

# Lattice Preferred Orientation of Graphite in a Graphite Ore as Investigated by the Anisotropy of Out-of-phase Magnetic Susceptibility

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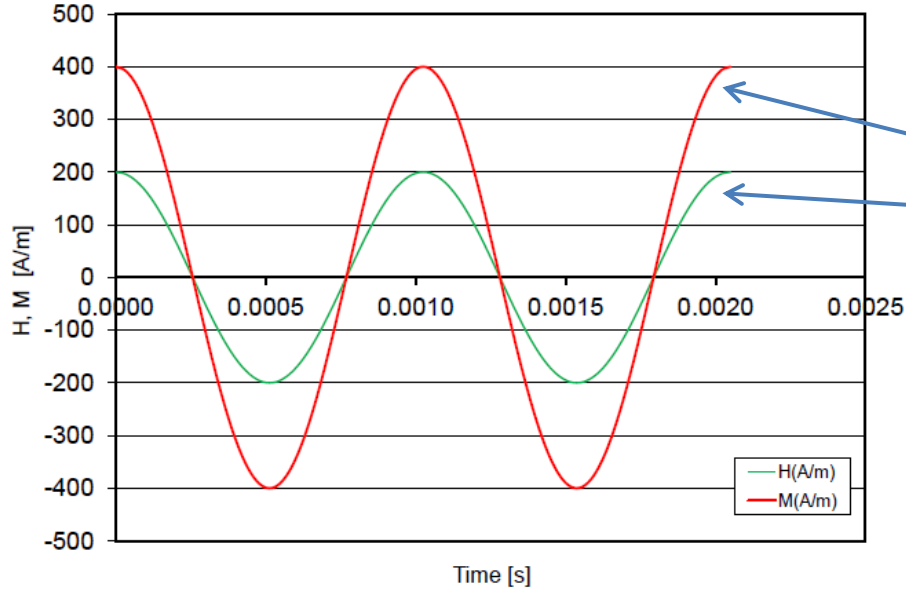
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# In-phase and Out-of-phase Responses

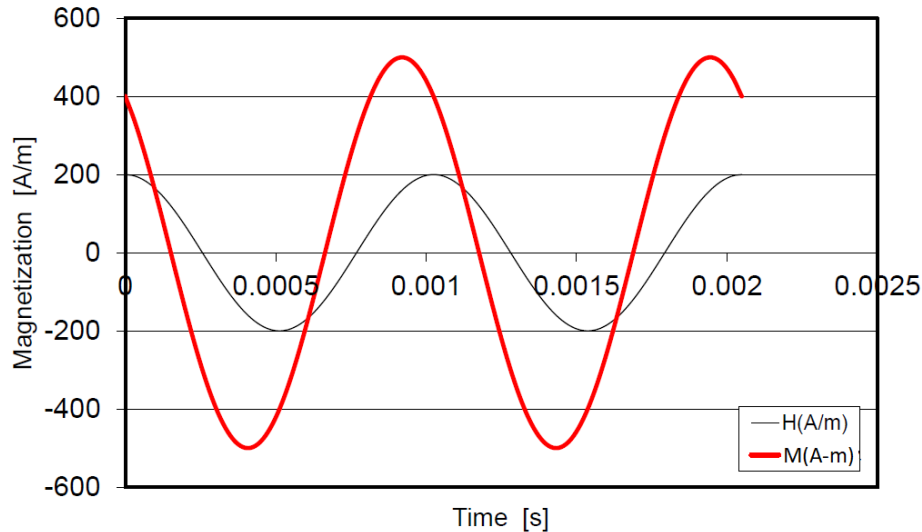


## In-phase Response

Magnetization  $M$  is in-phase with driving field  $H$ . Susceptibility is  $k = M/H$ .

$$H(t) = H_0 \cos(\omega t), \quad M(t) = M_0 \cos(\omega t)$$

**Examples:** all diamagnetic and paramagnetic minerals  
pure MD magnetite



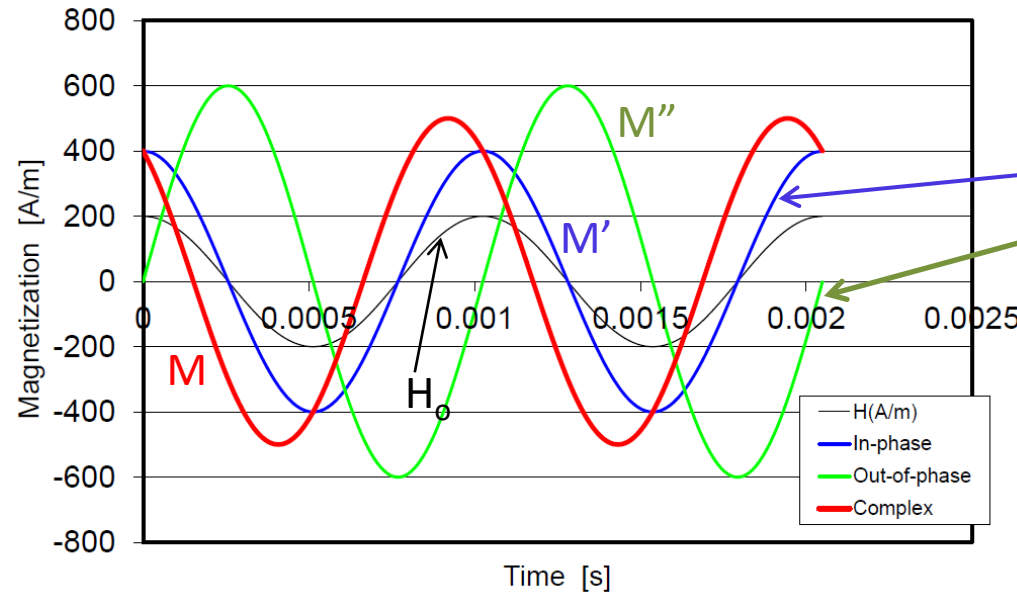
## Out-of-phase Response

Magnetization  $M$  delays behind driving field  $H$ . Three susceptibilities may be obtained, complex, in-phase, and out-of-phase one.

$$M(t) = M_0 \cos[\omega(t - \Delta t)] = M_0 \cos(\omega t - \delta)$$

**Examples:** titanomagnetites,  
pyrrhotite, MD hematite,  
SP/SSD magnetite

# Definition of Out-of-phase Susceptibility



Using harmonic analysis, magnetization curve can be formally resolved into *in-phase (cosine)* and *out-of-phase (sine)* components

$$M(t) = H_o k' \cos(\omega t) + H_o k'' \sin(\omega t)$$

defining in-phase ( $k'$ ) and out-of-phase ( $k''$ ) susceptibilities.

$$\text{In-phase Susceptibility} \quad k' = M'/H_o$$

$$\text{Out-of-phase Susceptibility} \quad k'' = M''/H_o$$

## **Physical Mechanisms of Out-of-phase Susceptibility (after Jackson, 2003-4):**

- (1) Viscous Relaxation (ultrafine particles on SP to SD transition)
- (2) Eddy Currents (conductive materials, e.g. graphite)
- (3) Weak-field Hysteresis (ferromagnetics with wide hysteresis loop)

# Eddy Currents Controlled Out-of-phase Susceptibility

Complex apparent susceptibility of isotropic conducting sphere controlled by eddy currents (after Landau & Lifshitz, 1960):

$$k = \frac{3\mu(\sinh\alpha - \alpha\cosh\alpha) + 3/2\mu_M(\sinh\alpha - \alpha\cosh\alpha + \alpha^2\sinh\alpha)}{\mu(\sinh\alpha - \alpha\cosh\alpha) - \mu_M(\sinh\alpha - \alpha\cosh\alpha + \alpha^2\sinh\alpha)}$$

where  $\alpha = r\sqrt{i\sigma\mu\omega - \varepsilon\mu\omega^2}$ . The individual parameters are:  $r$ ,  $\sigma$  – sphere radius and conductivity,  $\mu$  – sphere permeability ( $\mu = \mu_r\mu_0$ ;  $\mu_0 = 4\pi \times 10^{-7}$  H/m),  $\varepsilon$  – sphere permittivity,  $\omega$  – angular frequency of the applied field ( $\omega = 2\pi f$ ),  $\mu_M$  – permeability of surrounding medium (matrix, air),  $i$  – imaginary unit.

The following Table 1 shows the estimates of in-phase (IPS), out-of-phase (OPS) susceptibilities and phase angle for the susceptibility measured at operating frequency 1 kHz of important rock-forming minerals, some ore minerals, and some metals of spherical shapes 1 mm in radius being embedded in a zero-susceptibility matrix.

# Theoretical IPS and OPS of Some Minerals

The IPS, OPS and phase angles for important rock-forming minerals, some ore minerals, and some metals, according to Eq. (1) at frequency 1 kHz.

Mineral	Susceptibility [ $\times 10^{-6}$ ]	Conductivity [S/m]	$r = 1 \text{ mm}$			
			Skin Ratio $\gamma$	IPS [ $\times 10^{-6}$ ]	OPS [ $\times 10^{-6}$ ]	Phase Angle [ $^{\circ}$ ]
feldspar	-12	$3.1 \times 10^2$	$1.1 \times 10^{-3}$	-12	0	178.83
olivine	124-4270	$2.5 \times 10^2$	$9.9 \times 10^{-4}$	124	0	0.09
pyroxene	133-3250	$3.4 \times 10^2$	$1.2 \times 10^{-3}$	133	0	0.12
hornblende	746-1368	$1 \times 10^{-6}$ - $2 \times 10^{-2}$	$8.9 \times 10^{-6}$	746	0	0.00
muscovite	36-710	$1 \times 10^{-14}$ - $9 \times 10^{-2}$	$1.9 \times 10^{-5}$	36	0	0.00
biotite	873-3040	$1 \times 10^{-6}$ - $2 \times 10^{-2}$	$8.9 \times 10^{-6}$	873	0	0.00
serpentine	153	$3 \times 10^{-3}$ - $2 \times 10^{-2}$	$8.9 \times 10^{-6}$	153	0	0.00
siderite	2773-3170	$1 \times 10^{-6}$ -0.1	$2.0 \times 10^{-5}$	2770	0	0.00
magnetite	$3-50 \times 10^6$	$5.7 \times 10^{-3}$ - $5 \times 10^5$	0.32	2830167	3290	0.07
hematite	6500	$1 \times 10^{-7}$ - $3.5 \times 10^3$	$3.7 \times 10^{-3}$	6486	3	0.02
ilmenite	8042	$5 \times 10^{-1}$ - $1 \times 10^3$	$2.0 \times 10^{-3}$	8020	1	0.01
chromite	3080	$1 \times 10^{-6}$ -0.1	$2.0 \times 10^{-5}$	3077	0	0.00
pyrrhotite	$0.33 \times 10^6$	$5 \times 10^2$ - $6.5 \times 10^6$	0.18	297253	7368	1.42
pyrite	42	$0.7-2.9 \times 10^5$	$3.4 \times 10^{-2}$	42	229	79.62
chalcopyrite	308-410	$3-1.2 \times 10^5$	$2.2 \times 10^{-2}$	308	95	17.11
sphalerite	-13	$1 \times 10^{-7}$ -0.7	$5.3 \times 10^{-5}$	-13	0	180.00
galena	-30 to +9	$3 \times 10^{-2}$ - $3 \times 10^5$	$3.4 \times 10^{-2}$	-30	237	97.23
graphite	-14	$1 \times 10^9$	$2.0 \times 10^{-2}$	-14	79	100.06
iron	$200 \times 10^6$	$1 \times 10^7$	2.82	2934068	55054	1.08
copper	-10	$5.9 \times 10^7$	0.48	-2038	46095	92.53

# Results

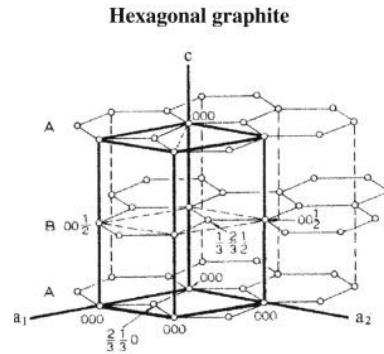
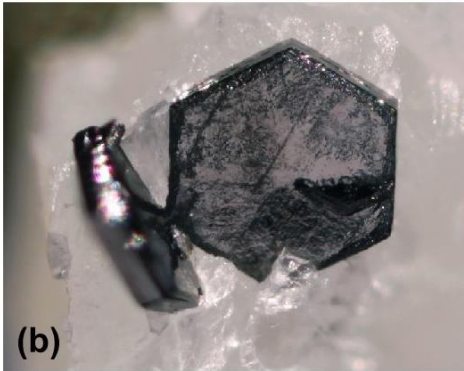
Most common rock-forming paramagnetic and diamagnetic minerals (mafic silicates, quartz, feldspars, calcite) are characterized by a vanishingly small OPS, so that the phase angle is effectively zero. This also applies to iron oxides such as magnetite, hematite, and ilmenite in the absence of magnetic viscosity and/or weak-field hysteresis effects.

The OPS of magnetite is relatively strong compared to that of other minerals, but still three orders of magnitude smaller than the IPS, resulting in effectively zero phase angle. The OPS of sulphide ores, and especially pyrrhotite, is remarkably stronger, but the phase angles remain relatively low. In case of pyrrhotite, the phase angles measured on natural samples are often significantly larger than those calculated as due to eddy currents. This probably results from strong effect of weak-field hysteresis.

**In GRAPHITE, which is diamagnetic and highly conductive, the OPS as well as the phase angle are relatively HIGH. Consequently, graphite-bearing rocks and graphite ores are good candidates for investigation of eddy currents controlled anisotropy of out-of-phase magnetic susceptibility.**

# Magnetic and Electrical Properties of Graphite

(after Krishnan and Ganguli, 1939)



Density  $2.26 \times 10^3 \text{ kg/m}^3$

Electrical Resistivity:

along basal plane  $10^{-4} \text{ ohm.cm}$

along c-axis  $2\text{-}3 \text{ ohm.cm}$

degree of anisotropy  $\sim 10^4$

Magnetostatic susceptibility (corresponding to in-phase component):

along basal plane  $-14.2 \times 10^{-6} \text{ [SI]}$

along c-axis  $-624.5 \times 10^{-6}$

degree of anisotropy  $\sim 44$

Out-of-phase susceptibility (due to eddy currents) and its anisotropy:

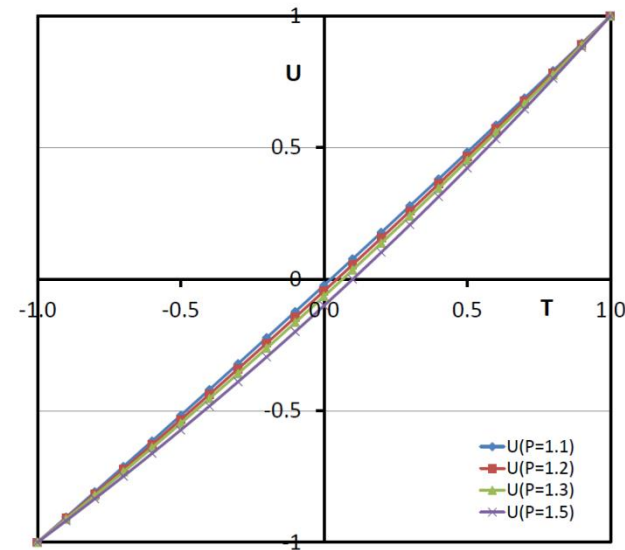
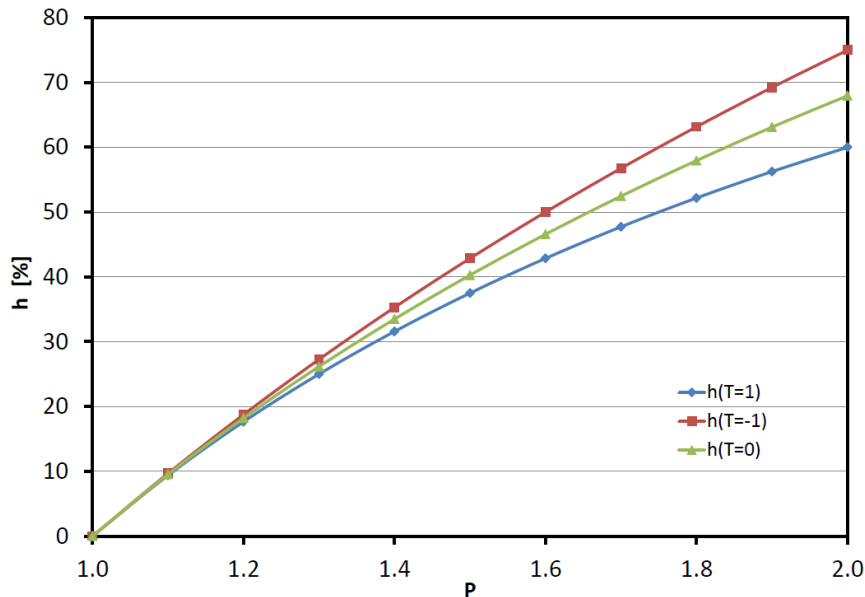
unknown for single crystals

positive as obtained from measurement of ores

# Degrees of AMS $P$ and $h$

## Shape parameters $T$ and $U$

Parameters  $P$  and  $T$ , which are probably the most frequently used ones in magnetic fabric studies, are not applicable to graphite ore with negative susceptibility. For this reason, we use parameters  $h$  and  $U$ , which are more convenient. They are defined below and figures show their relationships to the  $P$  and  $T$  parameters.



$$P = K_1 / K_3 \quad (K_1 > K_2 > K_3)$$

$$h = 100 (K_1 - K_3) / K_m$$

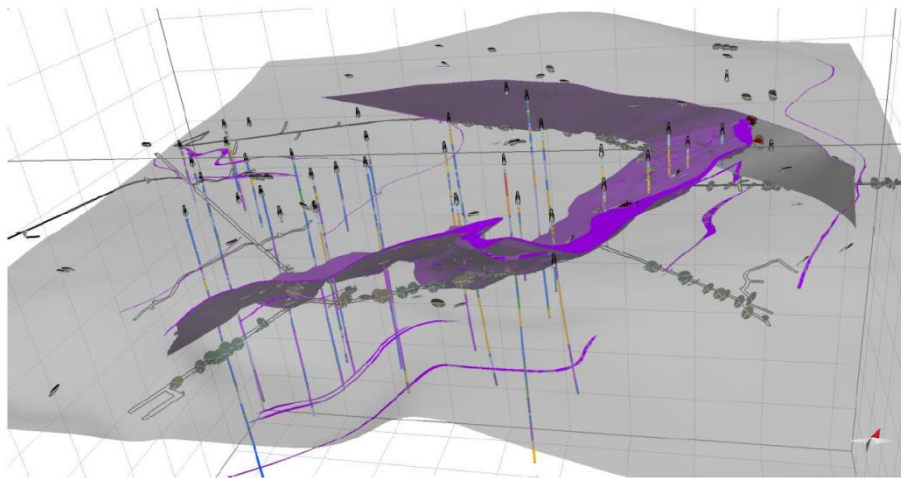
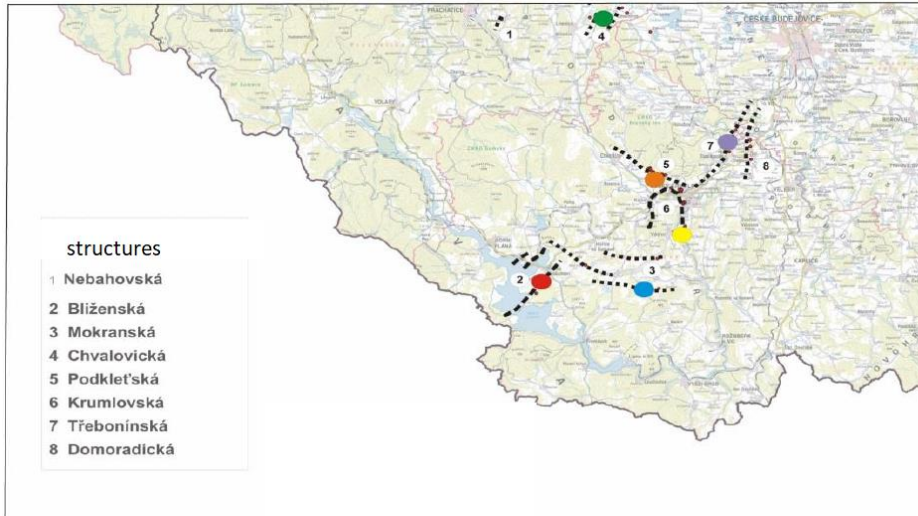
$$K_m = (K_1 + K_2 + K_3) / 3$$

$$T = (2 \ln K_2 - \ln K_1 - \ln K_3) / (\ln K_1 - \ln K_3)$$

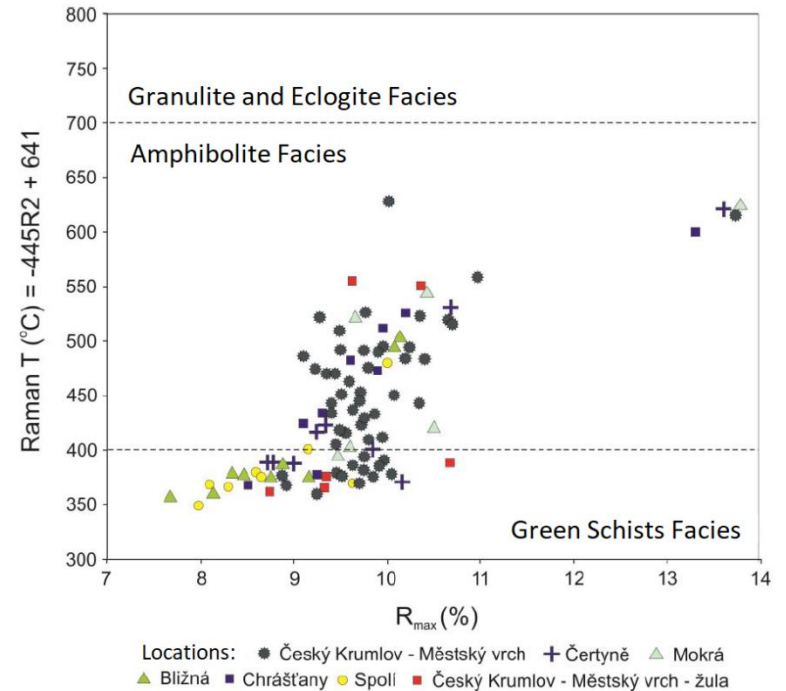
$$U = (2 K_2 - K_1 - K_3) / (K_1 - K_3)$$

# South Bohemian Graphite Deposits

(after Poňavič et al., 2017)



Scheme of Český Krumlov – Městský vrch Deposit



Deposits are located within meta-morphic rocks of the Moldanubian Zone of Variscan Orogeny.

# Locality GRF1- Český Krumlov, road cut

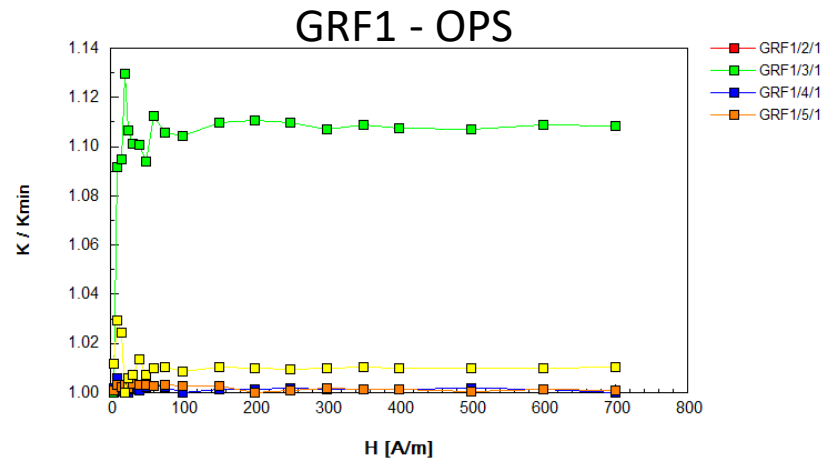
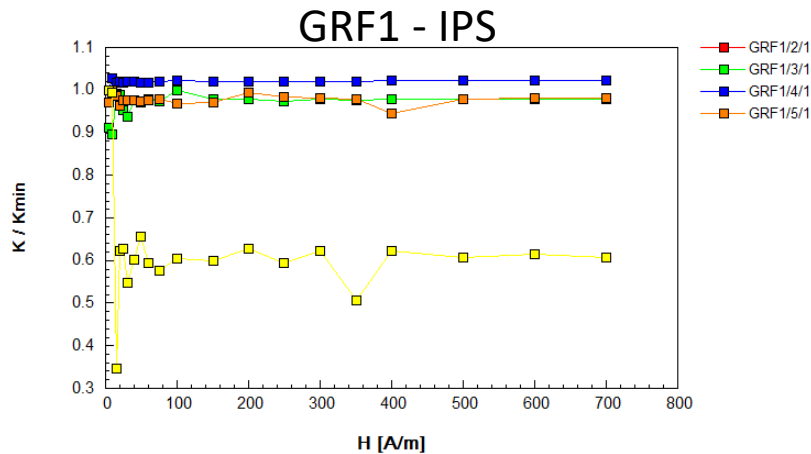


Artificial outcrop, Rybářská ulice, Český Krumlov

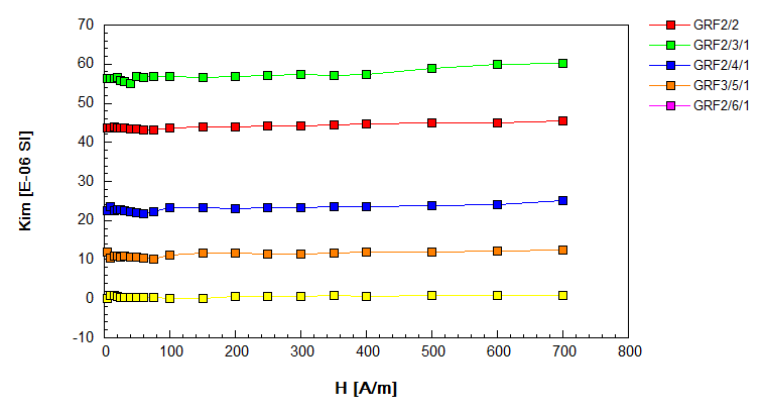
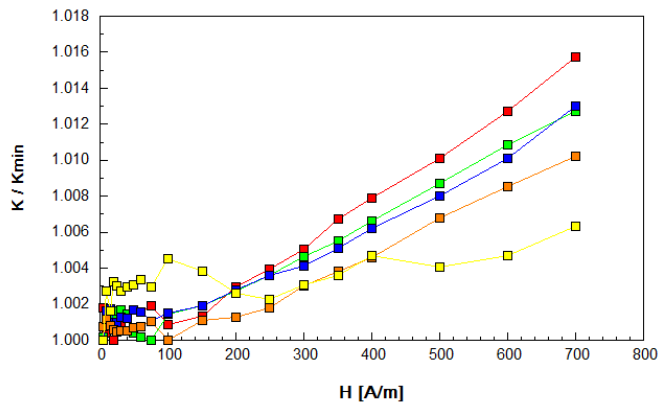


Microphotograph. Graphite leaves are parallel to schistosity.

# Field Variation of Susceptibility

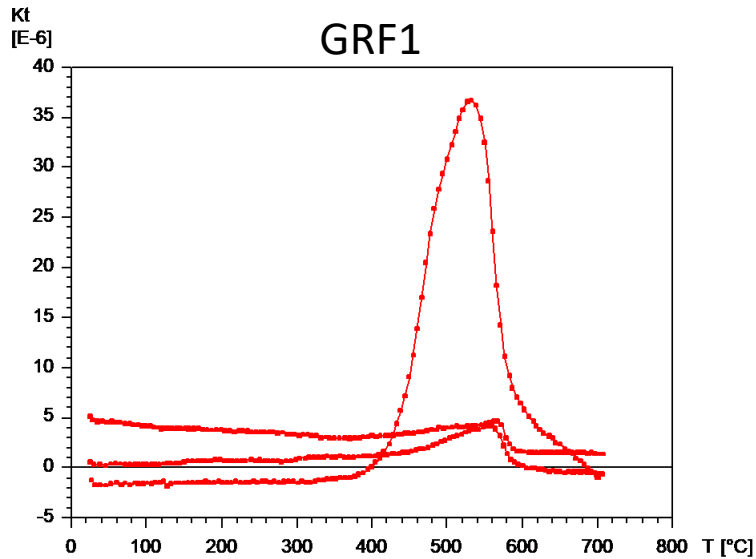


Normed (by minimum value) IPS and OPS show virtually no field variation.  
IPS is likely carried by paramagnetics, OPS by graphite.

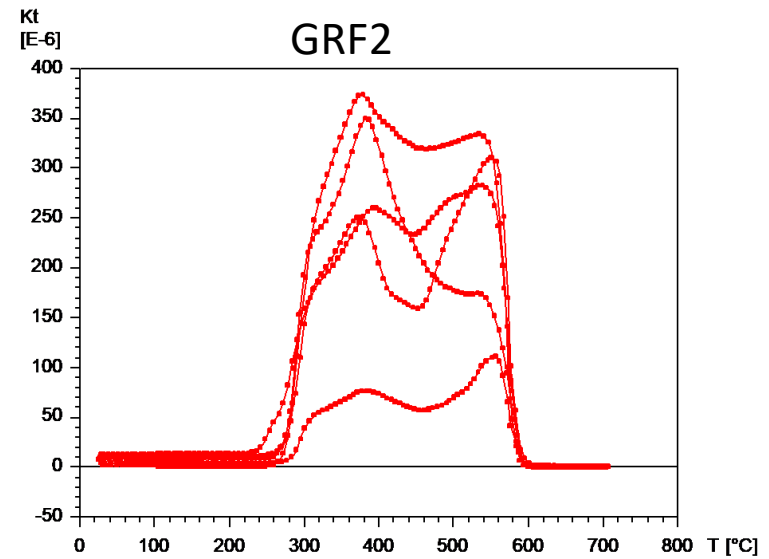


Normed IPS shows slight increase, unnormed OPS shows no field variation.  
IPS can be carried by para- and ferromagnetics, OPS by graphite.

# Temperature Variation of Susceptibility



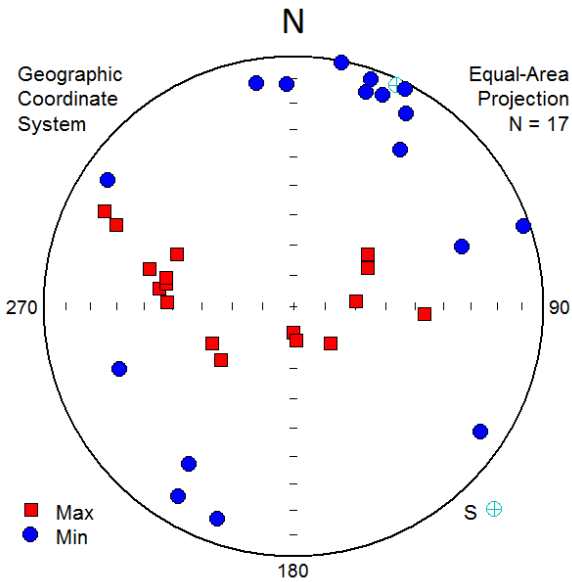
No IPS variation up to 400 °C, then rapid increase, probably due to creation of new ferromagnetic mineral of magnetite type.



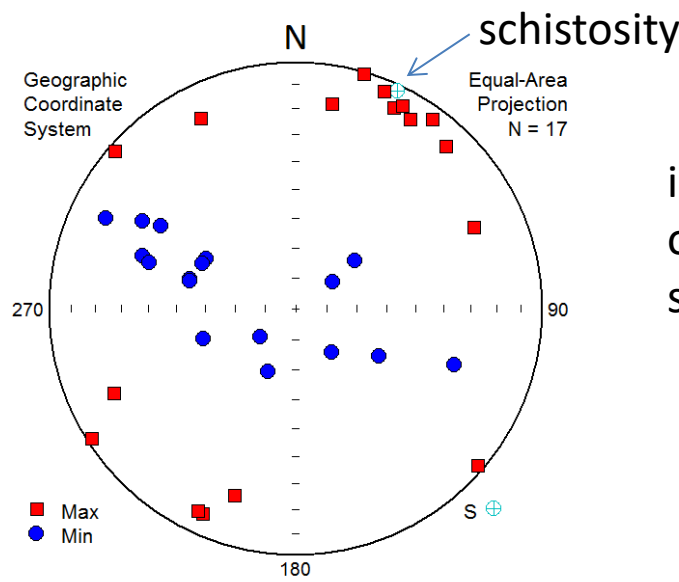
No IPS variation up to 250 °C, then rapid increase, probably due to creation of new ferromagnetic mineral. Modification of this mineral during advanced heating. Susceptibility drop at magnetite Curie temperature.

# Locality GRF1- Český Krumlov, road cut

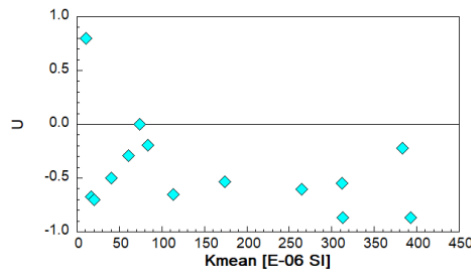
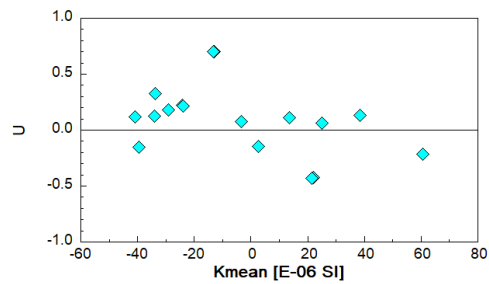
In-phase AMS



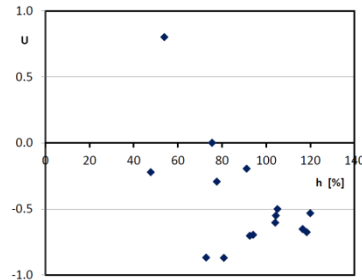
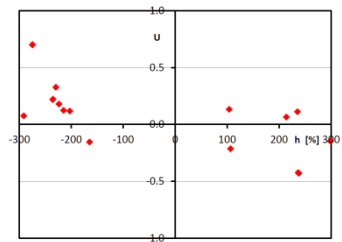
Out-of-phase AMS



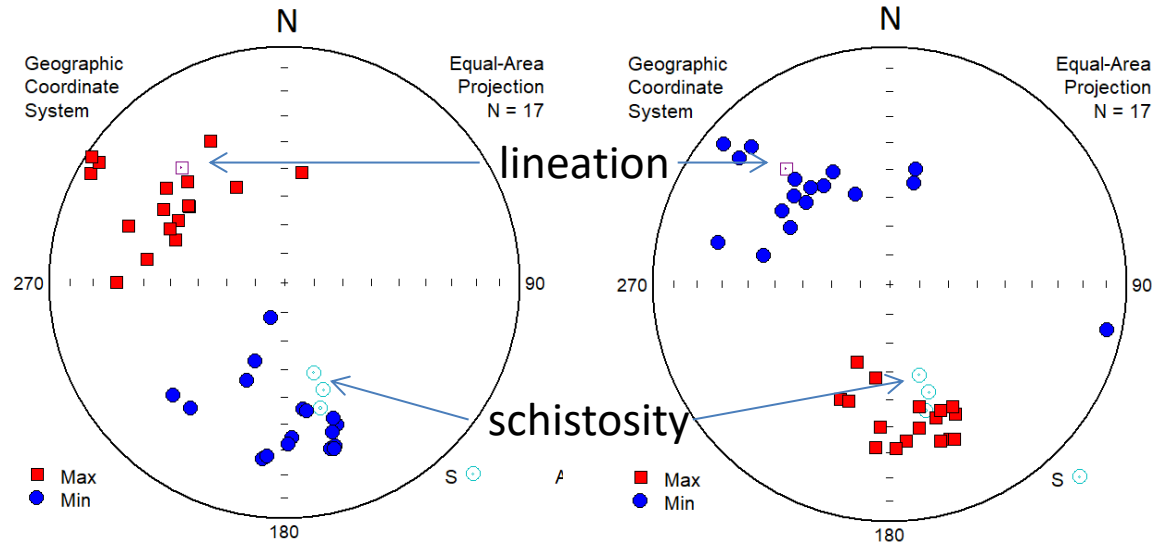
ipAMS foliation poles and  
opAMS lineations are near  
schistosity poles



ipAMS ellipsoids are neutral  
opAMS ellipsoids are prolate

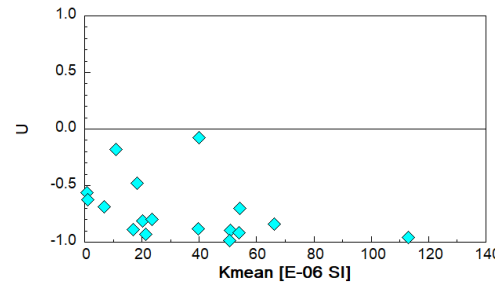
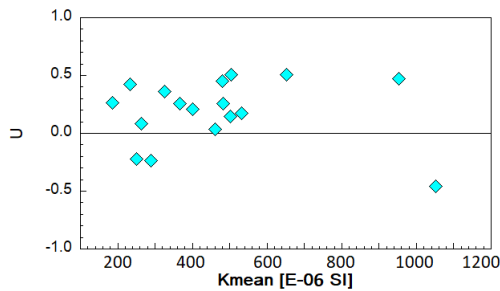


# Locality GRF2 - Český Krumlov, graphite mine



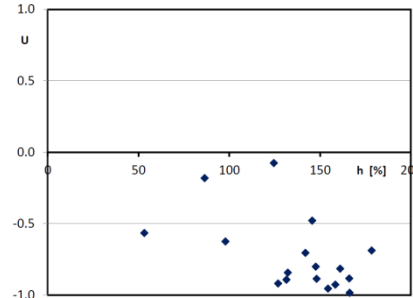
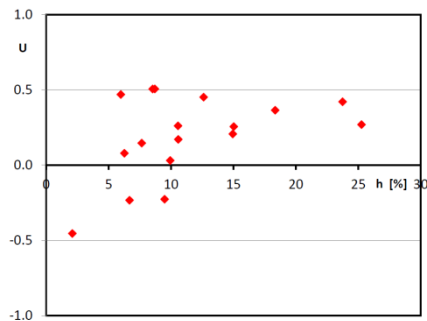
ipAMS foliation poles and opAMS lineations are near schistosity poles

ipAMS lineations and opAMS foliation poles are near mesoscopic lineation



ipAMS ellipsoids are neutral to weakly oblate

opAMS ellipsoids are prolate



# Concluding Remarks

The literature data on single crystals of graphite shows extremely strong anisotropy of electrical conductivity. Consequently, if the graphite crystals are oriented preferentially by crystal lattice (LPO) in the graphite ore, one would expect strong anisotropy of out-of-phase magnetic susceptibility (opAMS) of the ore.

South Bohemian graphite ore shows significantly high out-of-phase susceptibility, which is evidently due to eddy currents of electrically conductive graphite. The degree of opAMS of the ore is high, the opAMS foliation is closely related to the metamorphic foliation and the opAMS lineation is near the mesoscopic lineation in the ore and wall rocks. All this indicates a conspicuous LPO of graphite in the ore that was created during Variscan regional metamorphism and associated ductile deformation.