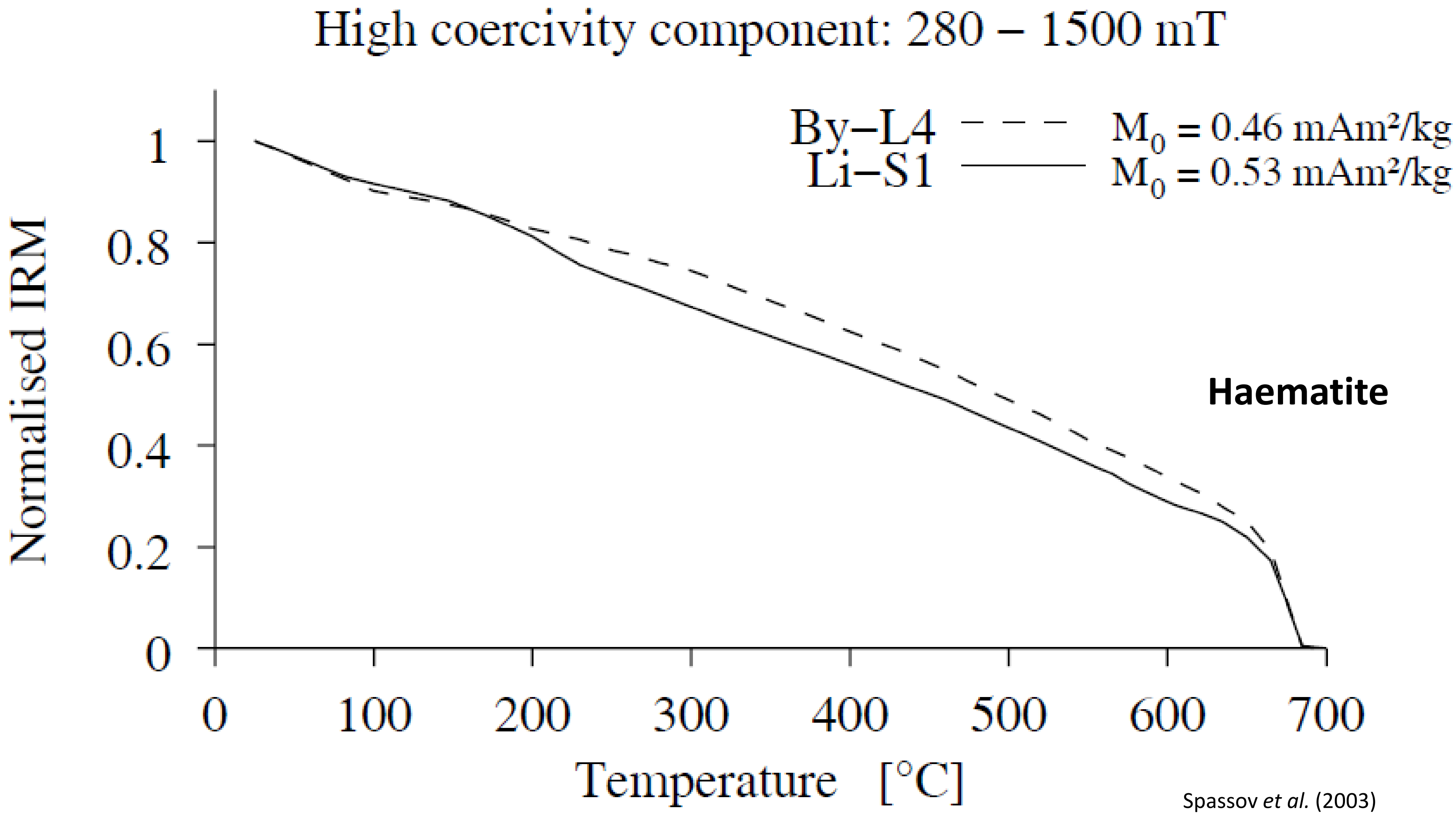


Table 5.1 *Maximum coercivities and blocking temperatures for some common ferromagnetic minerals*

Ferromagnetic mineral	Maximum coercivity [T]	Maximum blocking temperature [°C]
Magnetite	0.3	575
Maghemite	0.3	≈350
Titanomagnetite ($Fe_{3-x}Ti_xO_4$):		
$x = 0.3$	0.2	350
$x = 0.6$	0.1	150
Pyrrhotite	0.5–1	325
Hematite	1.5–5	675
Goethite	> 5	80–120

Lowrie (2007)

Thermal demagnetisation of IRM



Spassov *et al.* (2003)

1. Magnetise in strong field, e.g. 2 T, 2. demagnetise with alternating fields

Decay of IRM

Remanent magnetisation decays over time

$$M(t) = M_0\, e^{-t/\tau} + M_{eq}\,(1 - e^{-t/\tau})$$ for SD grains

$$M_{eq} = M(t \to \infty)$$
$$M_0 = M(t = 0)$$

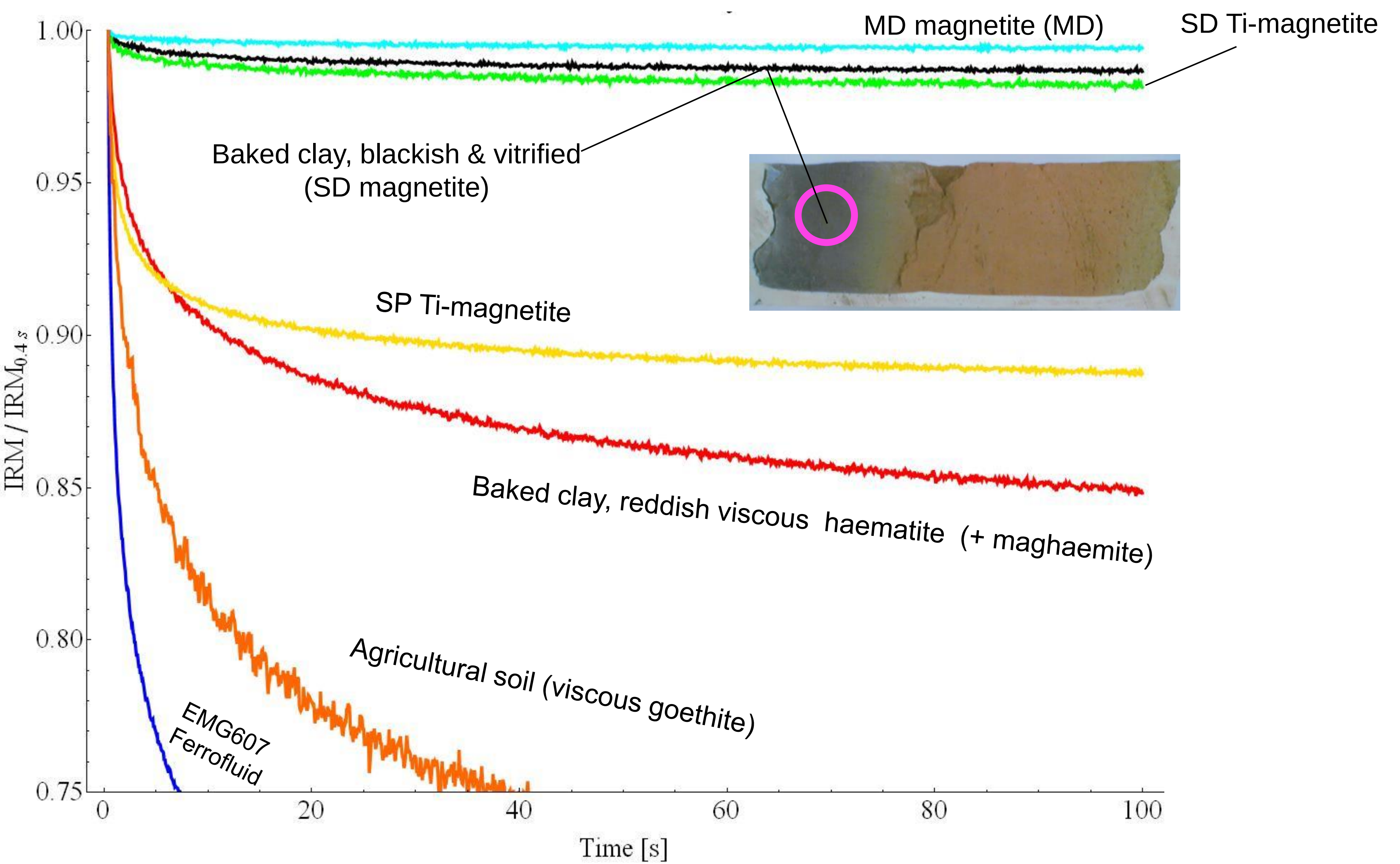
$\tau = f\,(V,\ M_s,\ H_k, H_0)$ relaxation time

H_k – micro-coercivity assuming shape anisotropy
H_0 – external field
V – lognormal distribution of volumes

Small grains, *e.g.* 30 – 40 nm magnetite/maghaemite or haematite loose their remanence quickly

Larger grains, i.e. single domain and multidomain do practically not loose their remanence.

Decay of IRM


MD magnetite (MD)
SD Ti-magnetite
Baked clay, blackish & vitrified
(SD magnetite)
SP Ti-magnetite
Baked clay, reddish viscous haematite (+ maghaemite)
Agricultural soil (viscous goethite)
EMG607
Ferrofluid
IRM / IRM0.4 s
1.00
0.95
0.90
0.85
0.80
0.75
0
20
40
60
80
100
Time [s]