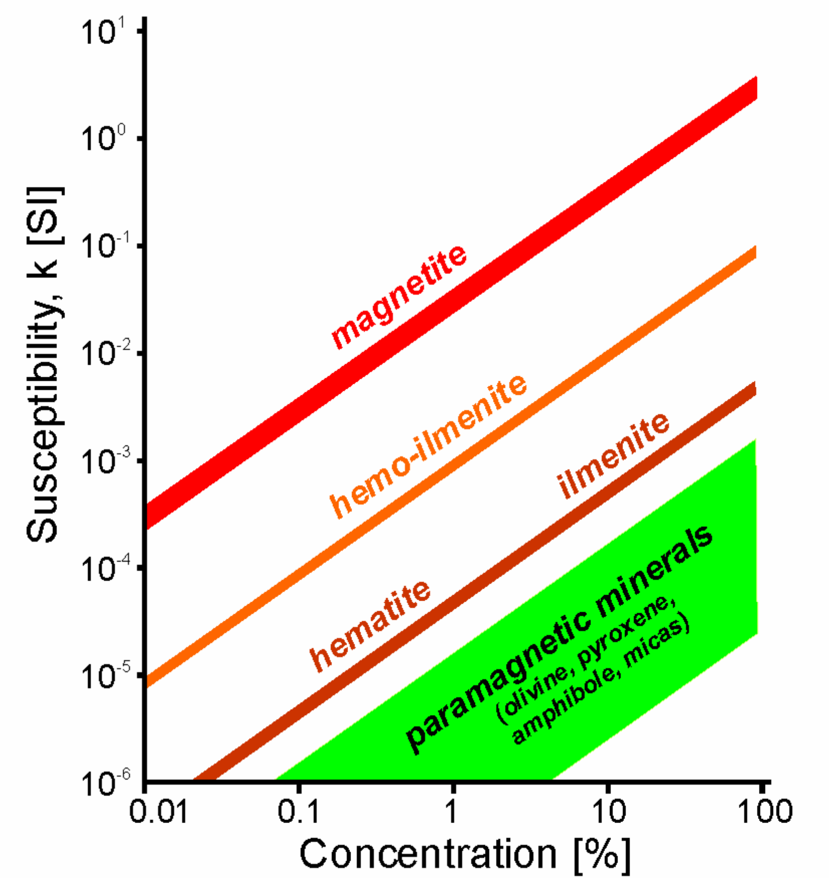
Magnetic susceptibility and its variations with temperature, measuring field and operating frequency
Examples from various rock types

Institute of Geology
Academy of Sciences

- Identification of magnetic minerals and phases
- Grain size assessment
- Paleotemperature estimation



Temperature variation of MS
$k(T)$

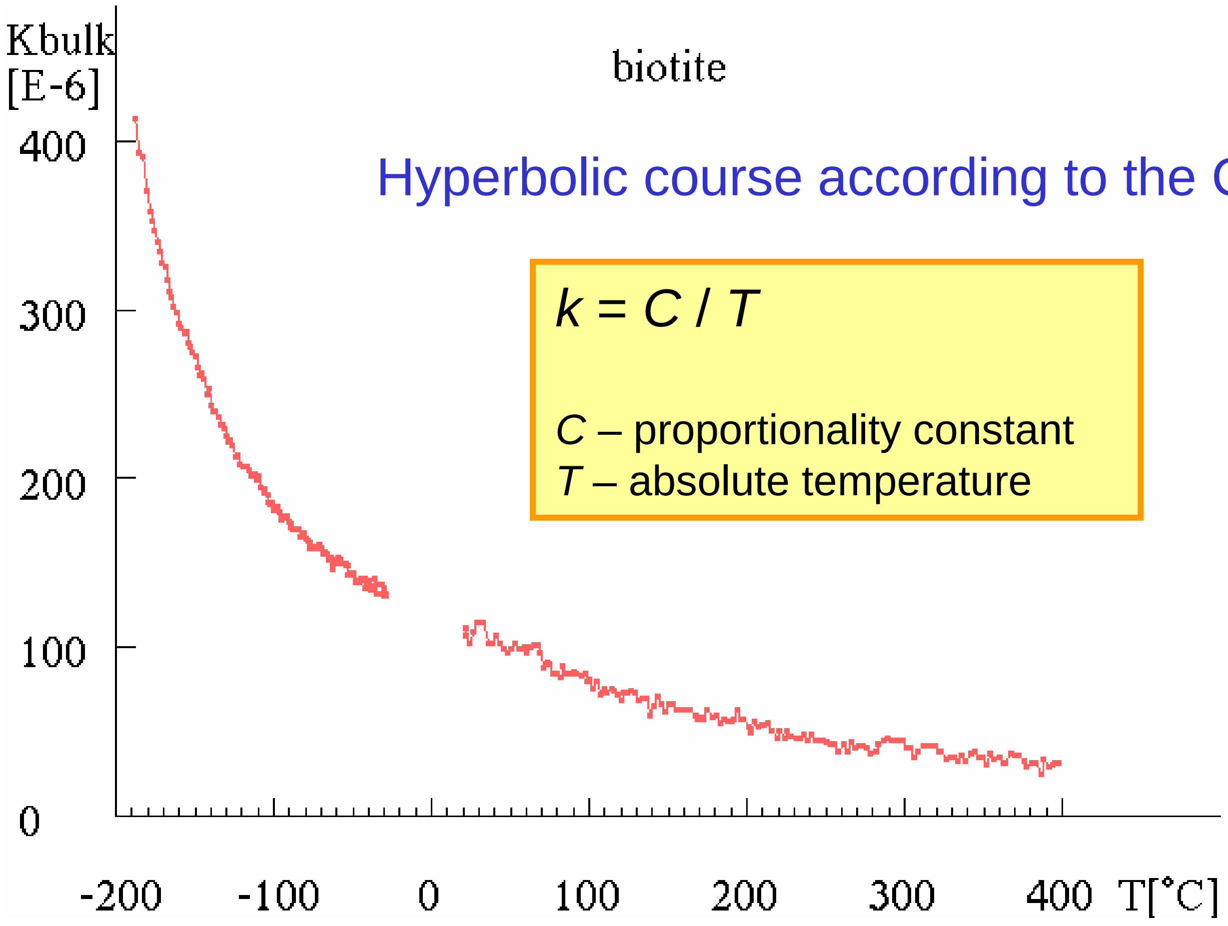
1. Characteristic temperatures → Identification of magnetic minerals and their chemical composition
2. Semi-quantitative resolution of ferromagnetic × paramagnetic contribution to MS
3. Numerical characterization of alteration during heating
4. Paleotemperature estimates

Paramagnetic minerals

Hyperbolic course according to the Curie Law

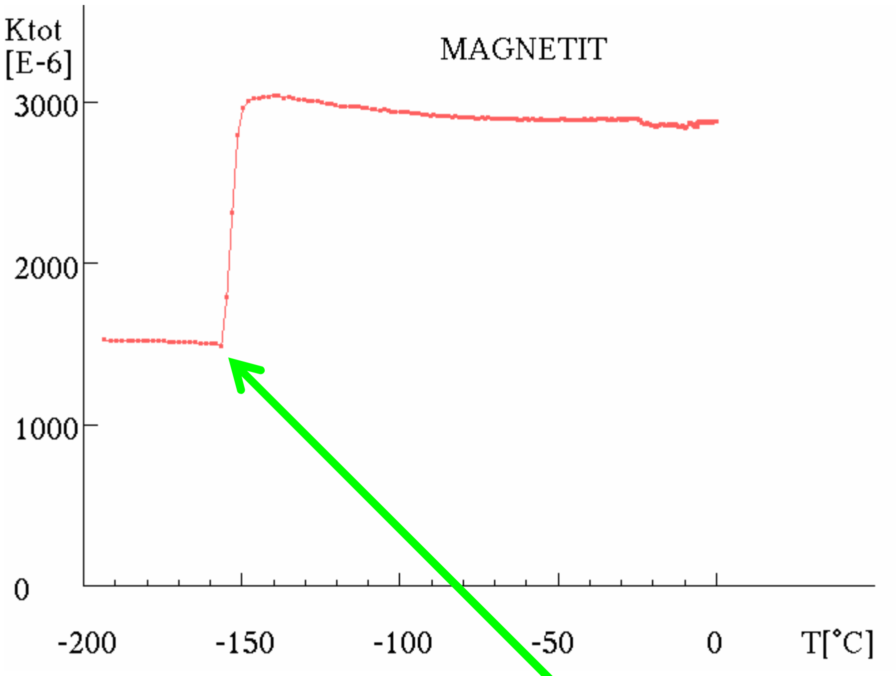
$k = C / T$

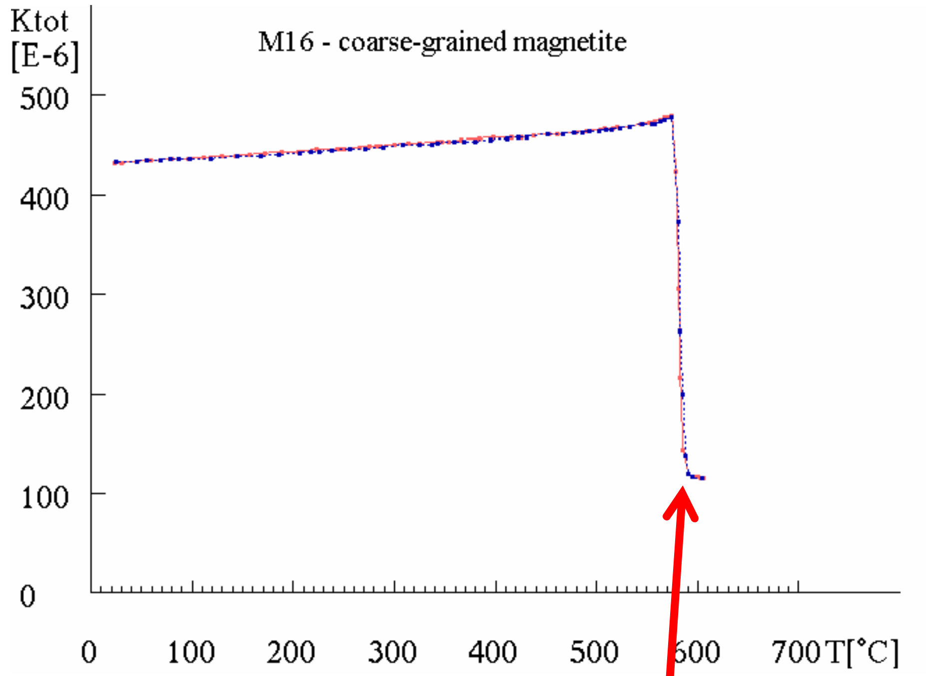
C – proportionality constant
T – absolute temperature



1. Characteristic temperatures

Magnetite





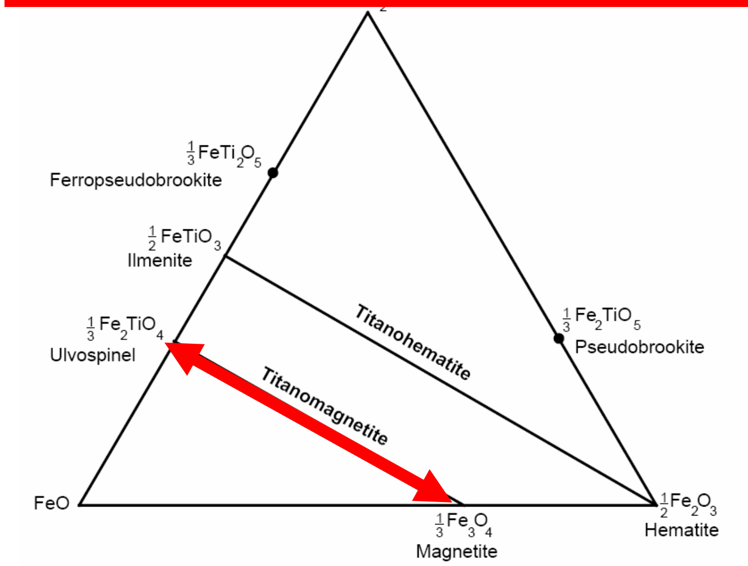
Verwey transition $T_v \sim -150$ °C

Transition from cubic to ortho-rhombic symmetry, decrease in susceptibility

Curie temperature $T_c \sim 585$ °C

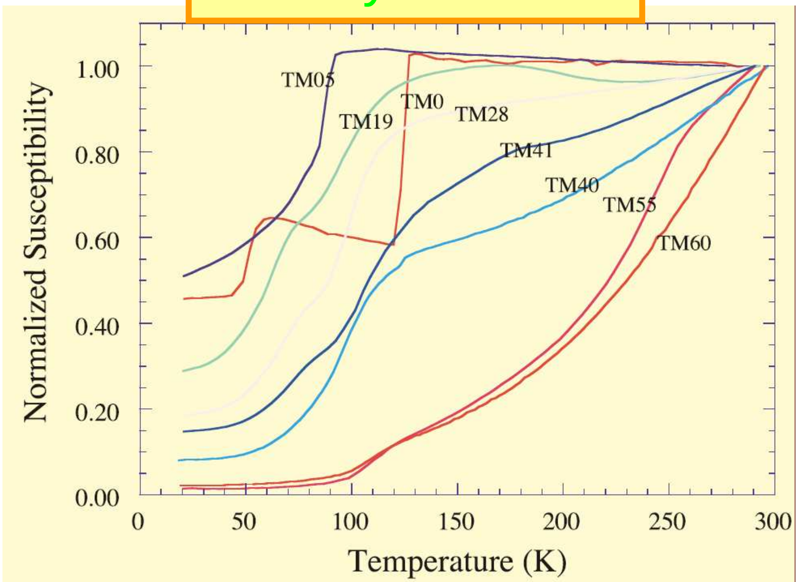
Transition from ferrimagnetic to paramagnetic state, rapid decrease of susceptibility

1. Characteristic temperatures



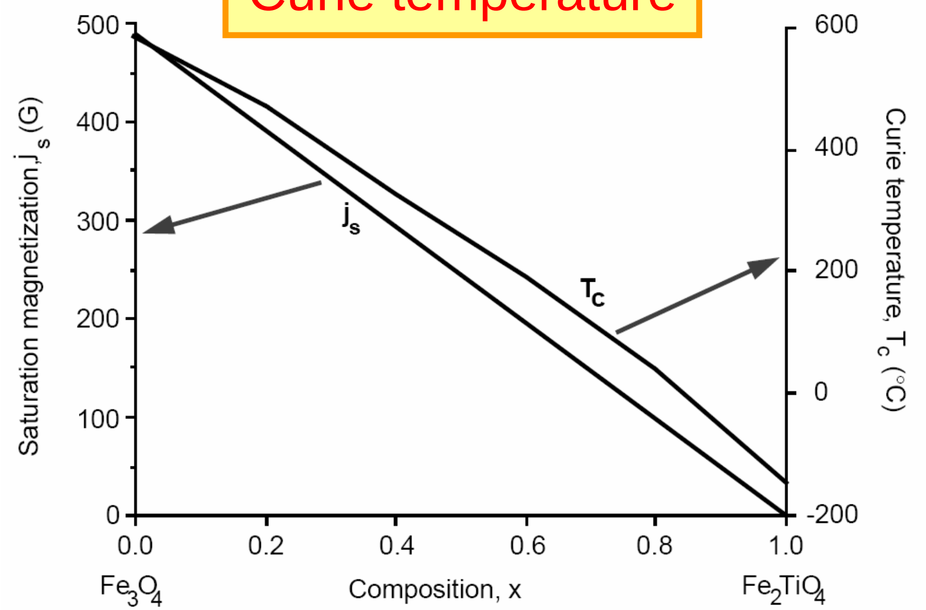
Variation of characteristic temperatures with chemical composition in titanomagnetites

Verwey transition



(Moskowitz et al.1998, EPSL)

Curie temperature



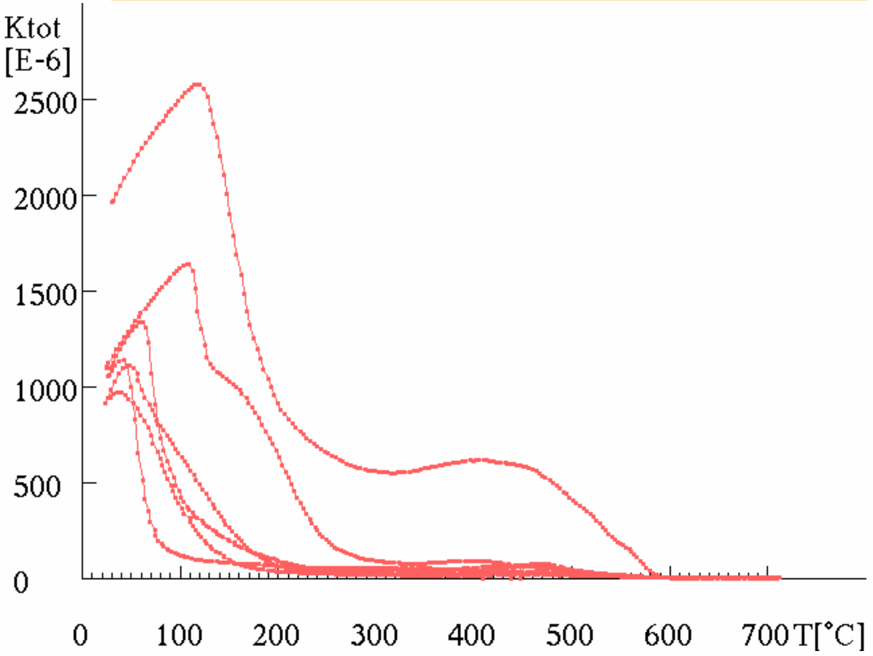
(after Nagata 1961)

1. Characteristic temperatures

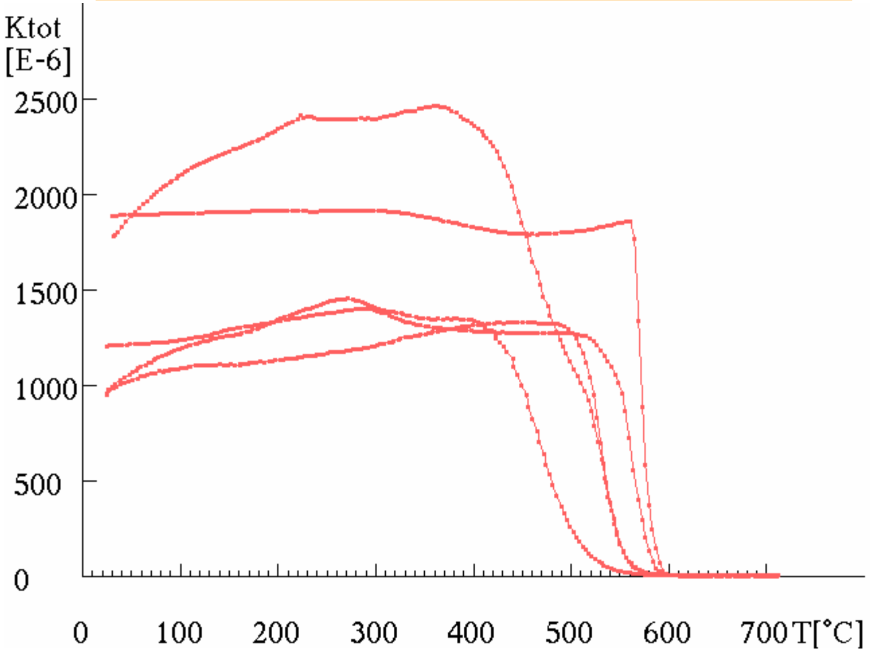
Examples: alkaline volcanic rocks

olivine nephelinite, basanite, olivine basalt
trachybasalt, tephrite, trachyte, phonolite

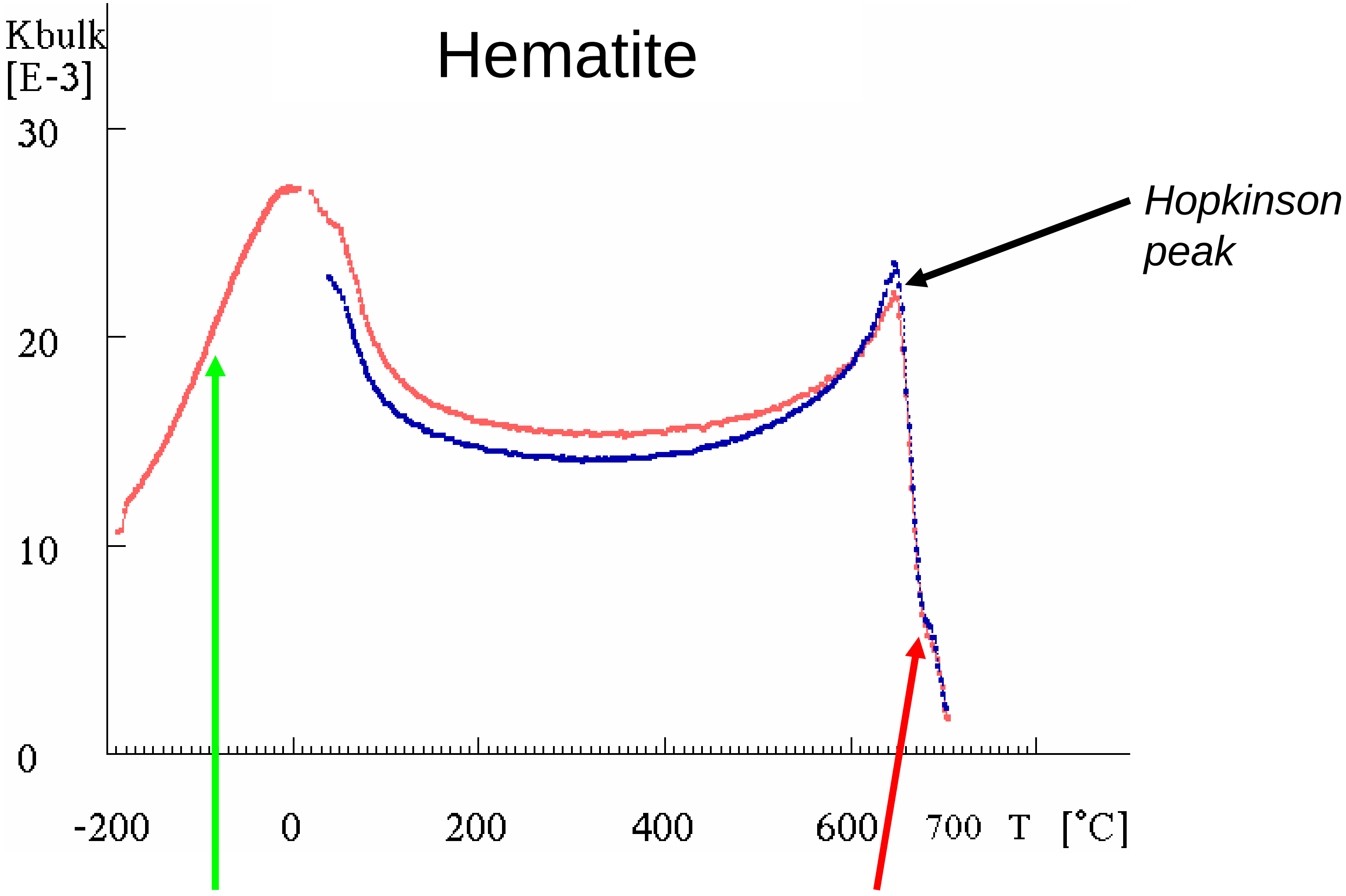
Ti rich Fe-Ti oxides



Ti poor titanomagnetites



1. Characteristic temperatures

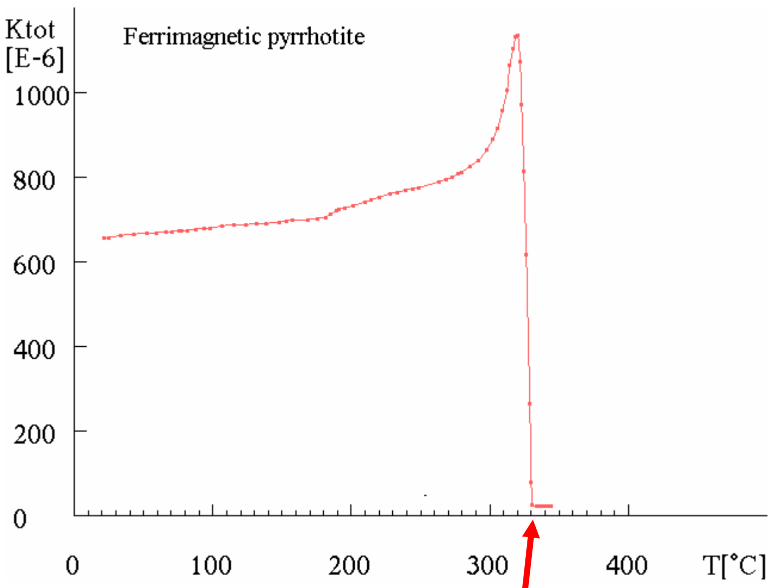


Morin transition
T_m ~ – 20 ℃

Curie temperature
T_c ~ 695 ℃

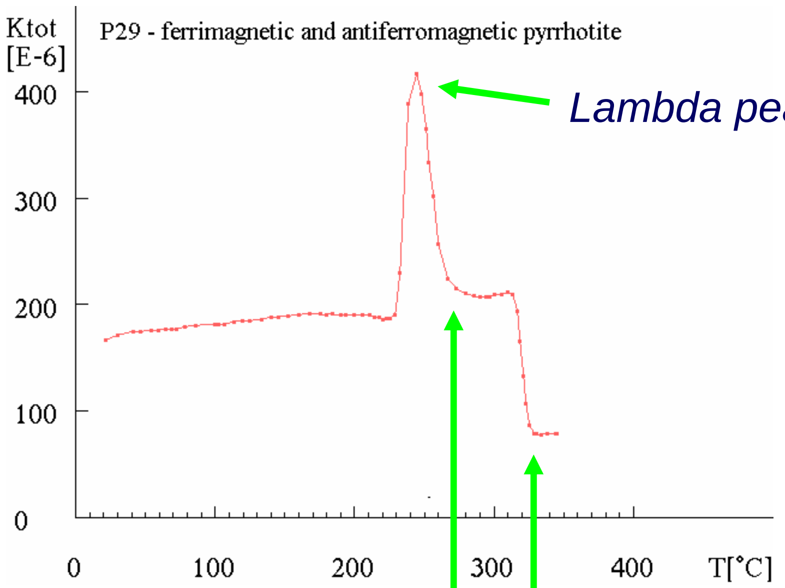
Pyrrhotite

Monoclinic pyrrhotite



Curie temperature
T_c = 325 ℃

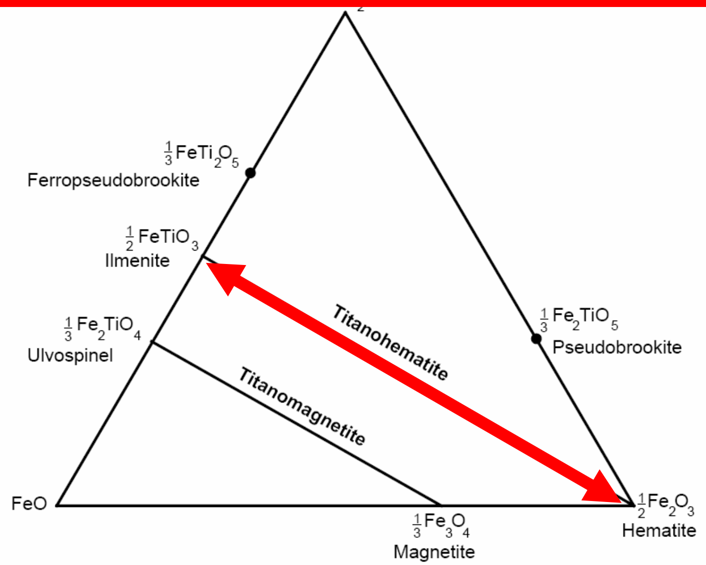
Mixture of monoclinic and hexagonal pyrrhotite



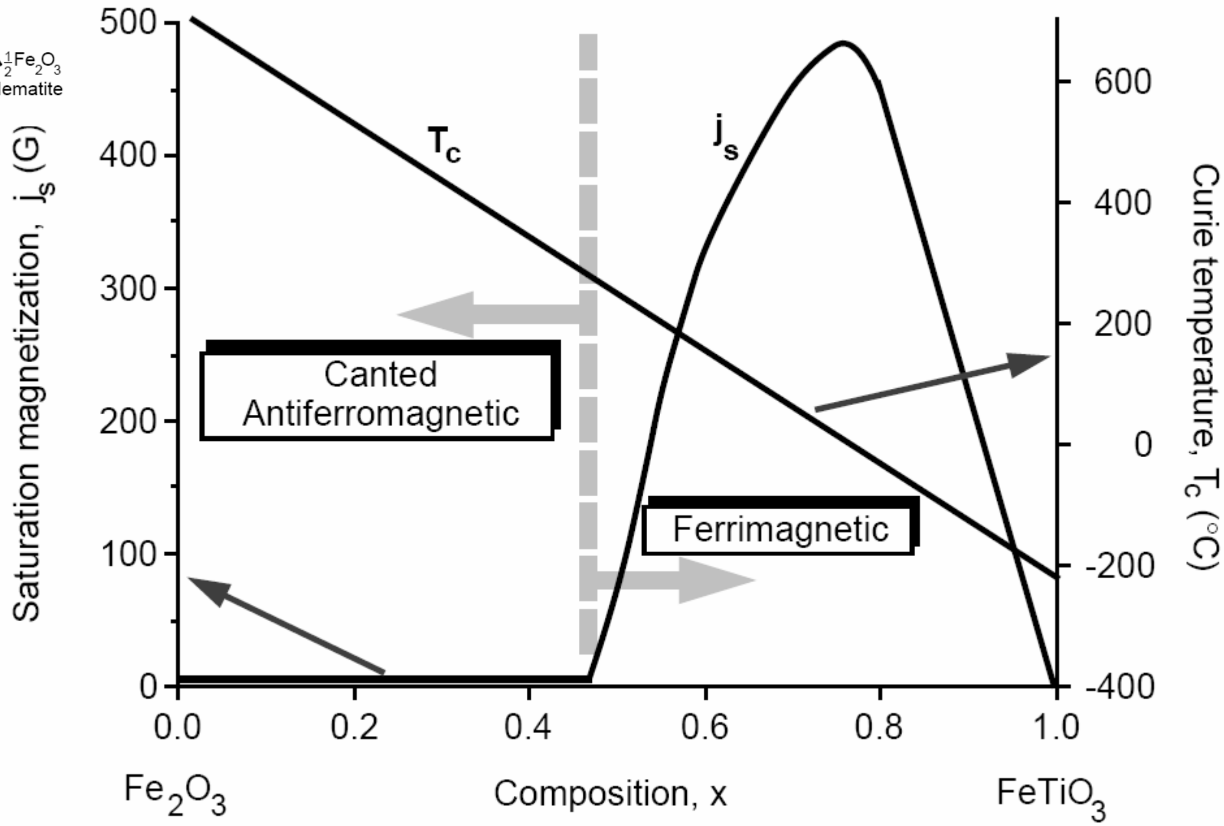
Lambda peak

T_c *antiferromagnetic* T_c *ferrimagnetic*

1. Characteristic temperatures

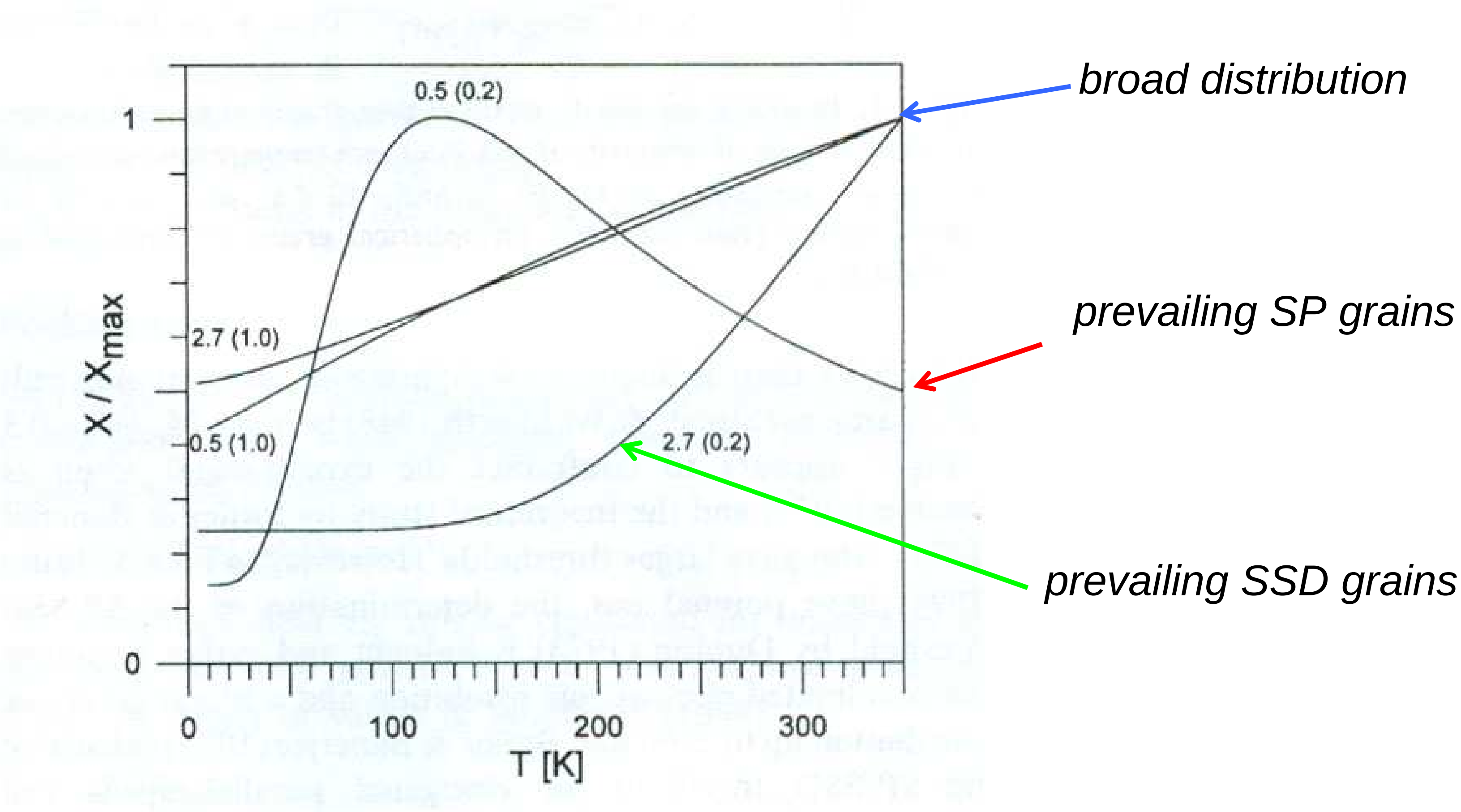


Variation of characteristic temperatures with chemical composition in titanohematites



(after Nagata 1961)

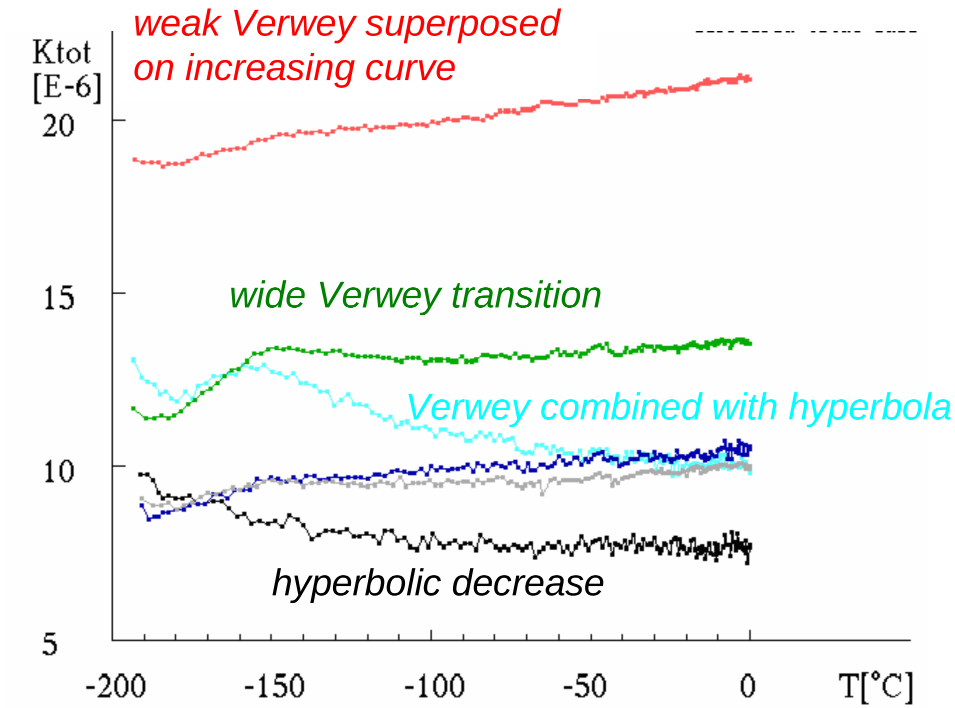
Mixture of SSD and SP particles - model

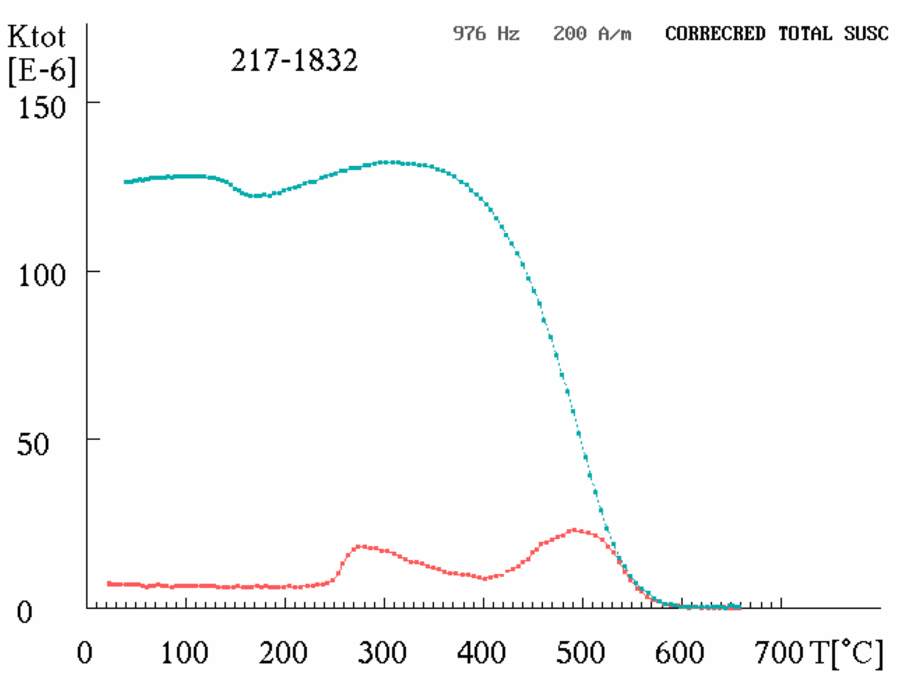


(after Worm, 1998, GJI)

1. Characteristic temperatures

Examples: environmental materials



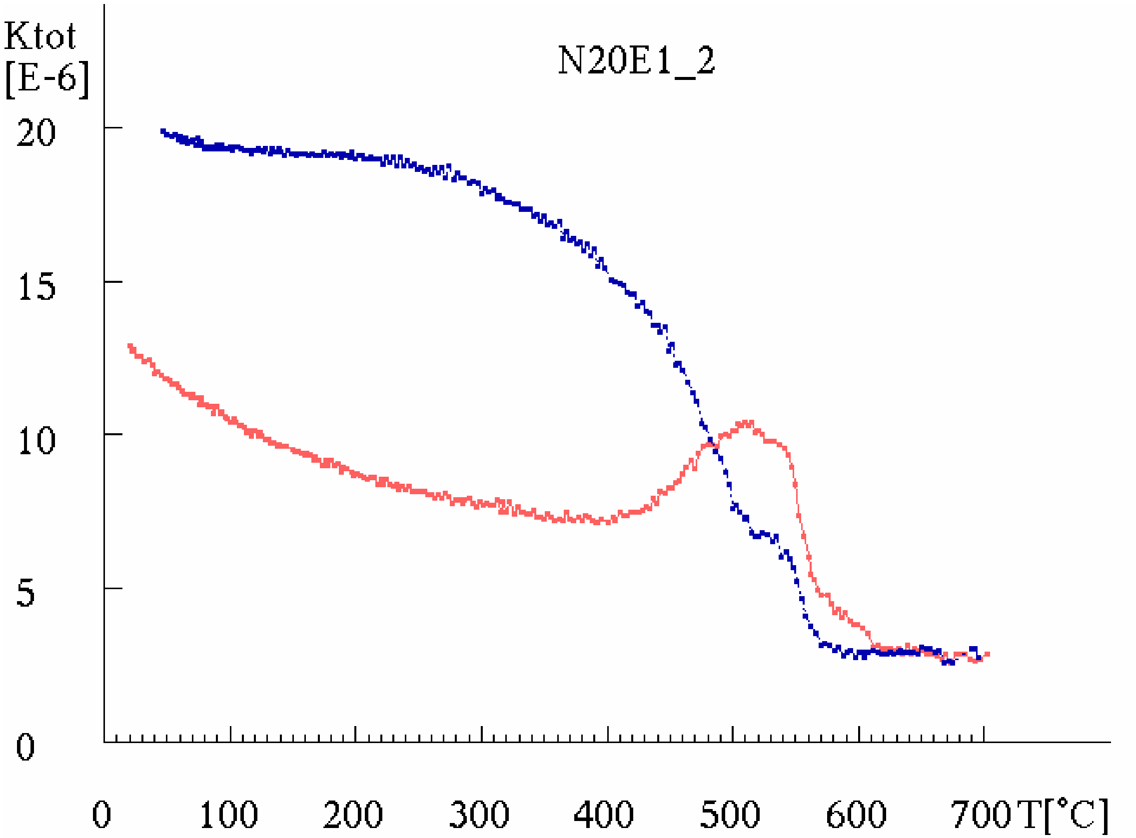


- *very different heating and cooling curves*
- *very wide Curie temperature decrease, probably due to mixture of minerals.*
- *creation of new minerals between 250 °C and 300 °C and above 400 °C*

2. Semi-quantitative resolution of contribution to MS

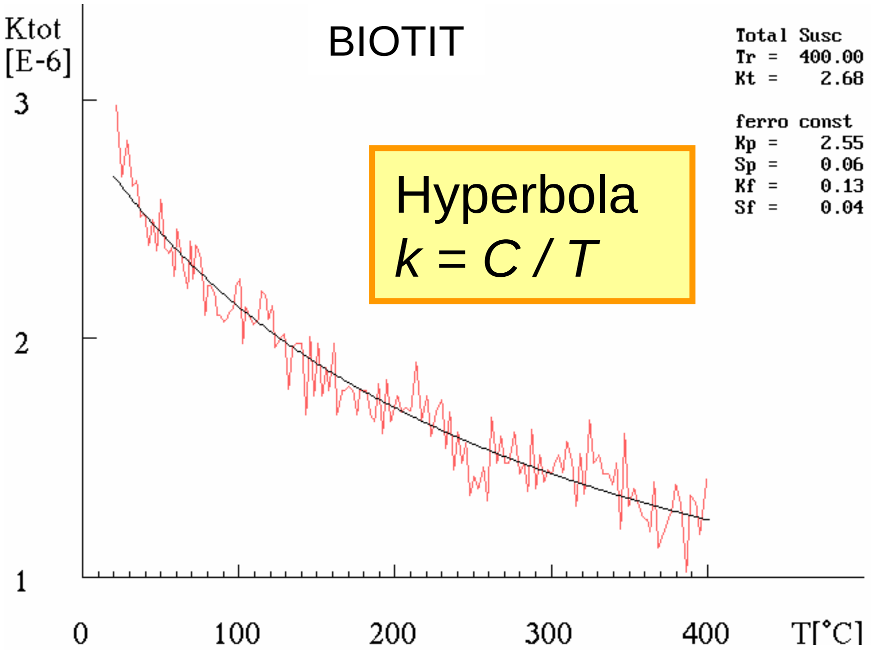
Example: rock with amphibole and magnetite

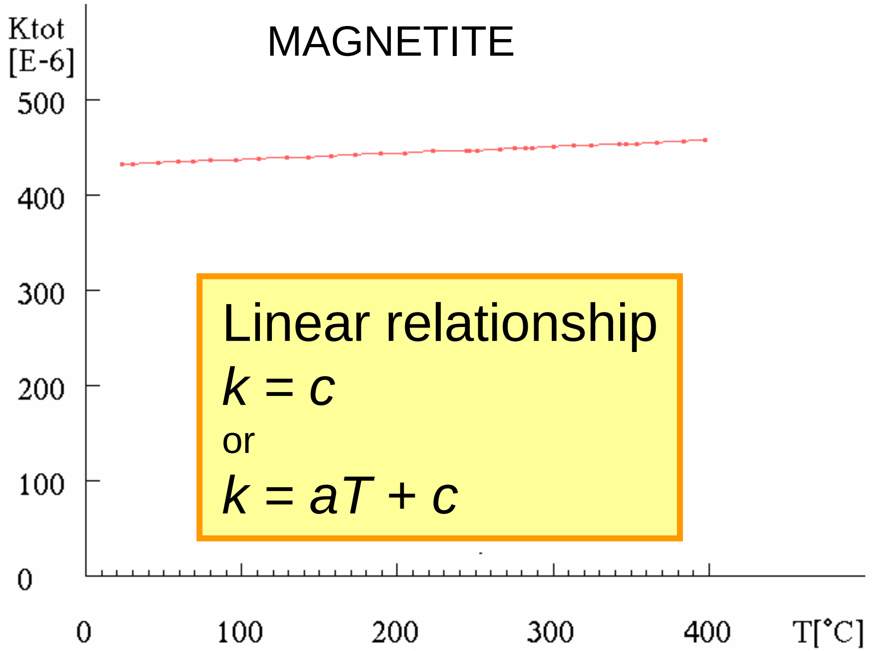
uncertainty whether magnetite was created by heating?



2. Semi-quantitative resolution of contribution to MS

Separation of paramagnetic and ferromagnetic contributions to magnetic susceptibility





p – portions on MS [%]

$$k_{tot} = p_{para}\,(C\ /\ T\ ) + p_{ferro}\,k_{ferro}$$

whole rock susceptibility

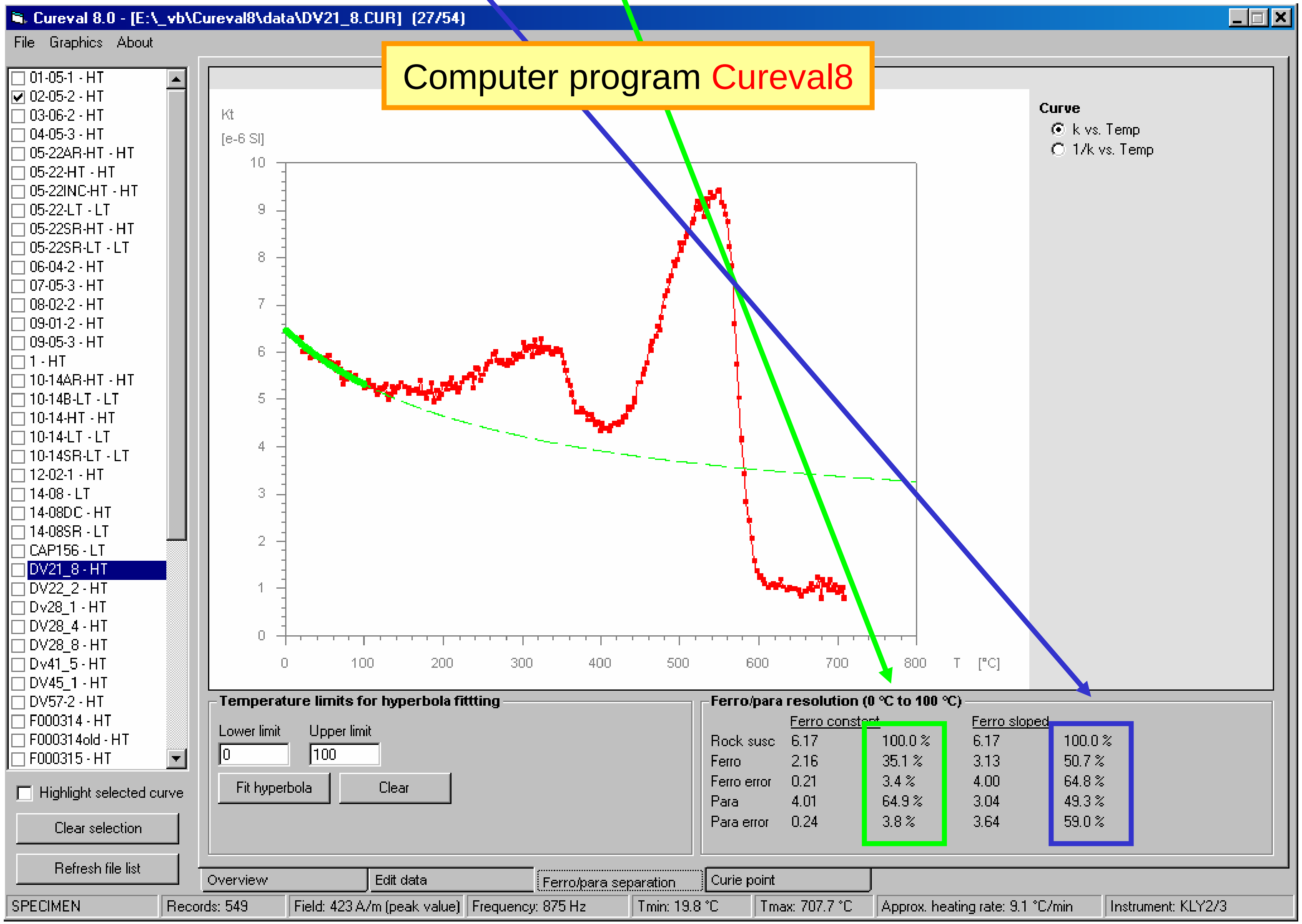
paramagnetic component

Ferromagnetic s.l. component

(Hrouda, 1994, GJI; Hrouda et al., 1997, GJI)

2. Semi-quantitative resolution of contribution to MS

By fitting a hyperbola offset along *y* axis or
hyperbola and a straight line
to *k* vs. *T* curve using least squares method we obtains p_{para} C and p_{ferro} k_f

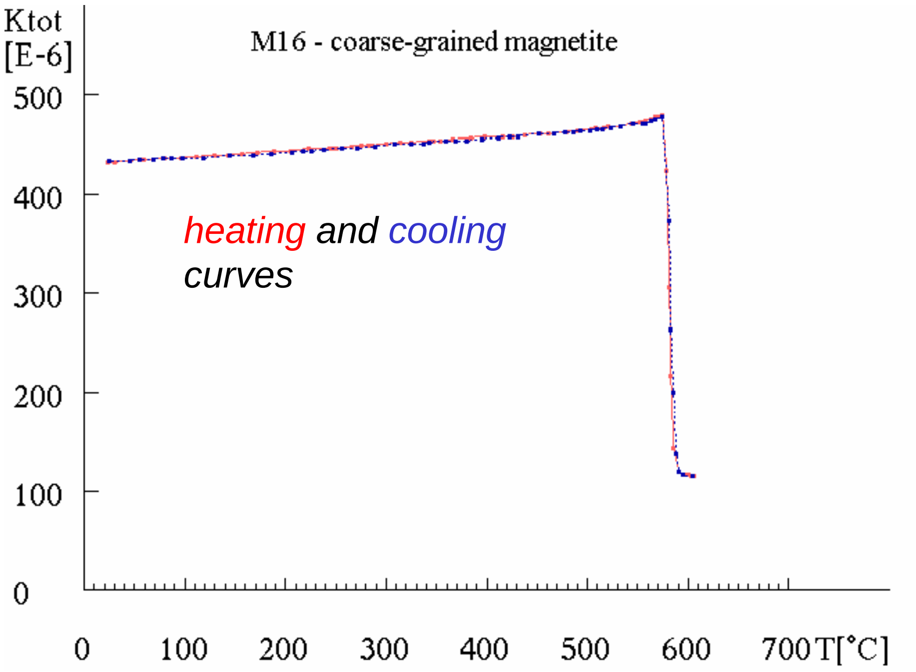


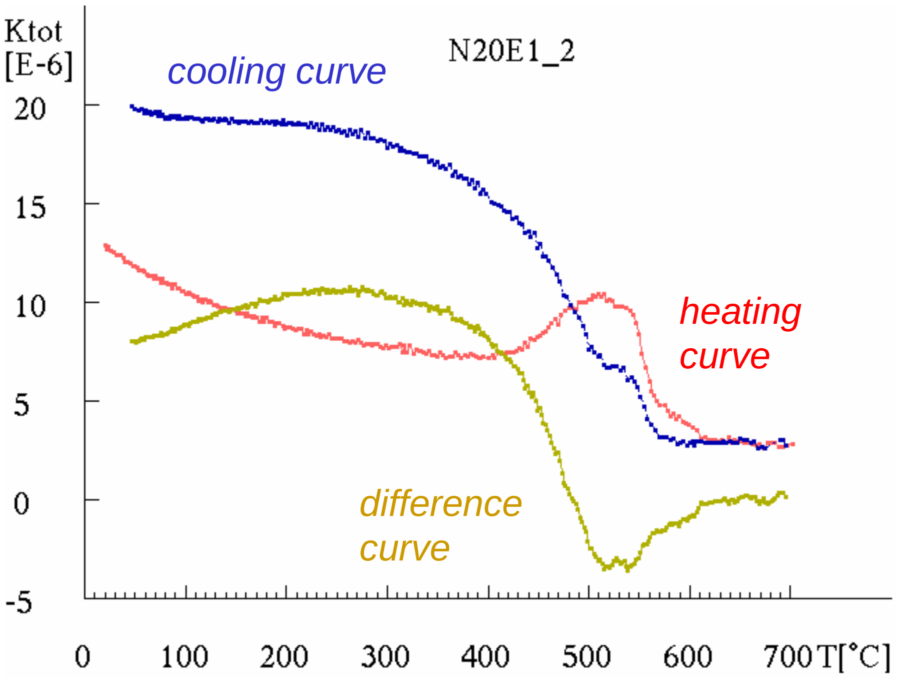
3. Numerical characterization of alteration during heating

- useful in comparing a large number of thermomagnetic curves
- pre-investigating heating alterations in palaeointensity studies
- useful in thermal enhancement of magnetic fabric

No alteration

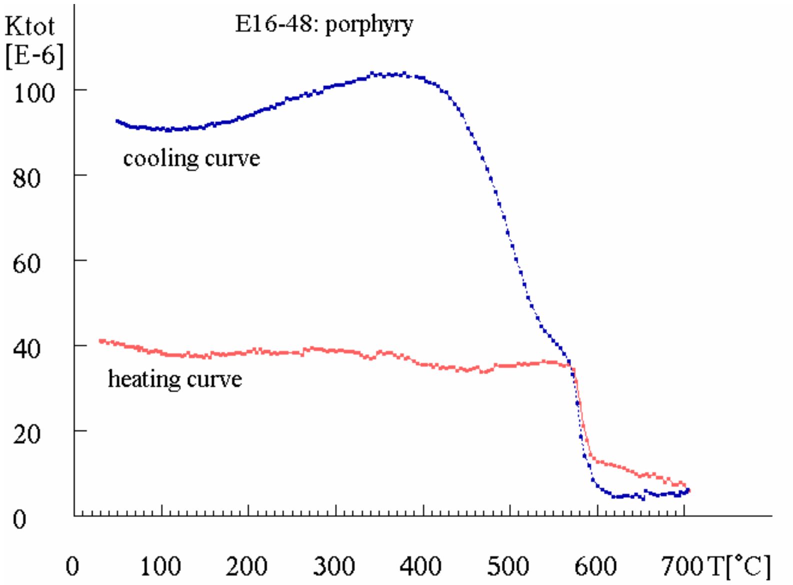
Complex alteration





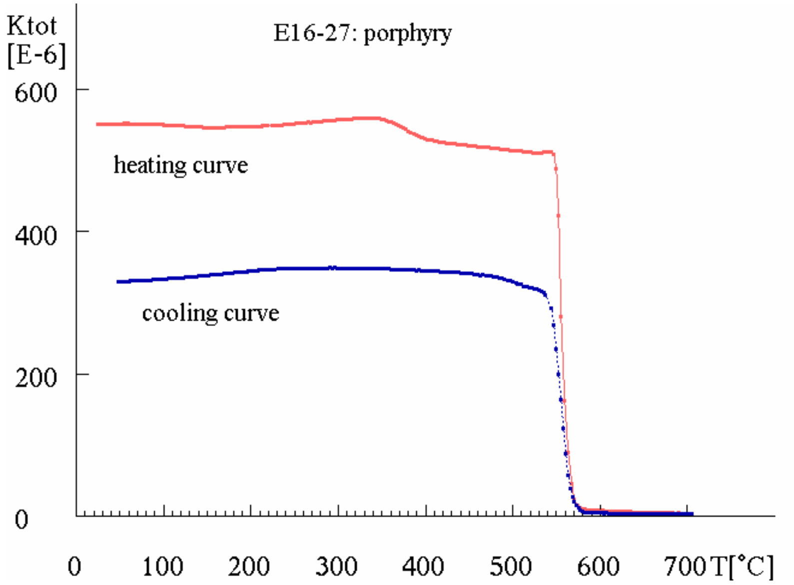
3. Numerical characterization of alteration during heating

Higher susceptibilities on cooling curves



Relatively frequent case – creation of new magnetite from weakly magnetic phases due to heating

Higher susceptibilities on heating curves



Relatively infrequent case – dissolving magnetite lamelae in less magnetic host mineral

3. Numerical characterization of alteration during heating

$$A_{40} = 100 \times (k_{40} - K_{40}) / K_{40} \quad [\%]$$

k_{40} – susceptibility on cooling curve at 40 °C
K_{40} – susceptibility on heating curve at 40 °C

Positive A_{40} value indicates higher cooling than heating susceptibilities and vice versa.
Useful, if the courses of heating and cooling curves are similar

$$A_{max\,(temp)} = 100 \times (k - K)_{max} / K_{40} \quad [\%]$$

$(k - K)_{max}$ – maximum difference between the cooling and heating curve susceptibilities at the same temperature (indicated in brackets at the index).

Heating curve susceptibilities are considered the leading ones, the cooling curve susceptibilities are interpolated to create pairs with heating curve susceptibilities

$$A_m = 100 \times \Sigma(k_i - K_i) / NK_{40} \quad [\%]$$

k_i, K_i – cooling and heating curve susceptibilities at the same temperature, N is the number of pairs considered,
K_{40} – heating susceptibility at 40 °C
(k_i - K_i) pairs are created in the step by 1 °C through linear interpolation.

$$A_{cr} = \Sigma(k_i - K_i) / \Sigma(|k_i| - |K_i|)$$

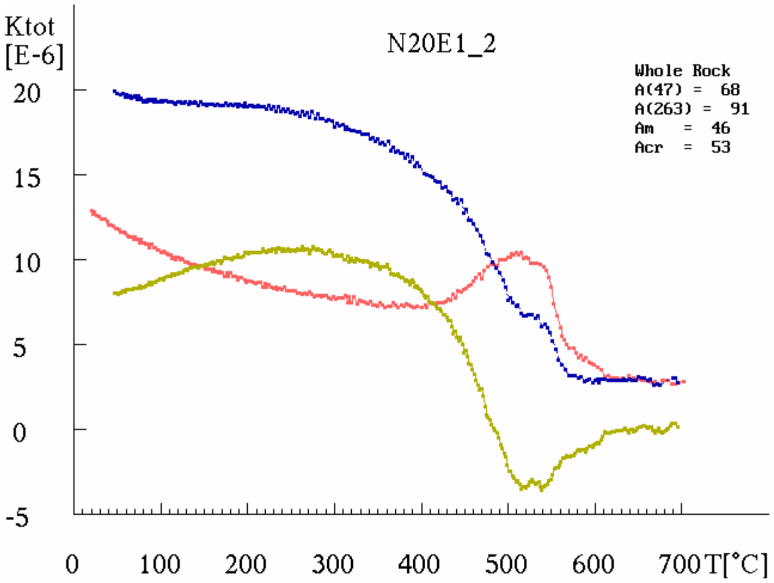
k_i, K_i – the cooling and heating curve susceptibilities at the same temperature, $|k_i|$,$|K_i|$ are their absolute values.

$A_{cr} = 1$ if the heating and cooling curves do not cross
$|A_{cr}| < 1$ if the heating and cooling curves do cross.

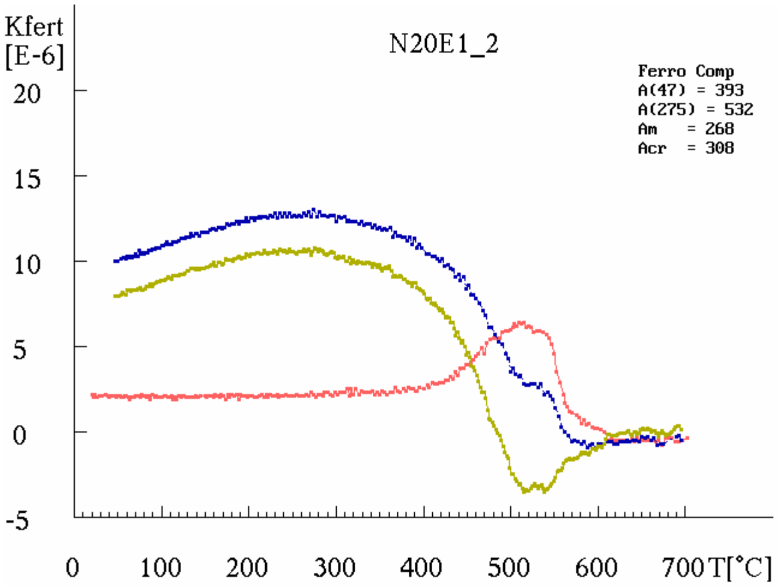
(Hrouda, 2003, Studia Geoph. Geod.)

3. Numerical characterization of alteration during heating

Whole rock alteration

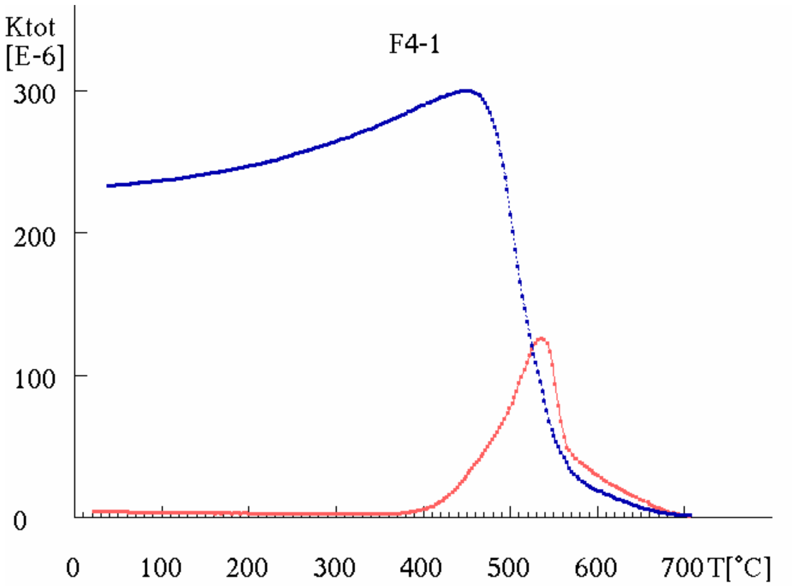


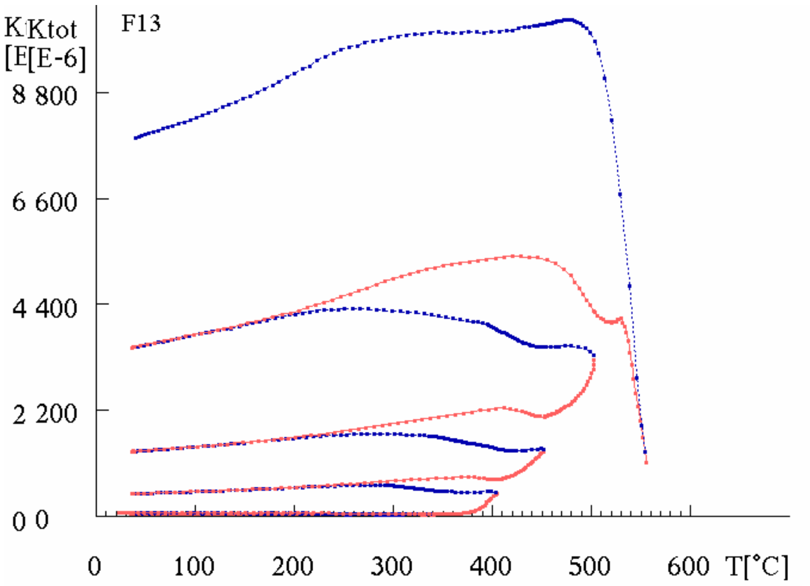
Ferromagnetic fraction alteration

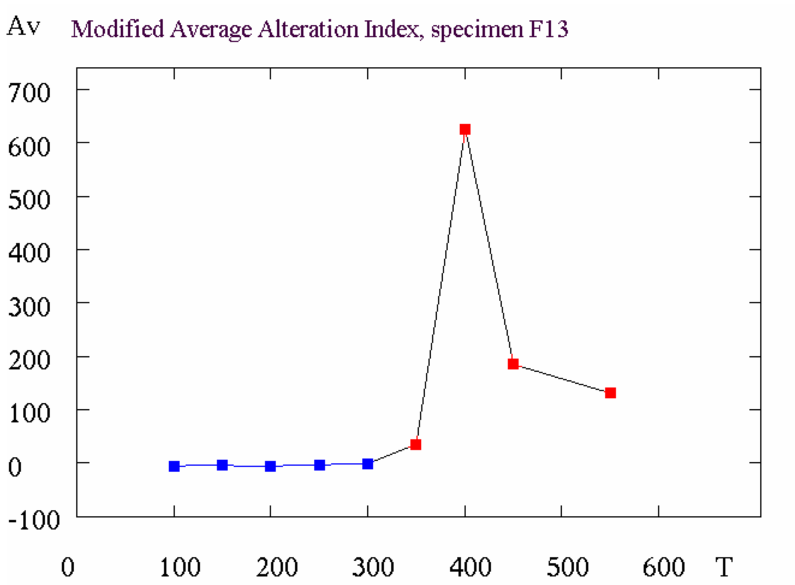


4. Paleotemperature estimates

Example: sediment from the Culm Formation





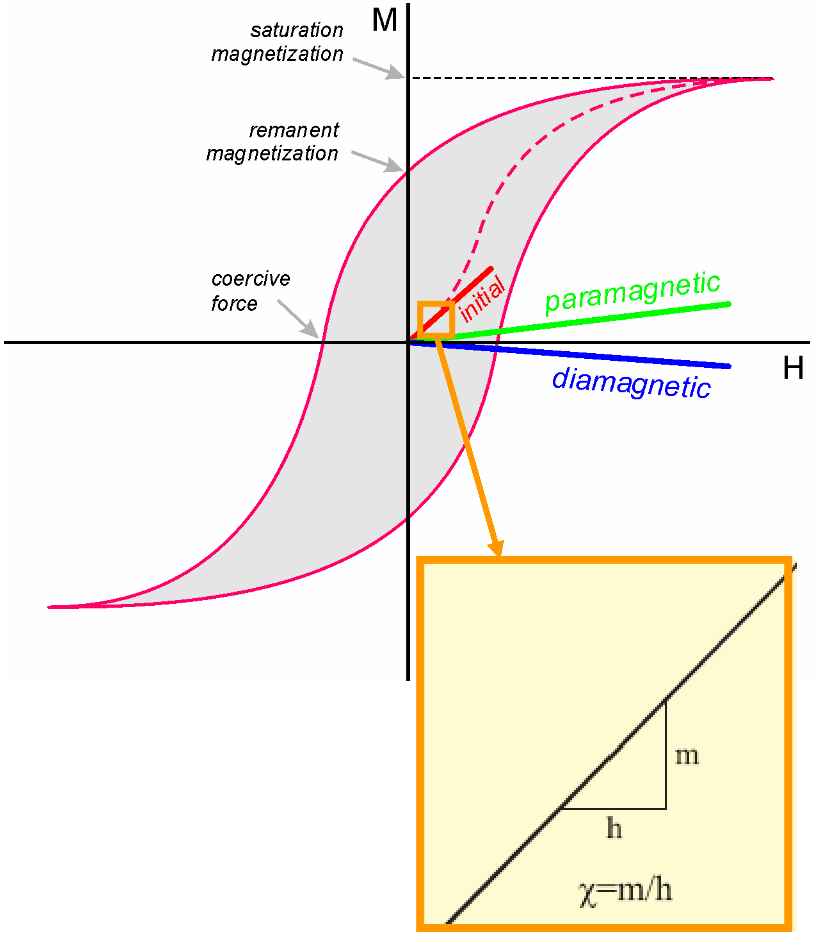


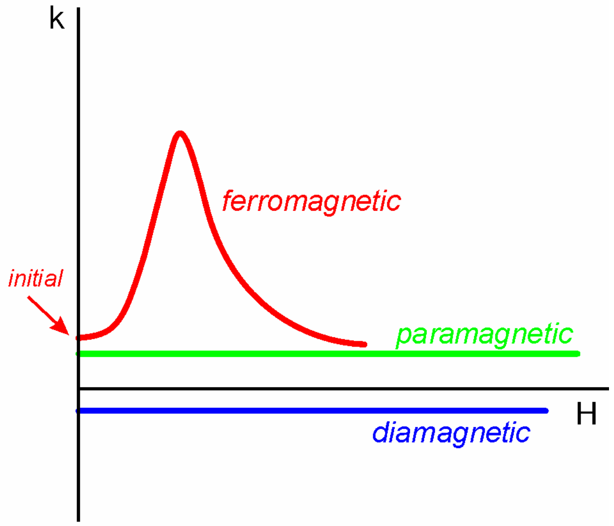
(Hrouda et al., 2003, Phys. Chem. Earth)

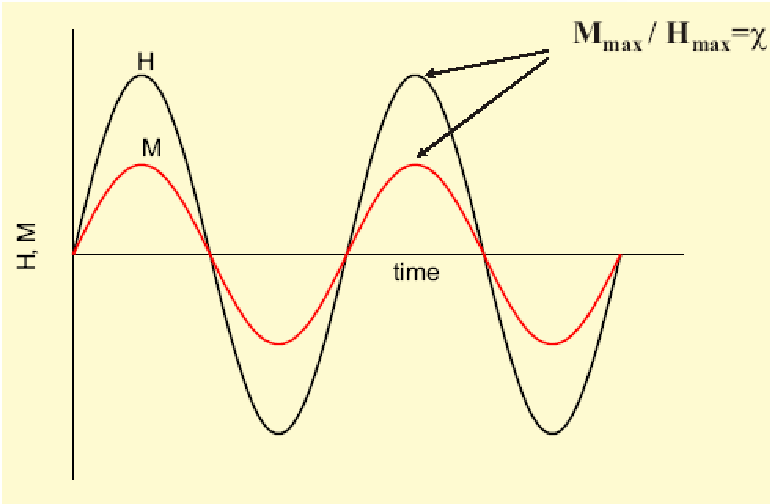
Field variation of MS
$k(H)$

1. Identification of ferromagnetic (s.l.) minerals
2. Chemical composition of titanomagnetites

Field dependence of MS







Field dependence of MS

$V_p = 100 \times (k_{450} - k_2) / k_2$ [%]

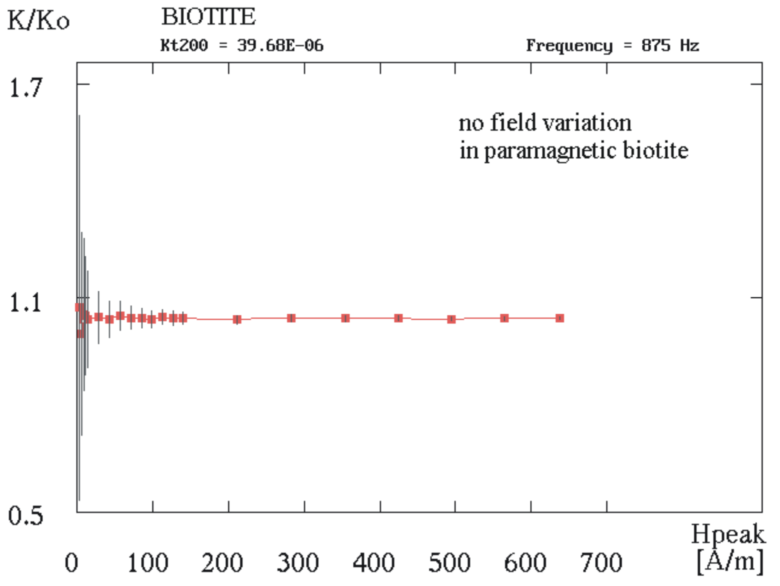
$V_m = 100 \times (k_{max} - k_{min}) / k_{min}$ [%]

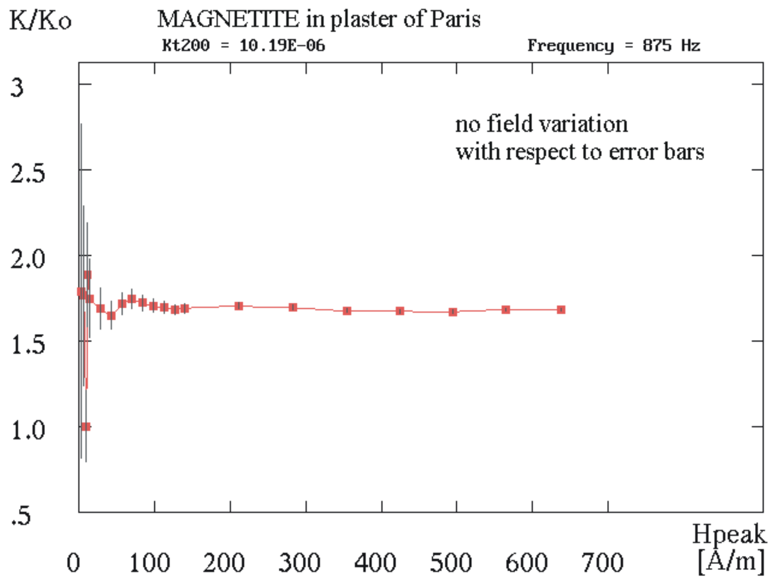
$V_p = 100 \times (k_{450} - k_i) / k_i$ [%]

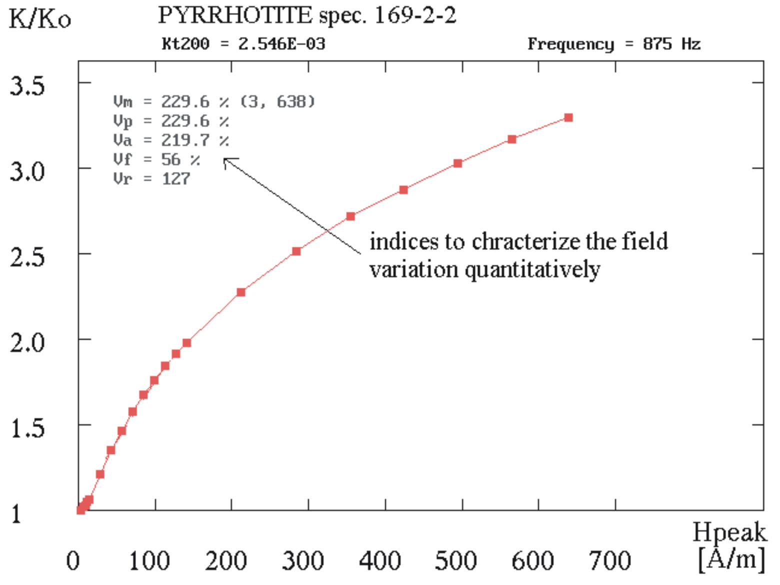
where $k_i = (k_2 + k_4 + k_6 + k_8)/4$, k_2, k_4, k_6, and k_8 are susceptibilities at 2, 4, 6, and 8 A/m, respectively, k_{450} is the susceptibility measured at 450 A/m. The V_a values are also given in %.

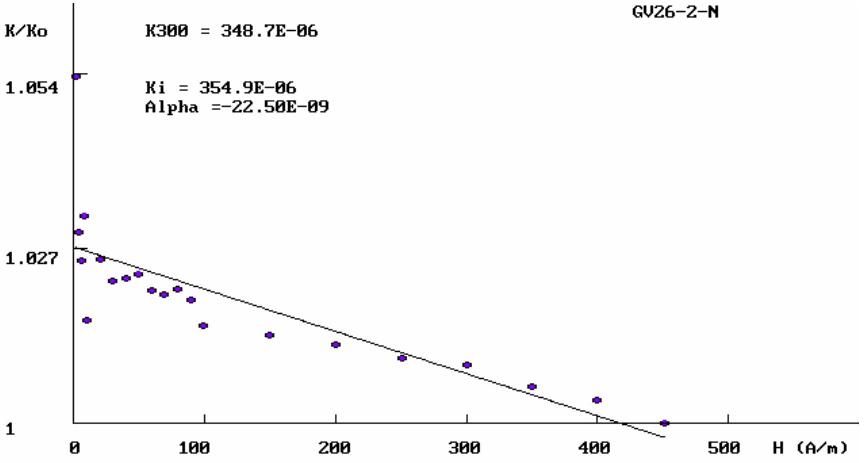
(Hrouda et al., 2006, Studia Geoph. Geod.)

Field dependence of MS

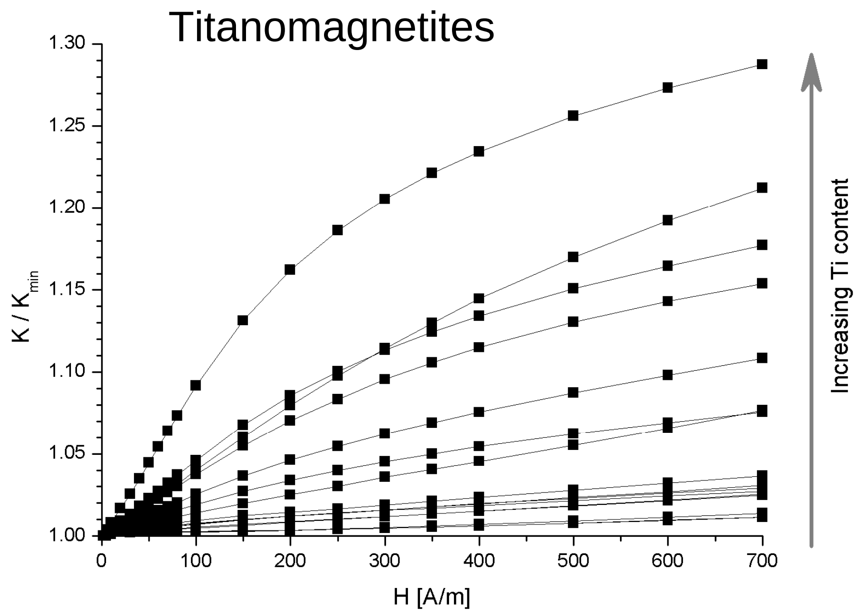


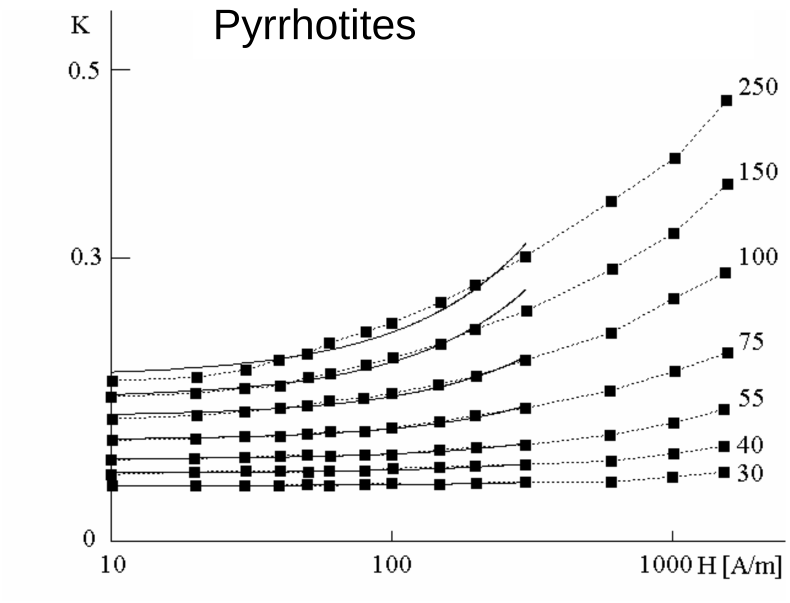






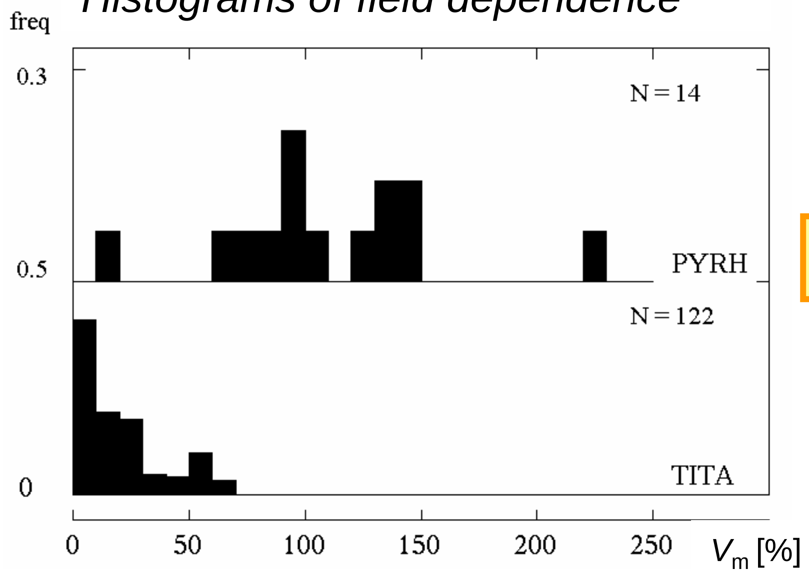
Field dependence of MS





(Worm et al., GJI, 1993)

Histograms of field dependence



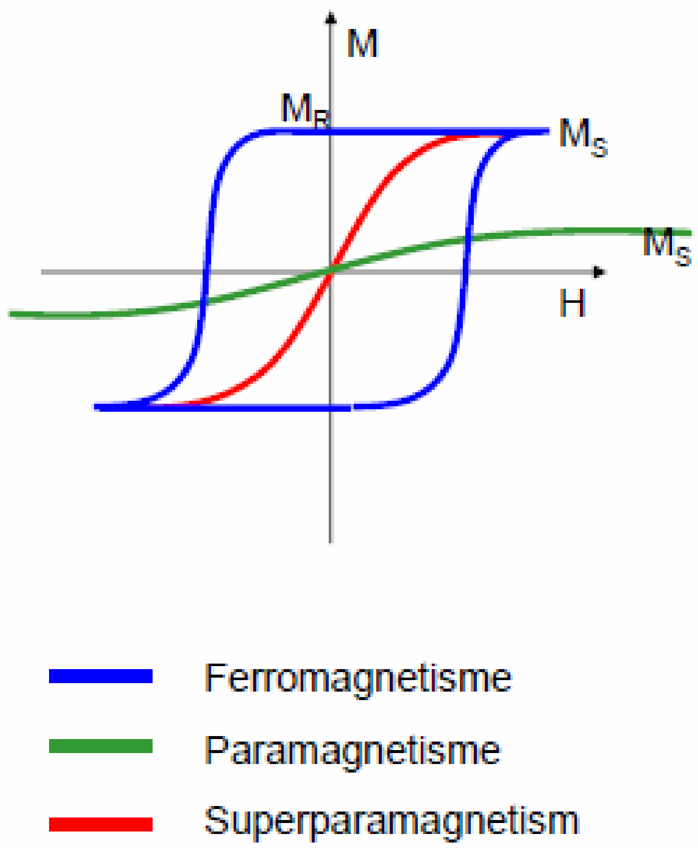
$V_m = 100 \times (k_{max} - k_{min}) / k_{min}$ [%]

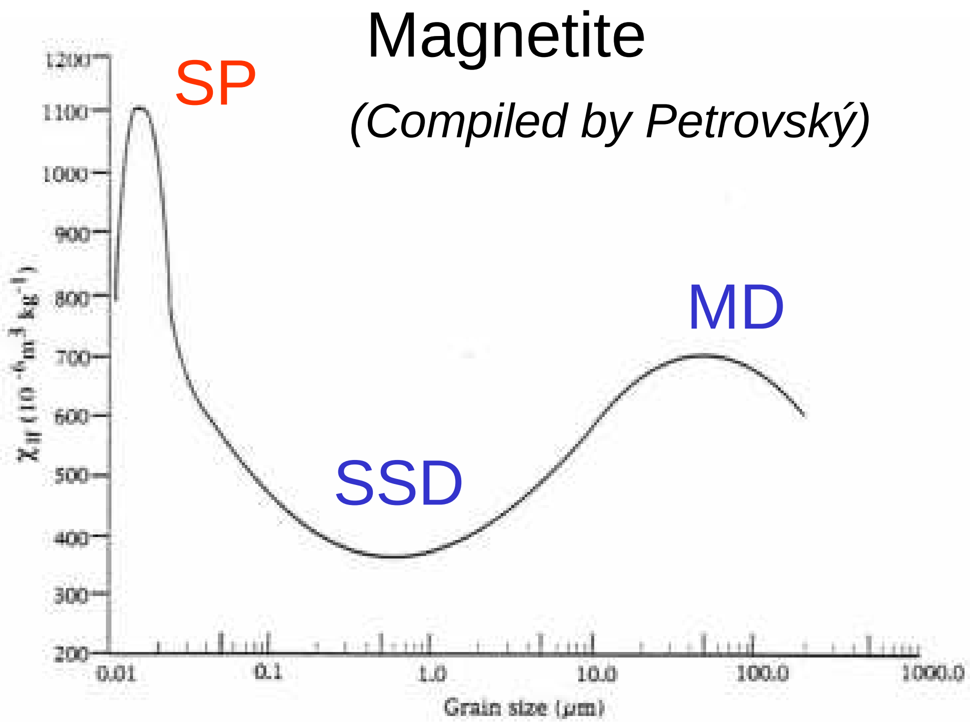
Frequency variation of MS
$k(f)$

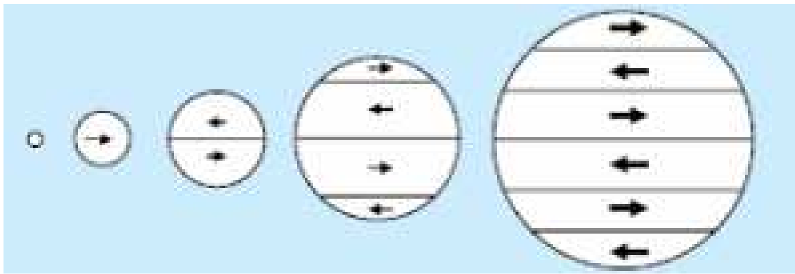
- Identification of grain-size
- Paleoclimatic estimation

Superparamagnetism

- very high susceptibility
- no remanence







Frequency dependence of MS

Frequency-dependent susceptibility results from interplay between SP and SSD or even MD magnetic particles even though some other phenomena, such as eddy currents, may also play a role mainly at high operating frequencies.

Materials exhibiting the frequency-dependent susceptibility must contain at least some SP particles !!!

$$\boxed{k_{FD} = 100 \times (k_{LF} - k_{HF}) / k_{LF} \qquad [\%]}$$

(Dearing et al., 1996, GJI)

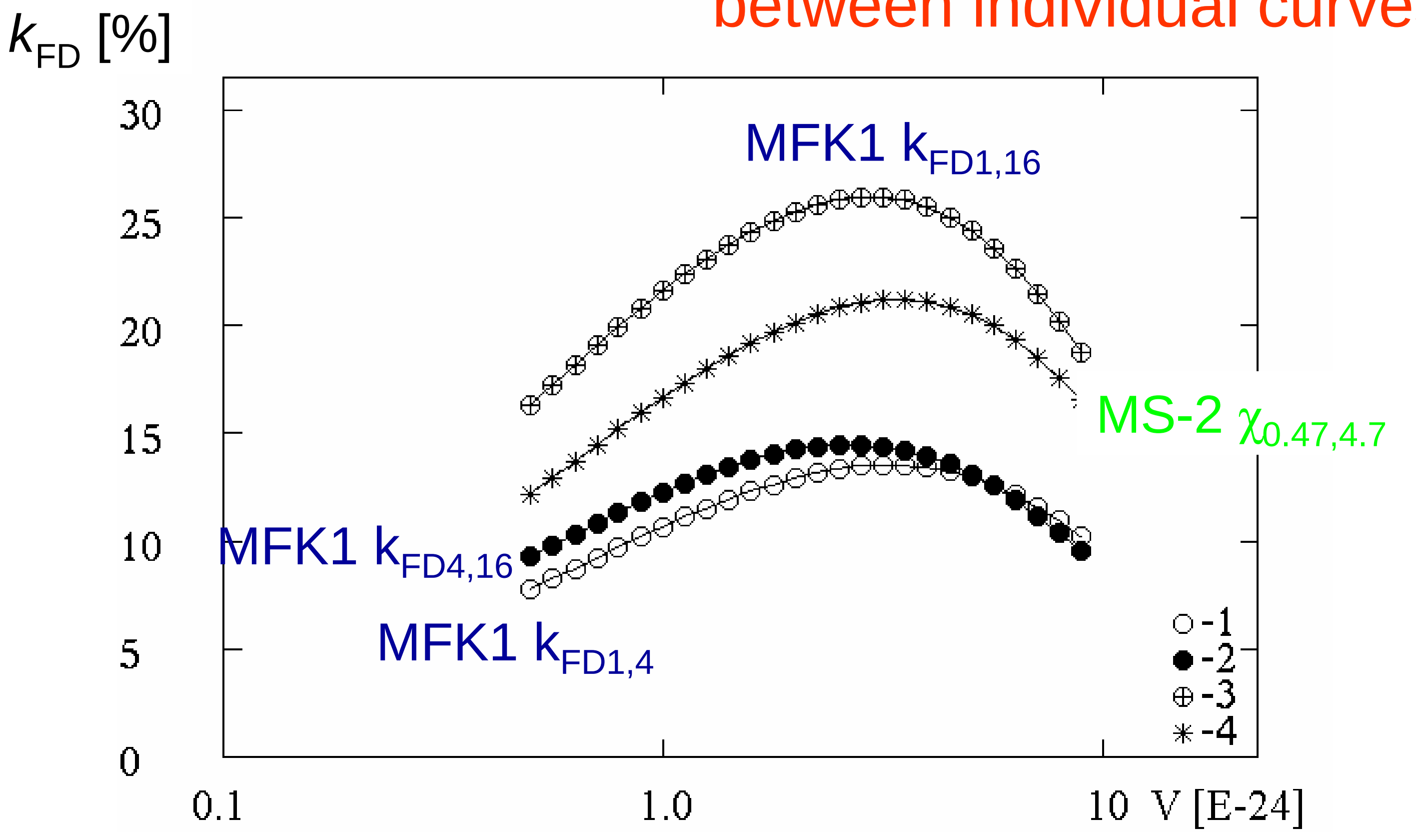
k_{LF} , k_{HF} are susceptibilities at the lower and higher frequencies.

Frequency dependence of MS

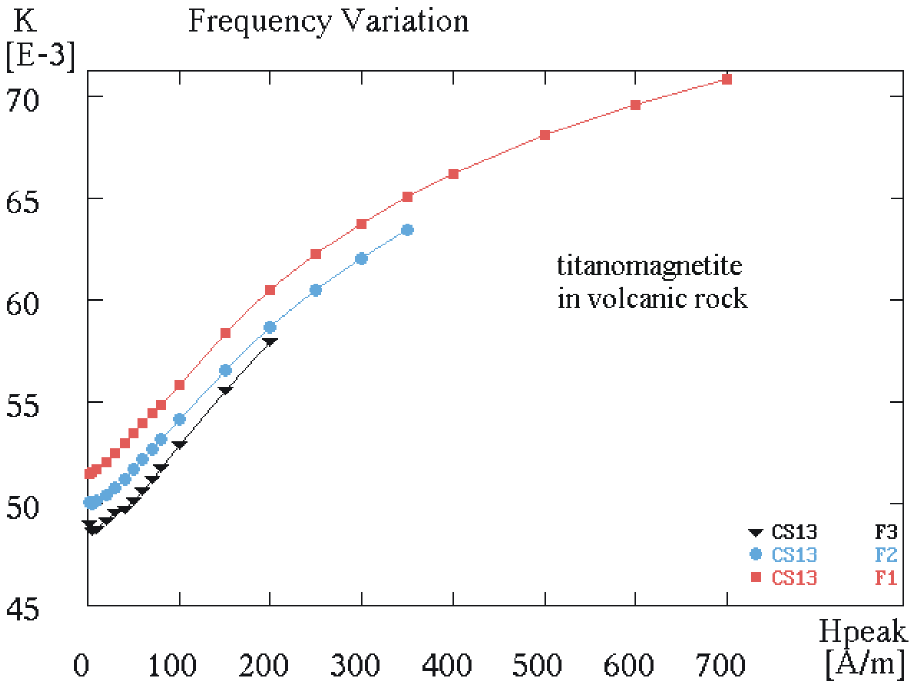
Comparison of MS-2 (Bartington) and MFK1-FA (Agico) instruments

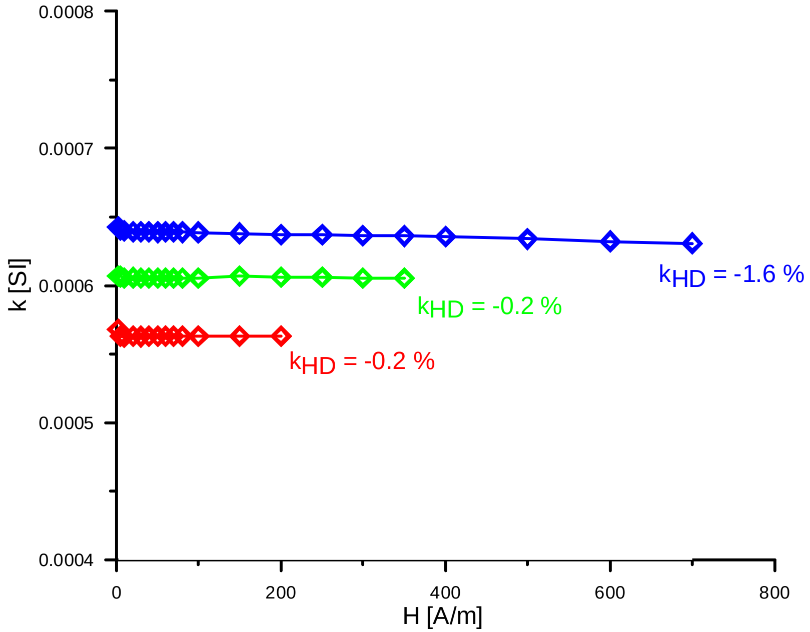
The MFK1-FA and MS-2 instruments use different operating frequencies for determining the k_{FD} parameters.

Large differences between individual curves

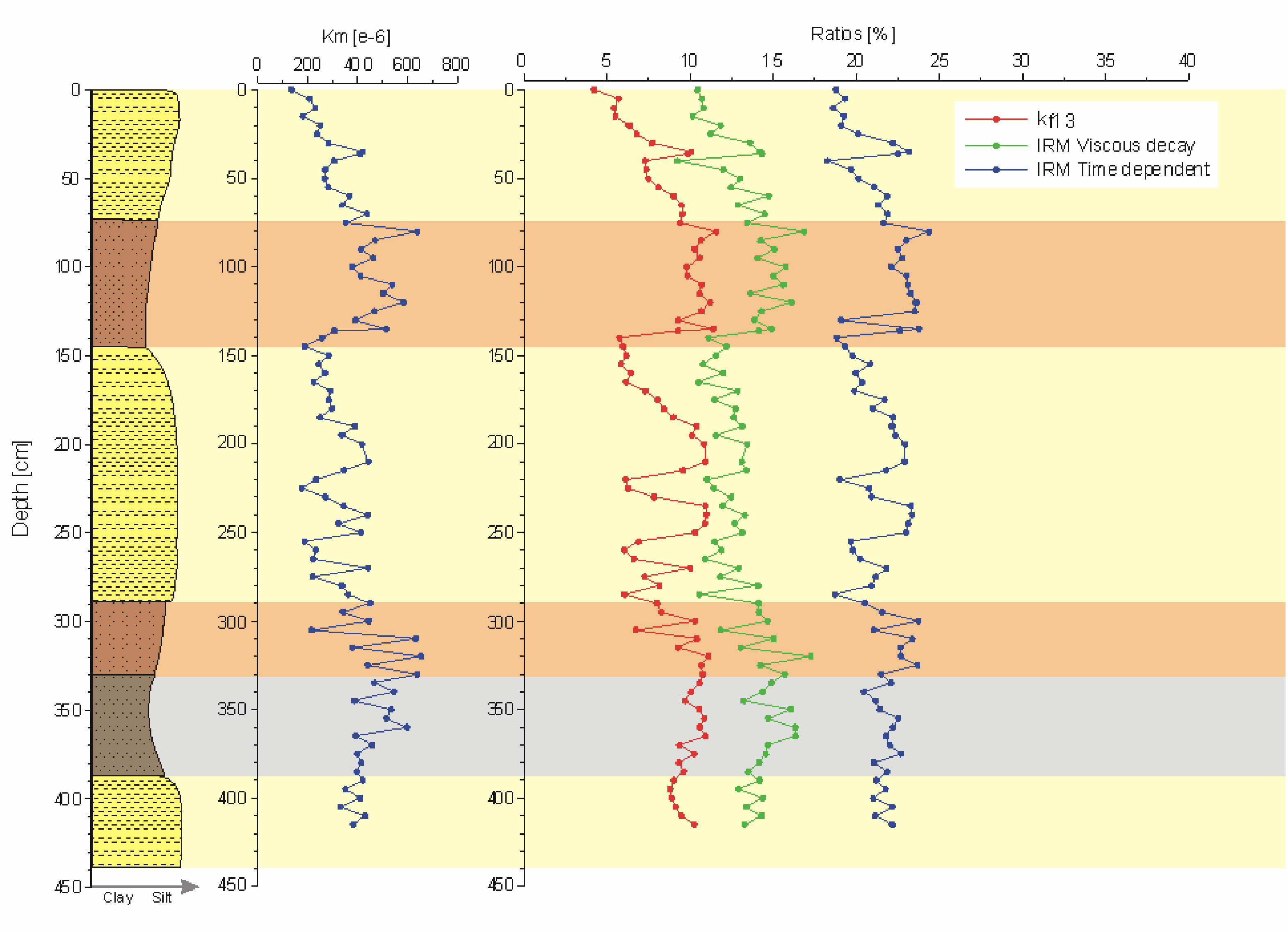


Frequency dependence of MS

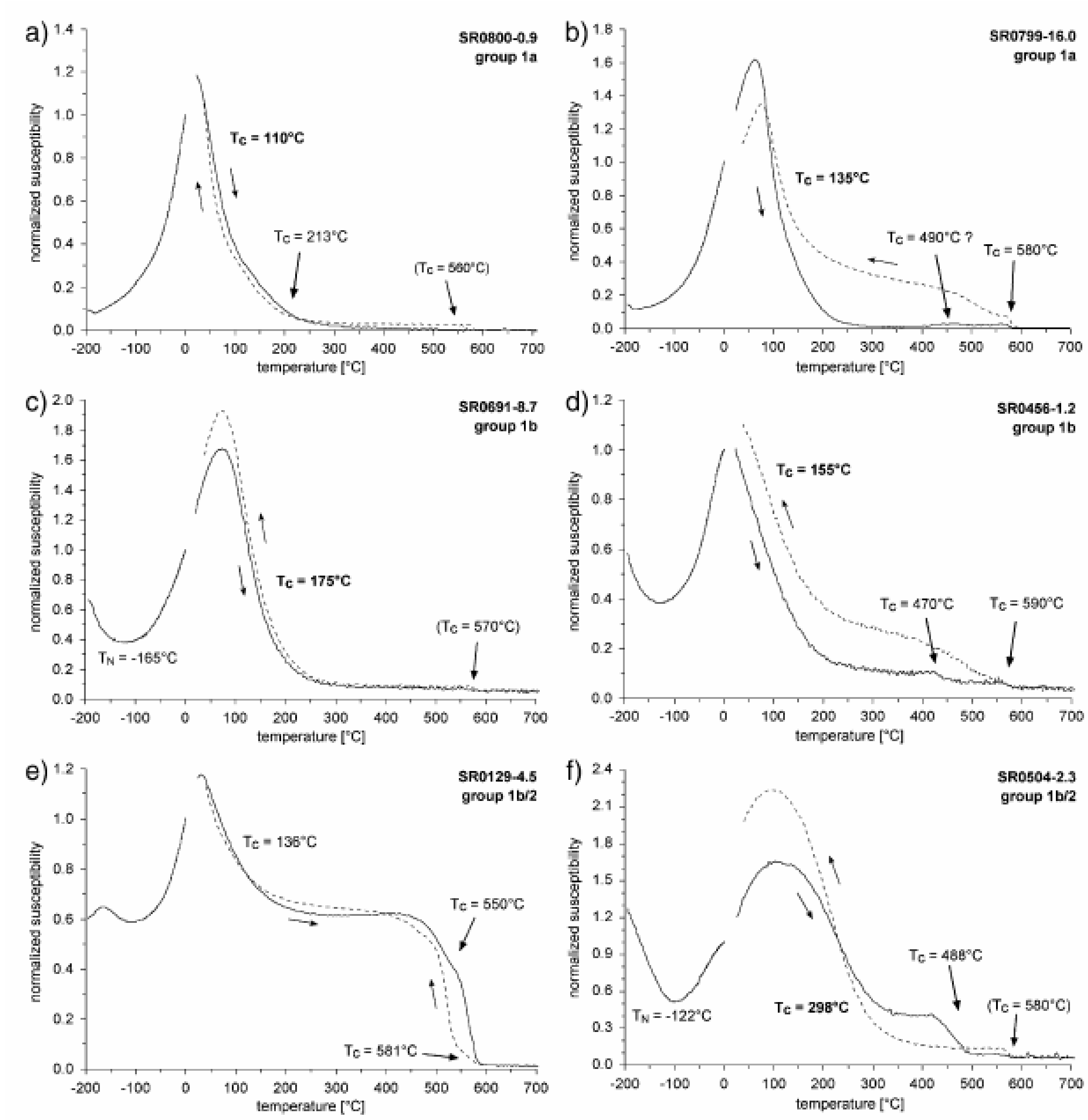




Frequency dependence of MS

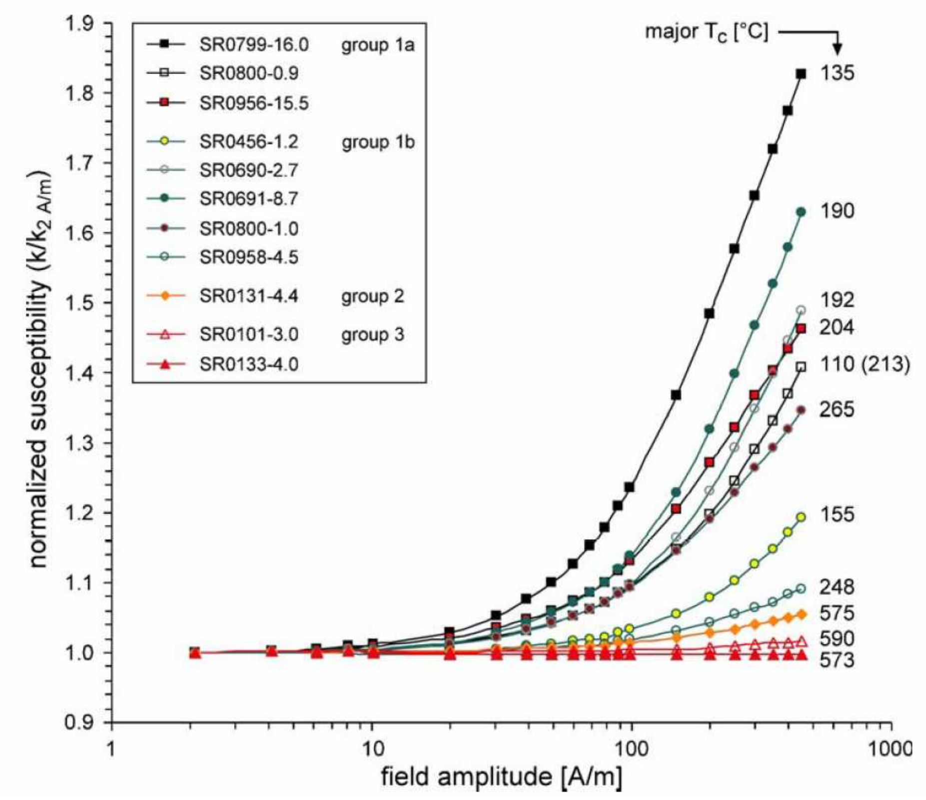


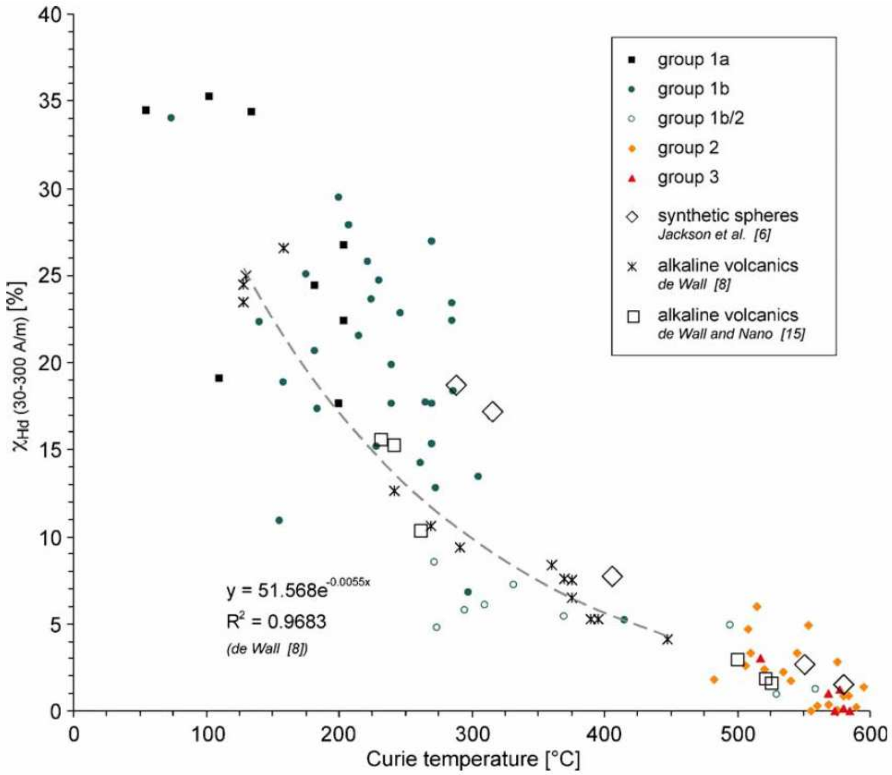
Example 1: k(T) and k(H) of various titanomagnetites



(Vahle and Kontny, 2005, EPSL)

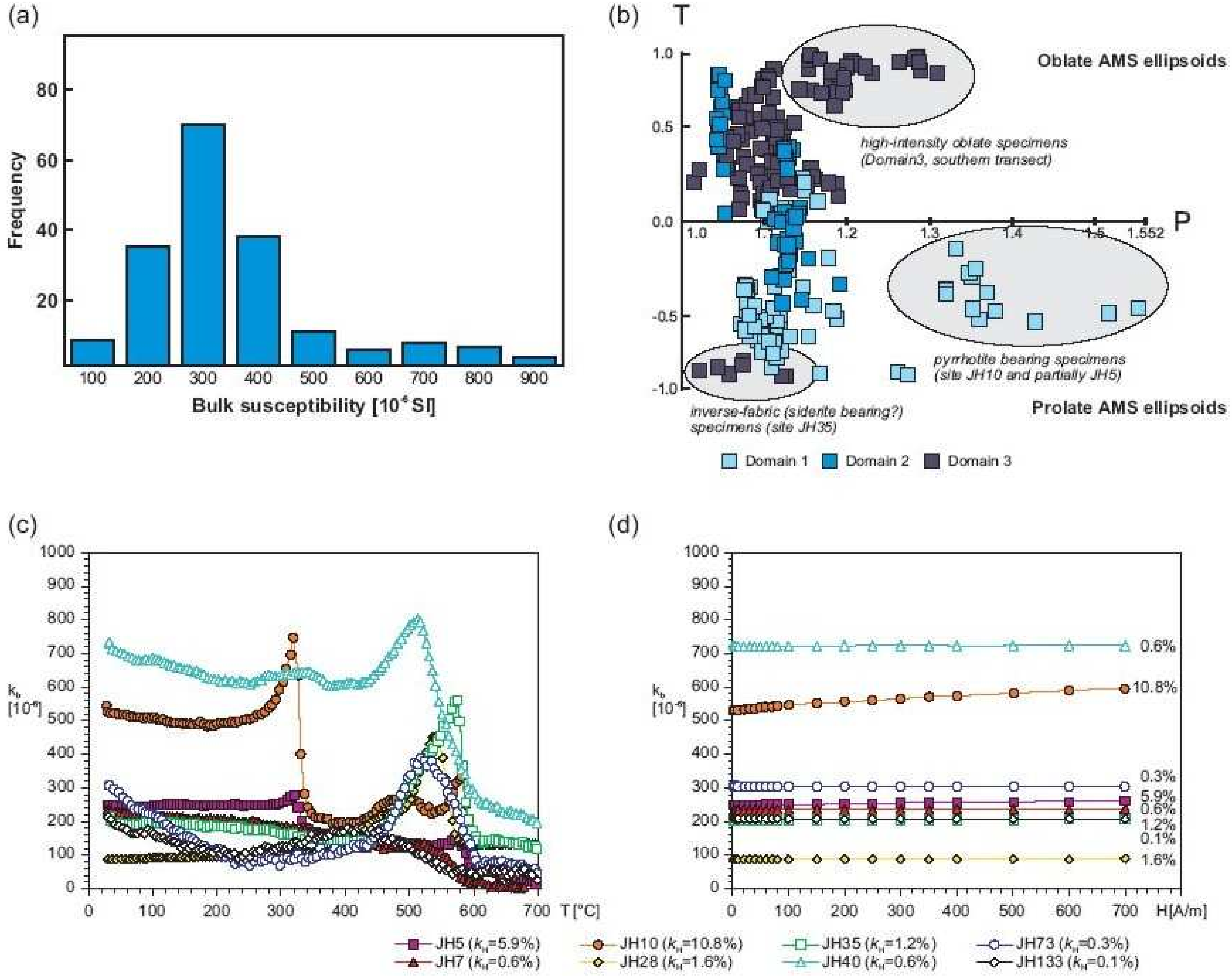
Example1: k(T) and k(H) of various titanomagnetites





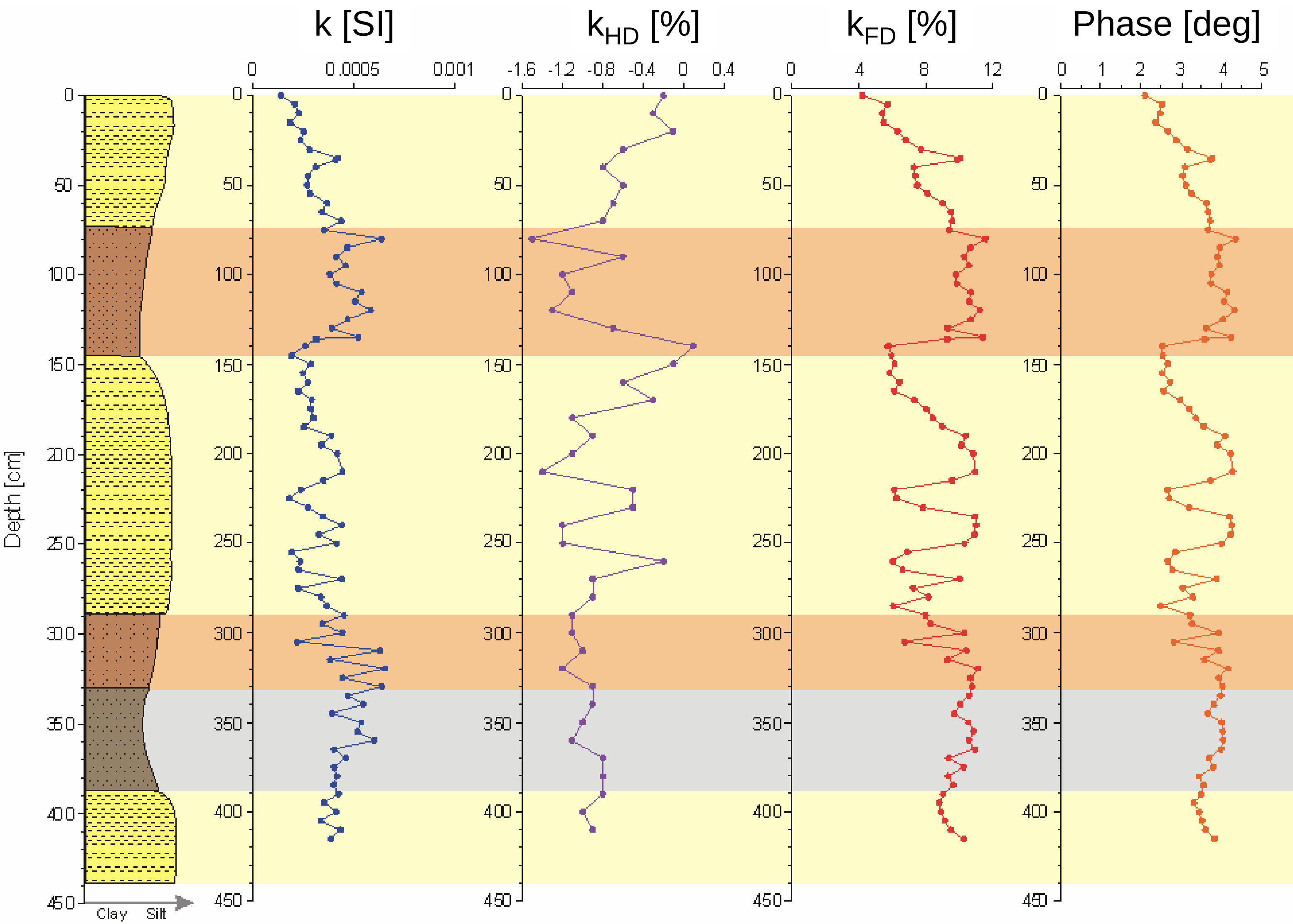
(Vahle and Kontny, 2005, EPSL)

Example 2: Flysch-like Proterozoic sediments

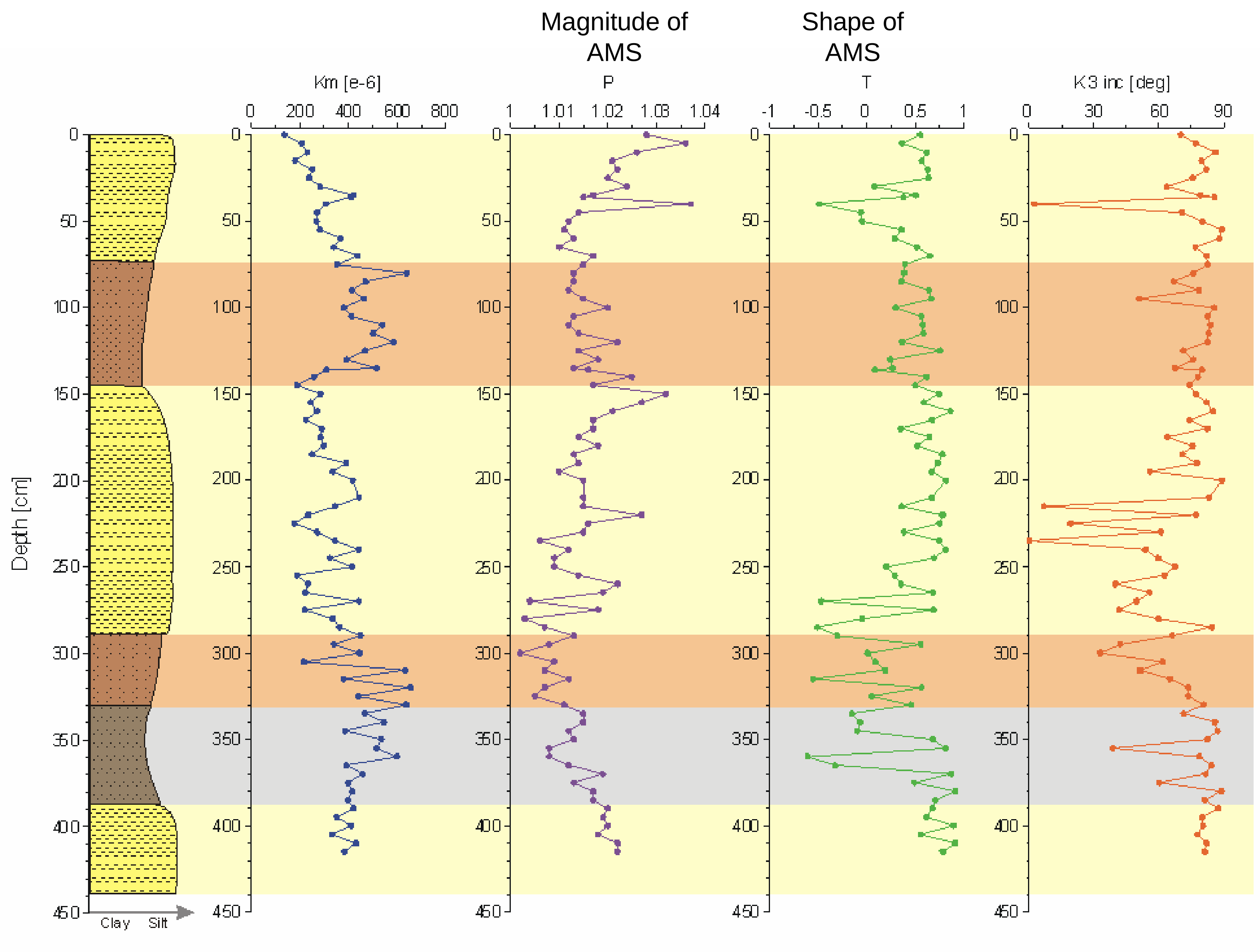


(Hajná et al., in press, Precam. Res.)

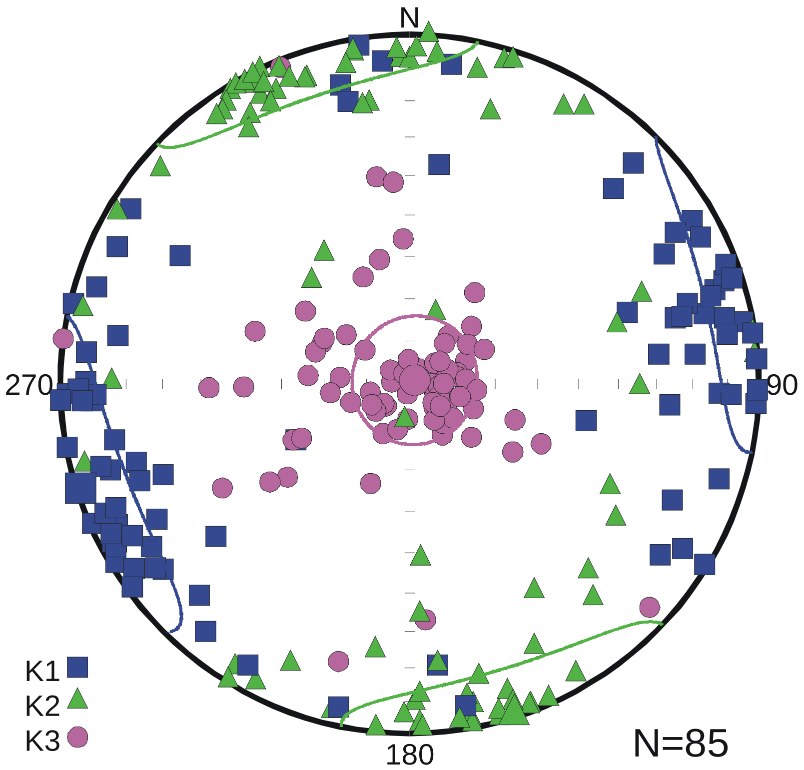
Example 3: Quaternary loess-paleosol section

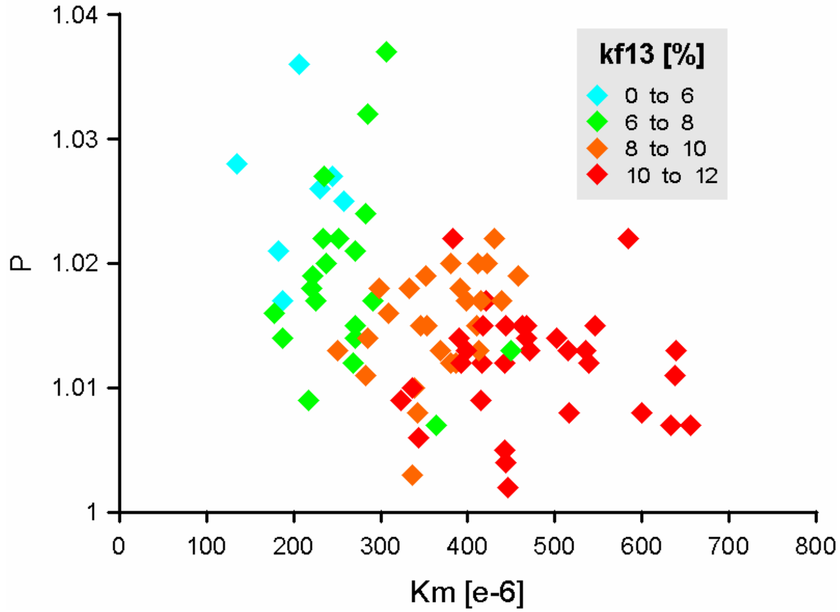


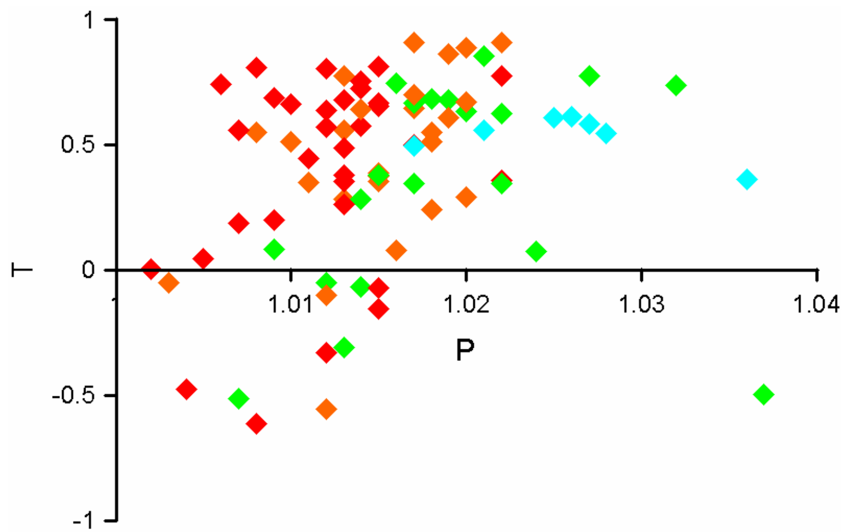
Example 3: Quaternary loess-paleosol section



Example 3: Quaternary loess-paleosol section







MFK1-FA + CS4

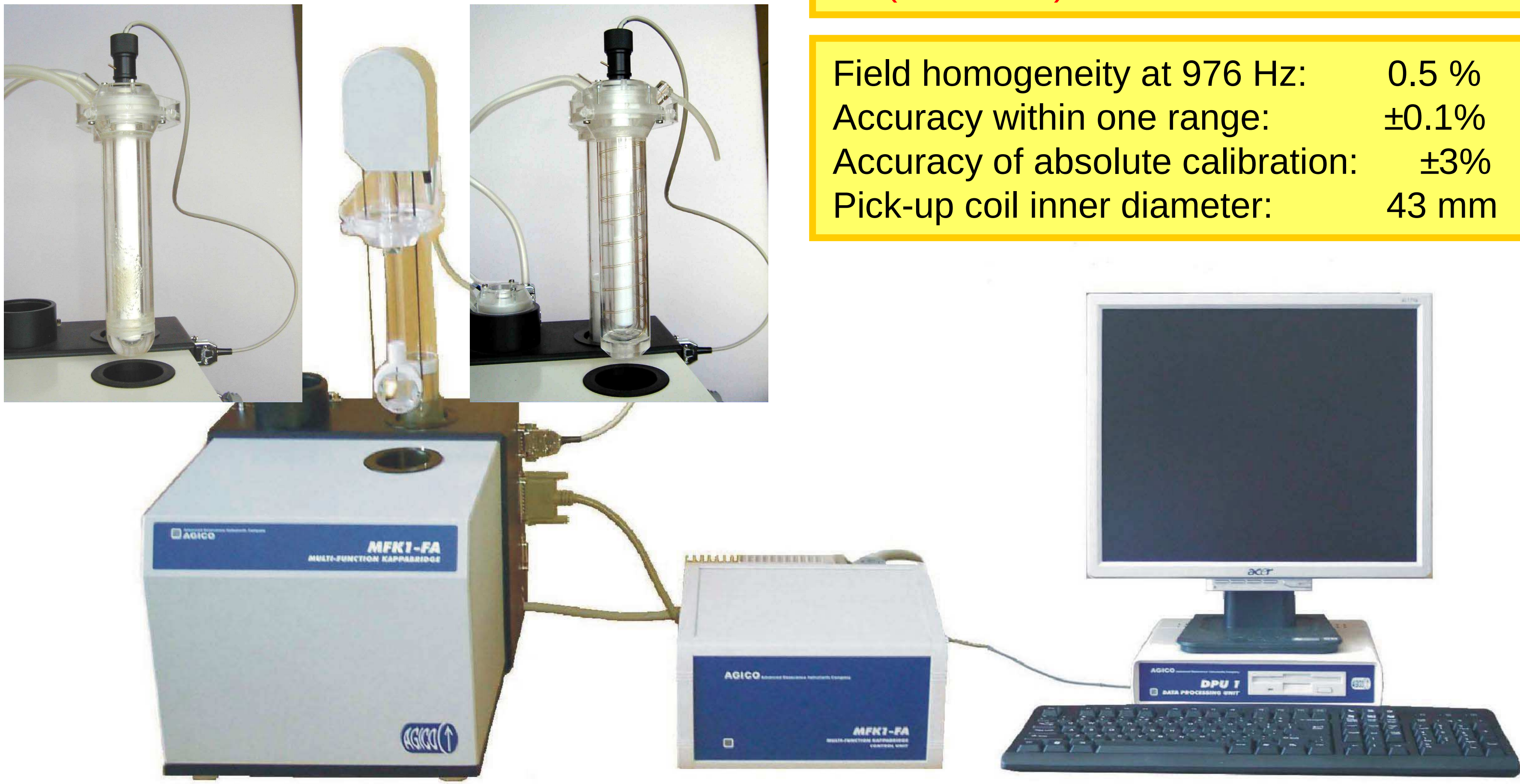
Temperature range

–192 ℃ up to 700 (800) ℃

Three operating frequencies and respective field ranges (peak values):

F1 (976 Hz):	2 - 700 A/m
F2 (3904 Hz):	2 - 350 A/m
F3 (15616 Hz):	2 - 200 A/m

Field homogeneity at 976 Hz:	0.5 %
Accuracy within one range:	±0.1%
Accuracy of absolute calibration:	±3%
Pick-up coil inner diameter:	43 mm



Instruments

www.agico.com

Software

www.agico.com/software

(Free of charge)

Contact

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