SAGA

The Soil Science & Archaeo-Geophysics Alliance

Training School 1

Lecture 11

MAGNETIC PROPERTIES OF SOIL: SAMPLING, MEASURING, INTERPRETING

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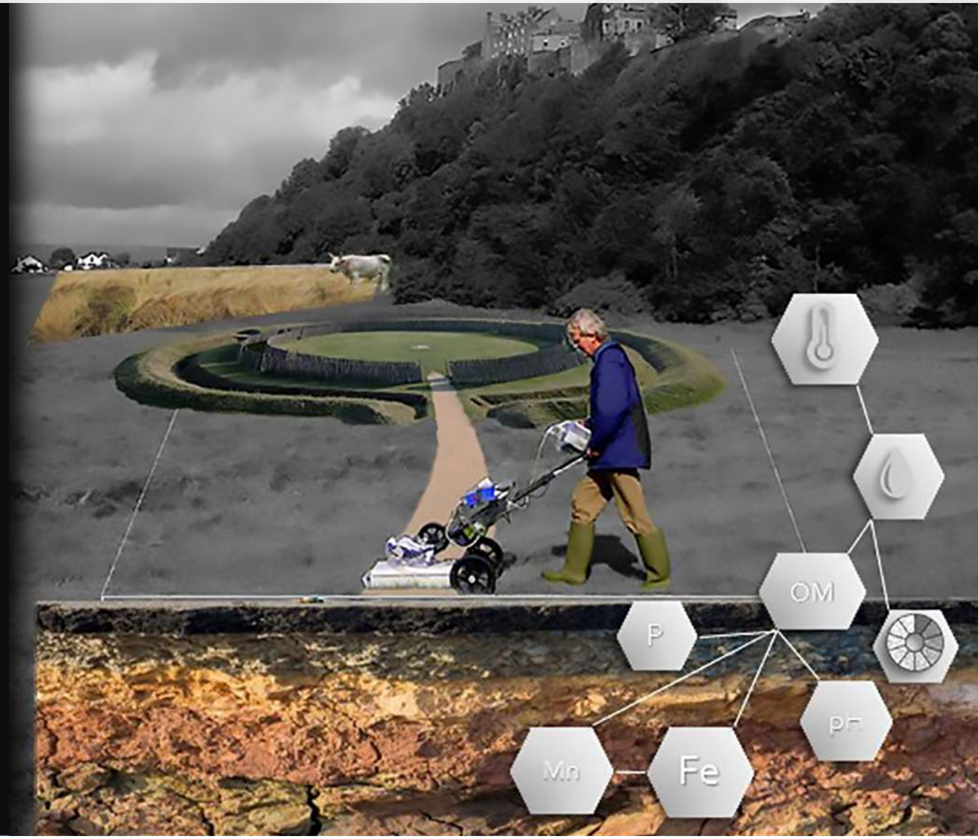
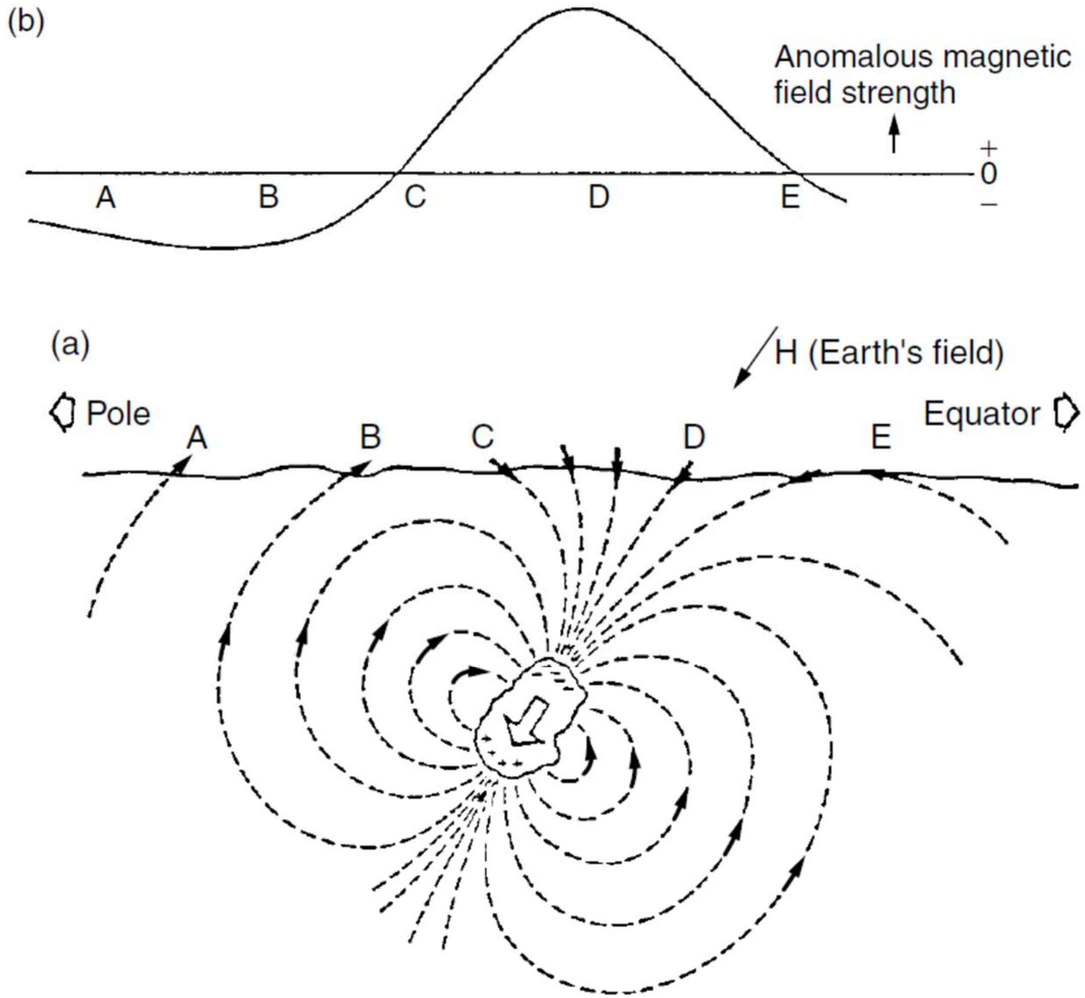
29 Jul - 2 Aug 2019, Auritz/Burguete



What are possible applications of soil magnetism in archaeology?

Interpretation of magnetic prospection data

Recognition of natural conditions under which the human lived in past, as well as anthropogenically influenced areas and layers


(b)
Anomalous magnetic field strength
+
0
−
A
B
C
D
E
(a)
H (Earth's field)
Pole
Equator
A
B
C
D
E

Magnetization of soil (rock, archaeological feature or object)

$$M = M_i + NRM$$

induced

natural remanent magnetization

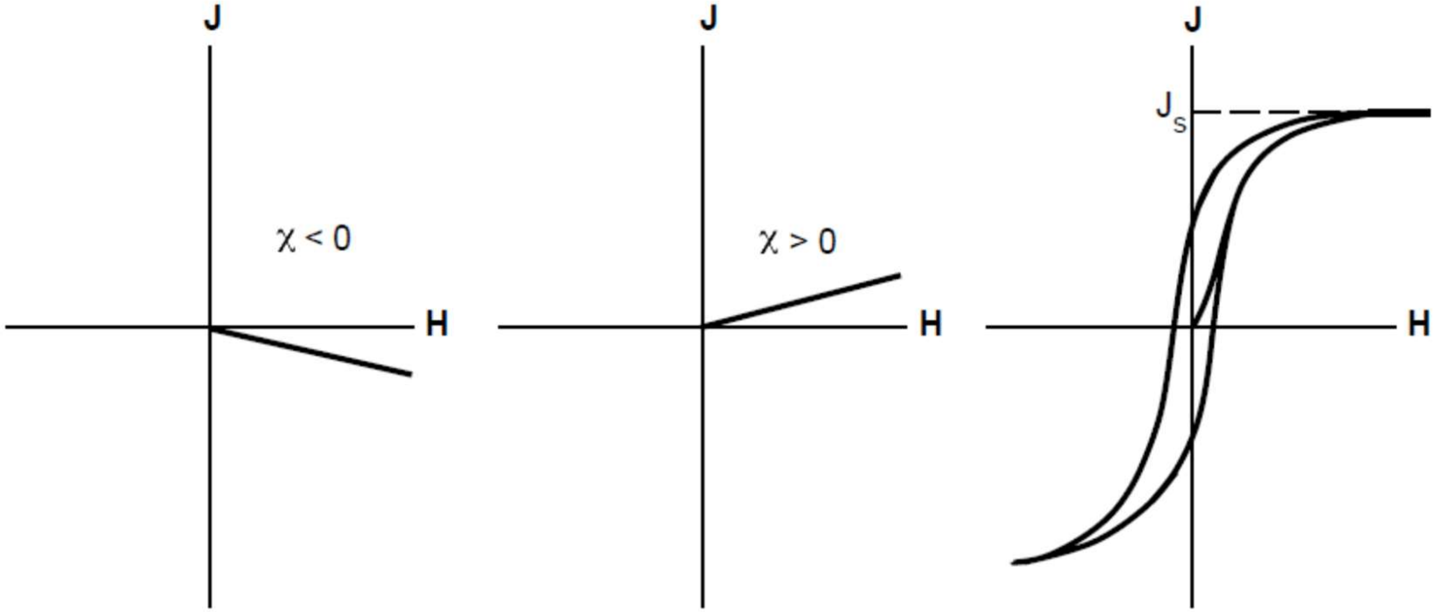
$$M_i = \kappa H$$

Magnetic susceptibility

Intensity of geomagnetic field

What are the carriers of induced and remanent magnetization in soil?

Diamagnetics | Paramagnetics | **Ferromagnetics**



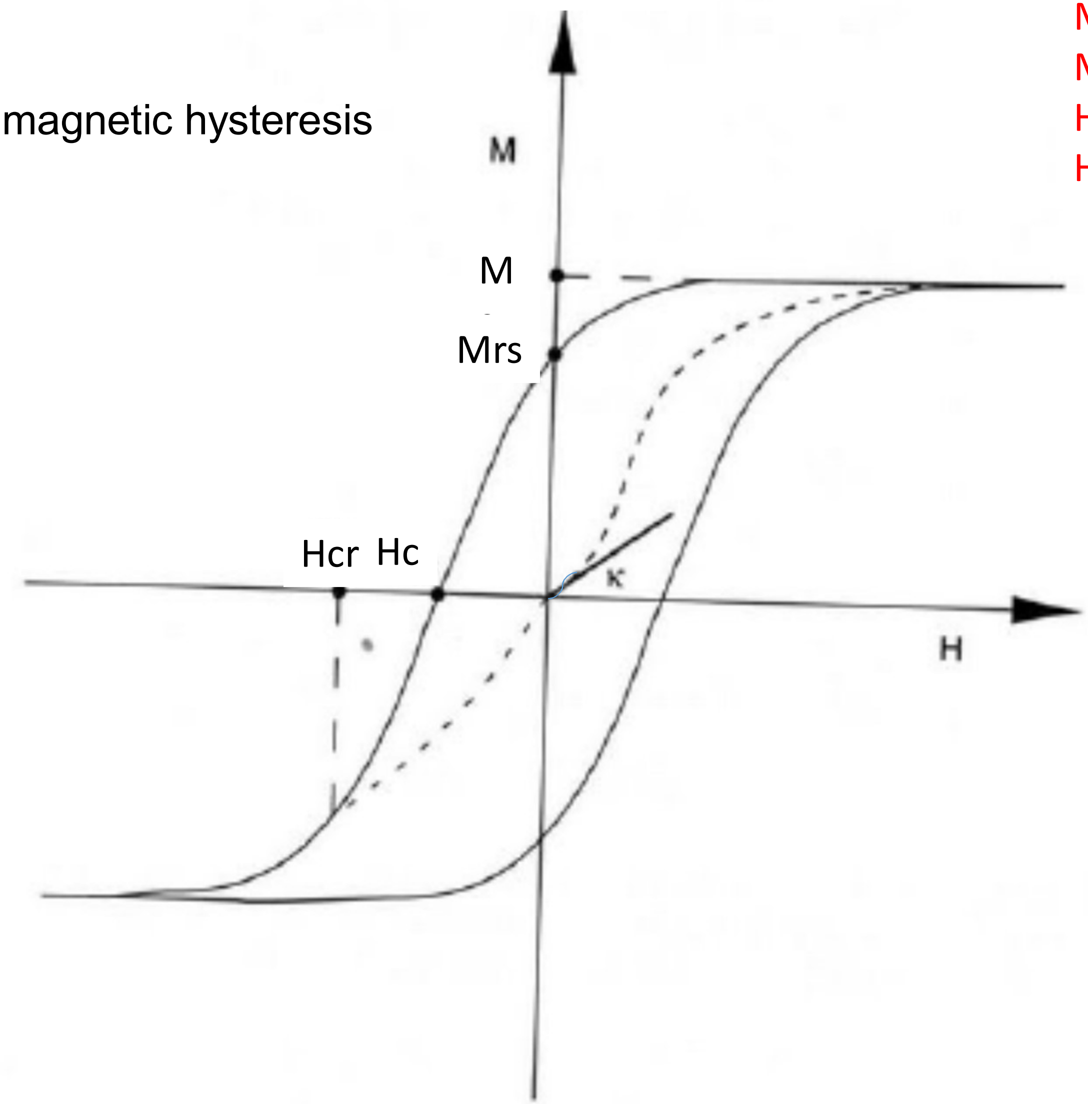
Quartz SiO_2
k = –0.8 x 10^{-7} SI units

Fayalite Fe_2SiO_4
k = 3.5 x 10^{-5} SI units

Magnetite Fe_3O_4

Ferromagnetics

The phenomenon of magnetic hysteresis

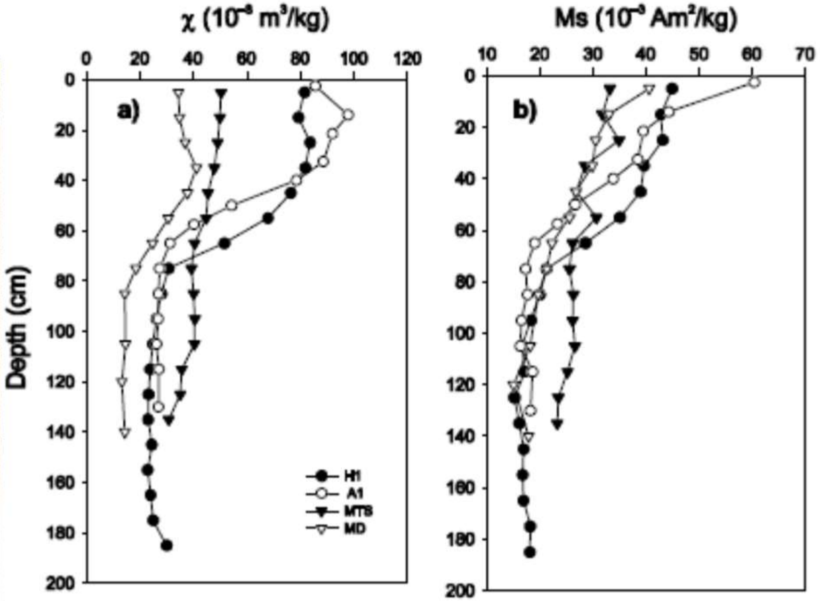


Ms – saturation magnetization
Mrs – saturation remanence
Hc – coercive force
Hcr – coercivity of remanence

What are the magnetic minerals in soil?

Mineral	Composition	M_s (kA/m or emu/cm^3)	T_C (°C)
Iron	αFe	1715	765
Magnetite	Fe_3O_4	480	580
Maghemite	γFe_2O_3	380	590–675 (Table 3.2)
Titanomagnetite	$Fe_{2.4}Ti_{0.6}O_4$	125	150
Hematite	αFe_2O_3	≈2.5	675
Goethite	$\alpha FeOOH$	≈2	120
Pyrrhotite	Fe_7S_8	≈80	320
Greigite	Fe_3S_4	≈125	≈ 330

The magnetic signal of soils is dominated by the presence of minor amounts of strongly magnetic ferrimagnetic iron (Fe) oxides
magnetite (Fe_3O_4),
maghemite (Υ-Fe_2O_3),
titanomagnetites ($Fe_{2\_x}Ti_xO_4$),
pyrhotite (Fe_3S_4) (rarely)



Hematite and goethite represent the prevailing (by volume or weight) phases of Fe oxides in soils.

Formation of magnetite (Fe_3O_4) in soil

- **Inorganic**
- In synthesis experiments the controled oxidation of ferrous iron yields magnetite (Maher & Taylor 1988)

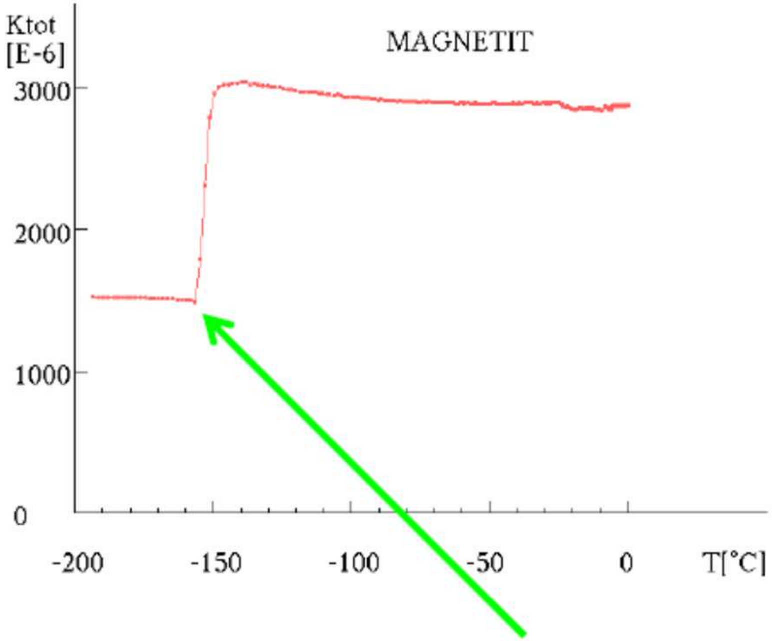
- **Biological induced**
- Dissimilatory iron-reduction bacteria, GS-15
- (Lovley, Stolz, Nord & Philllips, 1987)

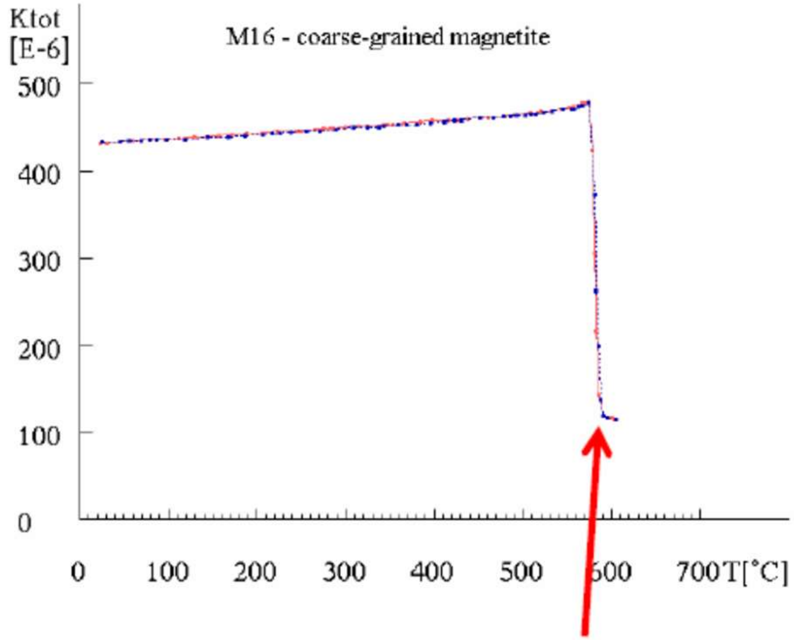
- **Biological controlled**
- Occurrence of magnetotactic soil bacteria
- (Fassbinder, Stanjek & Vali, 1990)

Formation of maghemite (γ - Fe_2O_3) in soil

- Low temperature oxidation of magnetite
- as result of burning
- dehydration of lepidocrocite (γ - FeOOH)
- via reduction-oxidation cycle occuring under „normal“ pedogenic conditions
- (C.E. Mullins, 1977)

Magnetite



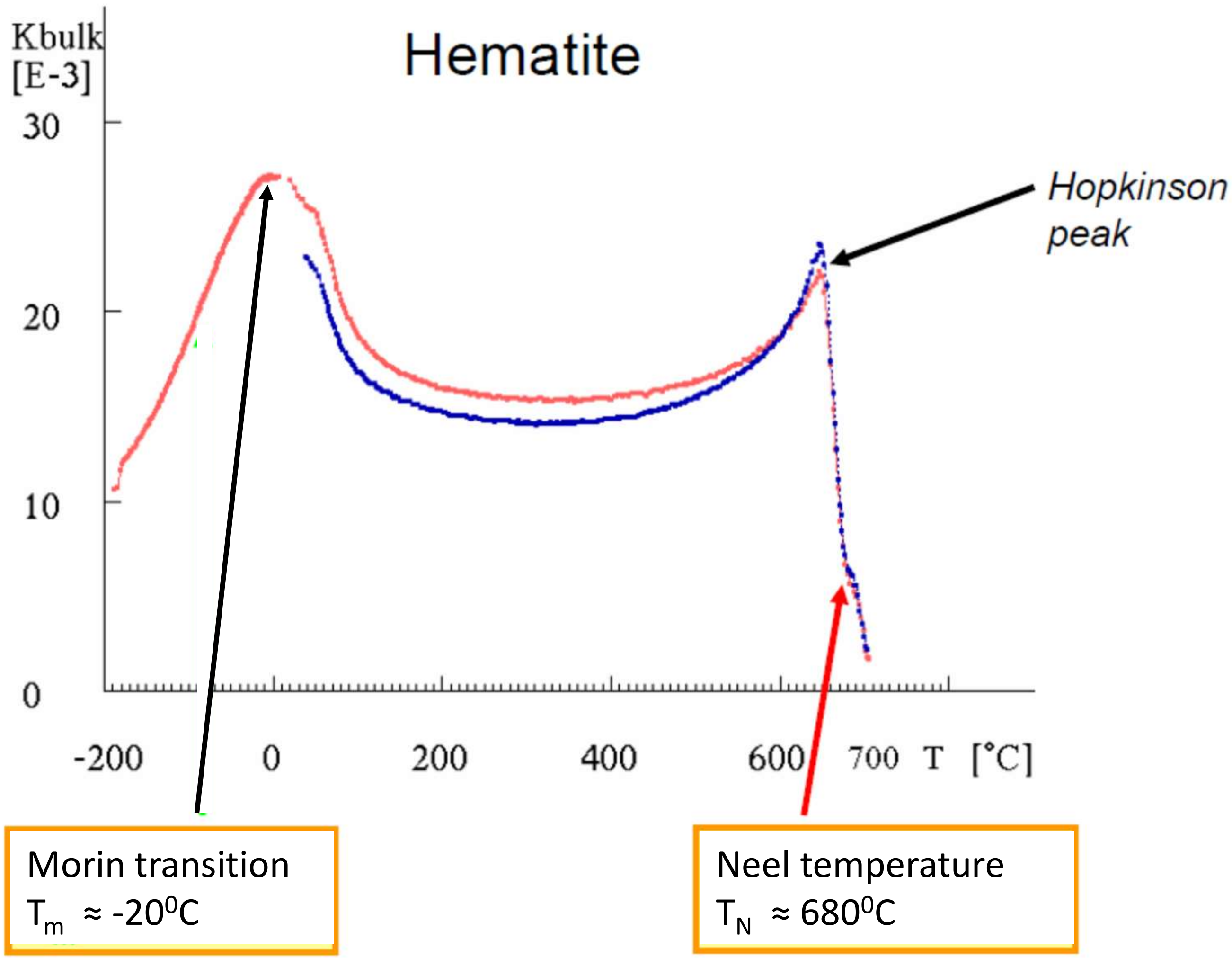


Verwey transition T_v ~ – 150 ℃

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

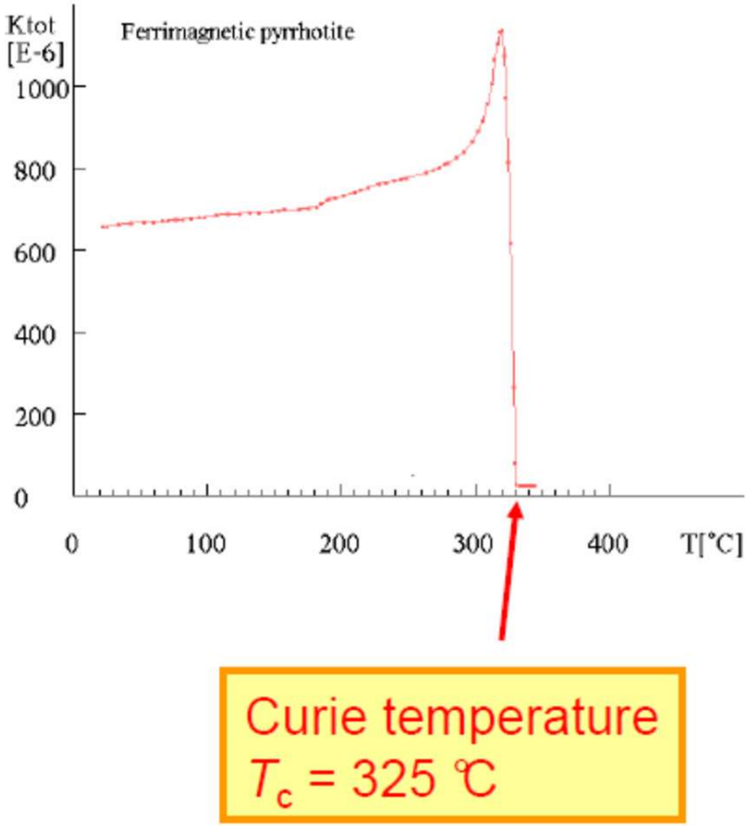
Curie temperature T_c ~ 580 ℃

Transition from ferrimagnetic to paramagnetic state, rapid decrease of susceptibility

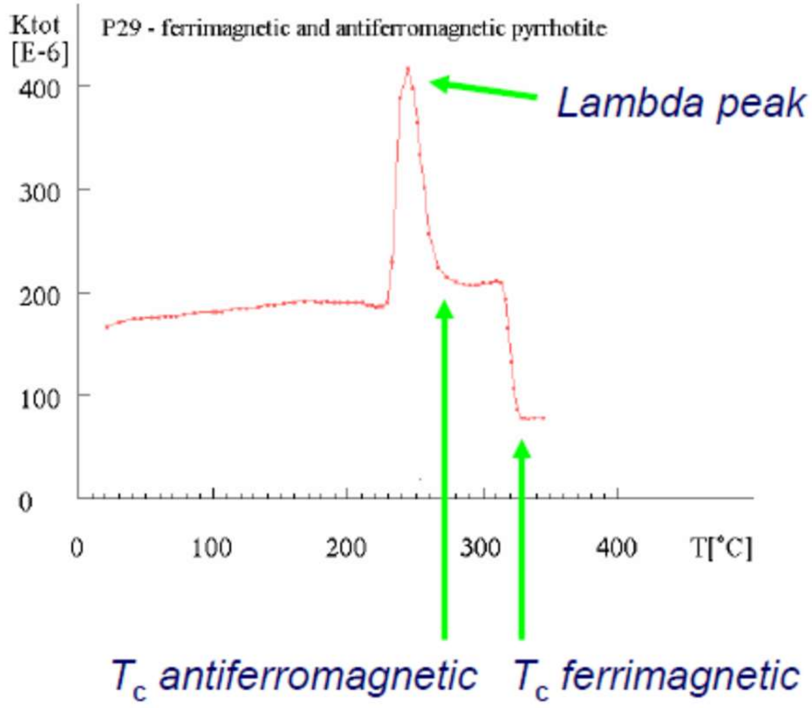

Hematite
Kbulk
[E-3]
30
20
10
0
-200
0
200
400
600
700
T [°C]
Hopkinson
peak
Morin transition
Tm ≈ -20°C
Neel temperature
TN ≈ 680°C

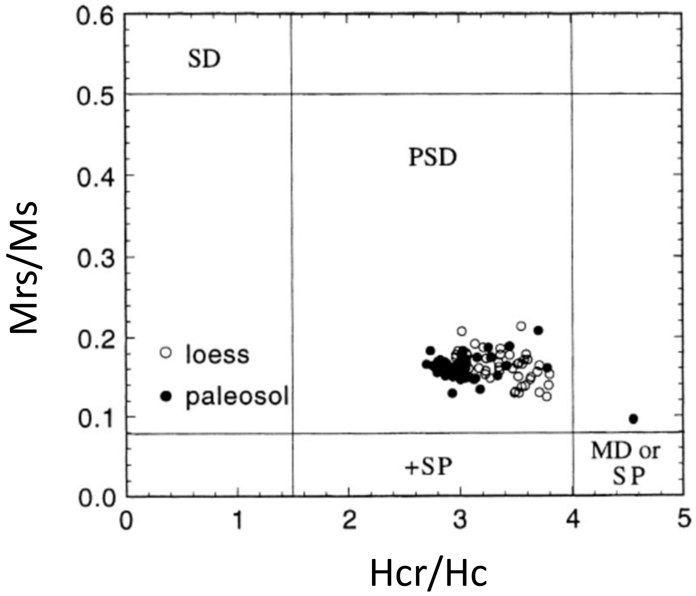
Pyrrhotite

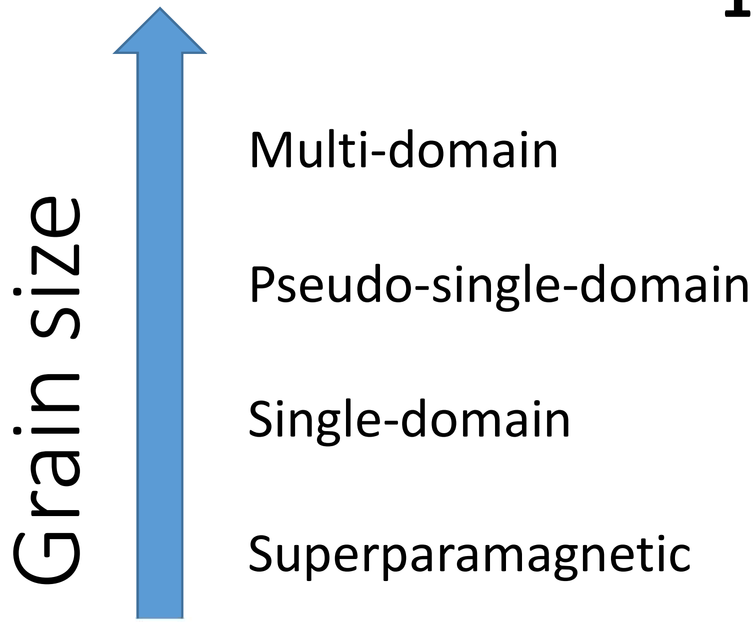
Monoclinic pyrrhotite

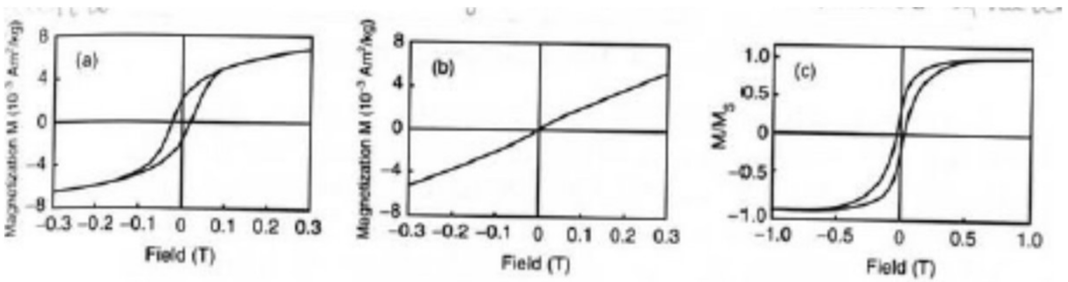


Mixture of monoclinic and hexagonal pyrrhotite





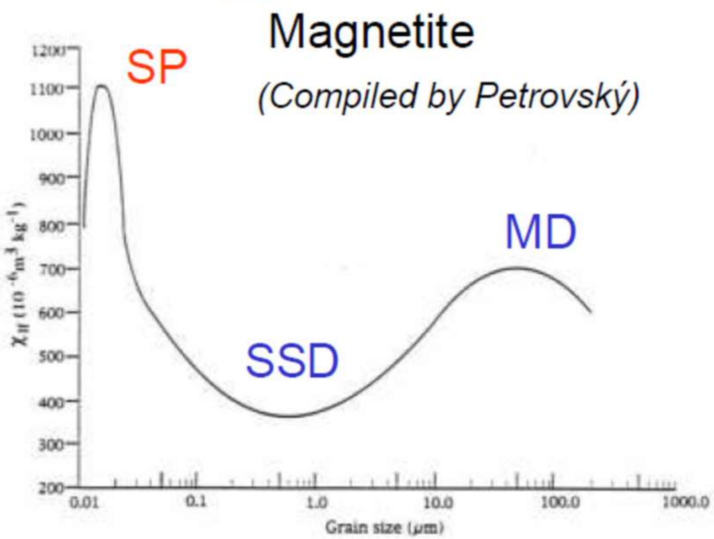




Single-domain magnetite

Coarser grained magnetic particles

Mixture of minerals



Sources of magnetic phases

Phase	Origin Pedogenic	Lithogenic	Anthropogenic
Magnetit	SP, SD	SD, PSD, MD	industrial dust
Maghemite	from Gt, Lp by fires	oxidized Mgt	oxidized Mgt, dust, pottery
Greigite	SP, SD	??	no
Hematite	yes	yes	burning, dust, potttery
Goethite	yes	yes	no
Ti-Mgt, Ti-Mgh	no	yes	pottery

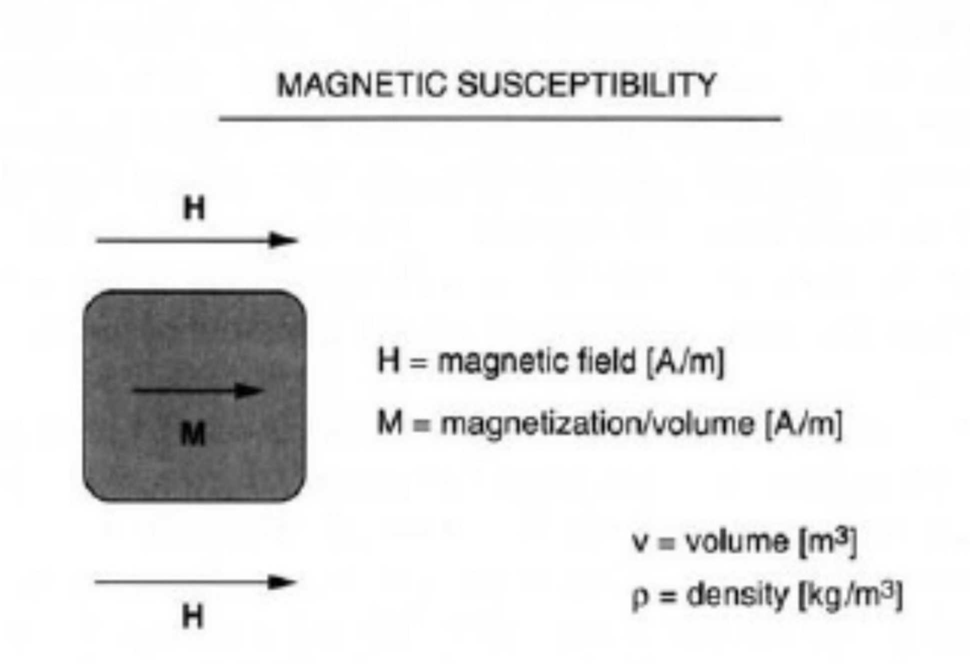
SP Superparamagnetic
SD Single domain
PSD Pseudo-single domain
MD Multi domain

The various environmagnetic parameters and their combinations are generally employed for the purpose of answering three questions:
Composition (i.e., which magnetic minerals are present?)
Concentration (i.e., how much of each one is present?)
Granulometry (i.e., what are the dominant grain size present?)

Parameter	Definition	Measurement units (SI)	Proxy for
Low field magnetic susceptibility (χ or χ_{lf})	$\chi = k/\rho$, where k is volume susceptibility; ρ is bulk density	m^3/kg	Concentration of strongly magnetic Fe oxides (magnetite, maghemite, titanomagnetite)
Frequency dependent magnetic susceptibility χ_{fd}	$\chi_{fd} = \chi_{lf} - \chi_{hf}$, where χ_{lf} and χ_{hf} are susceptibilities, measured at low- and high-frequency field (usually 0.47 and 4.7 kHz)	m^3/kg	Concentration of superparamagnetic strongly magnetic particles (magnetite, maghemite) within the grain size range (10–25 nm)
Percent frequency dependent magnetic susceptibility $\chi_{fd}\%$	$\chi_{fd}\% = 100^* (\chi_{lf} - \chi_{hf})/\chi_{lf}$	%	Relative proportion of the superparamagnetic fraction in the total magnetic susceptibility signal
High-field magnetic susceptibility (χ_{hf})	χ_{hf} is calculated from the high-field portion of the hysteresis loop	m^3/kg	Magnetic susceptibility of the paramagnetic minerals (e.g., clays) and high-coercivity antiferromagnetic Fe oxides (hematite, goethite)
Anhysteretic remanence (ARM)	ARM is acquired in the laboratory through simultaneous application of a weak dc-field (h) and an alternating magnetic field with decreasing amplitude	Am^2/kg	High values indicate higher concentration of magnetically stable single domain (SD) magnetite/maghemite grains
Anhysteretic susceptibility (χ_{arm})	$\chi_{arm} = ARM/h$	m^3/kg	The same as ARM but the dependence on the value of the inducing weak dc field is eliminated

Parameter	Definition	Measurement units (SI)	Proxy for
B_{cr}/B_c	Ratio of coercivity of remanence to coercive force	Dimensionless	Grain size sensitive in case of magnetite like carrier of the remanence. Values up to 3 are typical for SD magnetites, larger values—for PSD and MD grains
T_c (T_N)	Curie (Neel) temperature	Degrees Celsius (°C)	Mineral-specific value, depends only on the type of Fe oxide and the possible presence of substitutions in the crystal lattice. T_c of pure magnetite is 578°C; T_N of hematite—680°C
M_s	Saturation magnetization	Am^2/kg	M_s depends only on the type of Fe oxide and its concentration in the material
B_c	Coercive force	mT	Mineral, grain size and structural dependence
B_{cr}	Coercivity of remanence	mT	Mineral, grain size and structural dependence. For magnetite/maghemite Bc is in the range 20–30mT; for hematite—300–600 mT
M_{rs}/M_s	Ratio of saturation remanence to saturation magnetization	Dimensionless	Grain size sensitive in case of magnetite like carrier of the remanence. Values close to 0.5 are typical for SD magnetites, lower values—for larger PSD and MD grains

Magnetic susceptibility



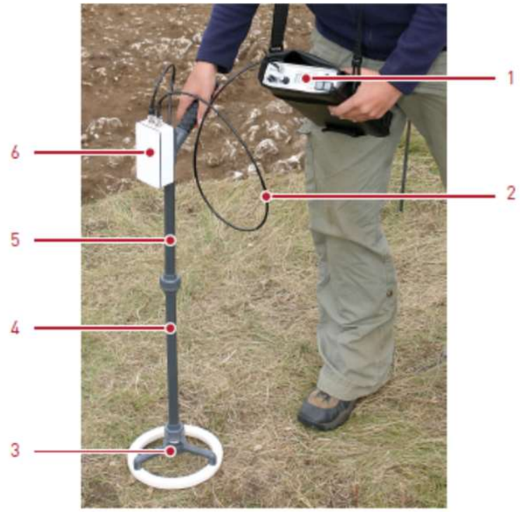
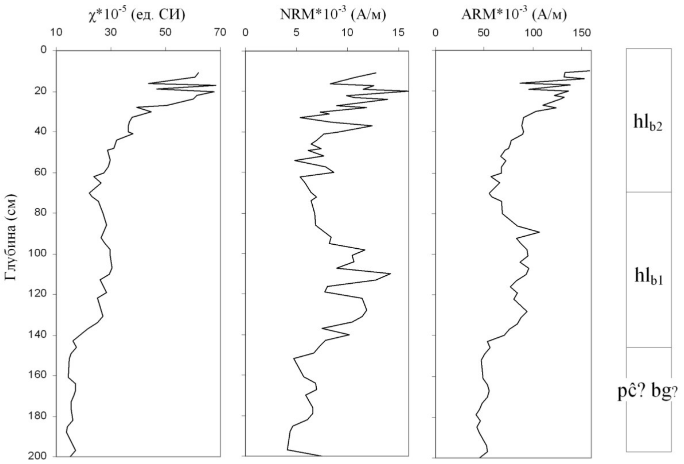


Figure 11. MS2 probe handle for use with probes type MS2D and MS2F

Volume susceptibility k=M/H [SI units] – in situ or on monolithic samples

Mass-specific susceptibility χ=k/ρ [m^3/kg] – on crushed or monolithic samples



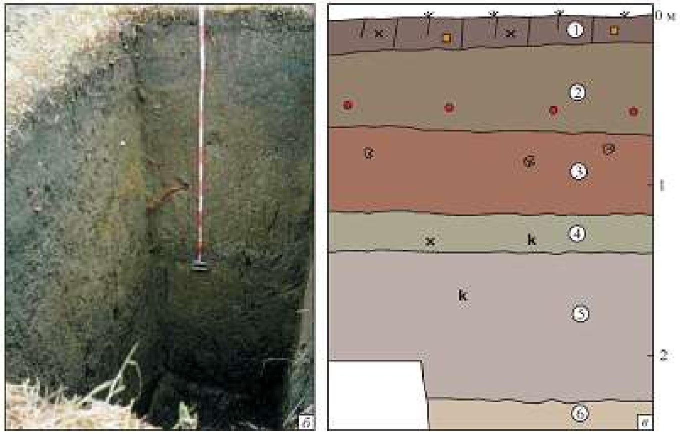
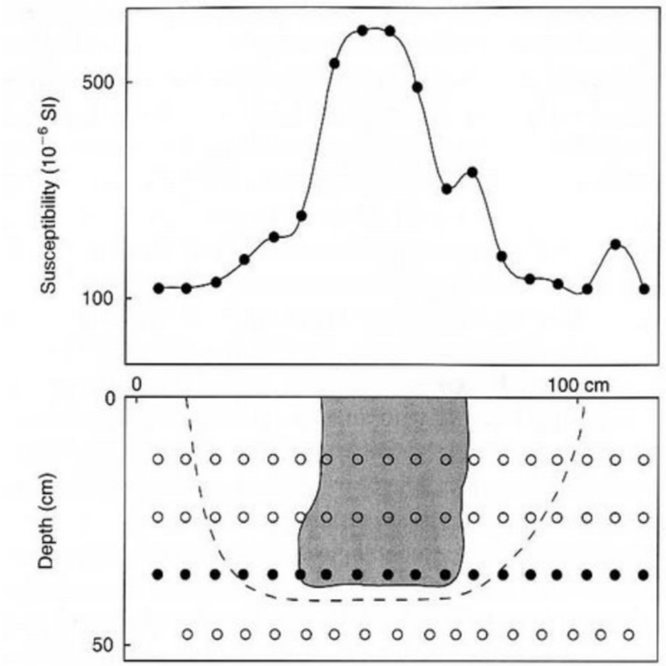
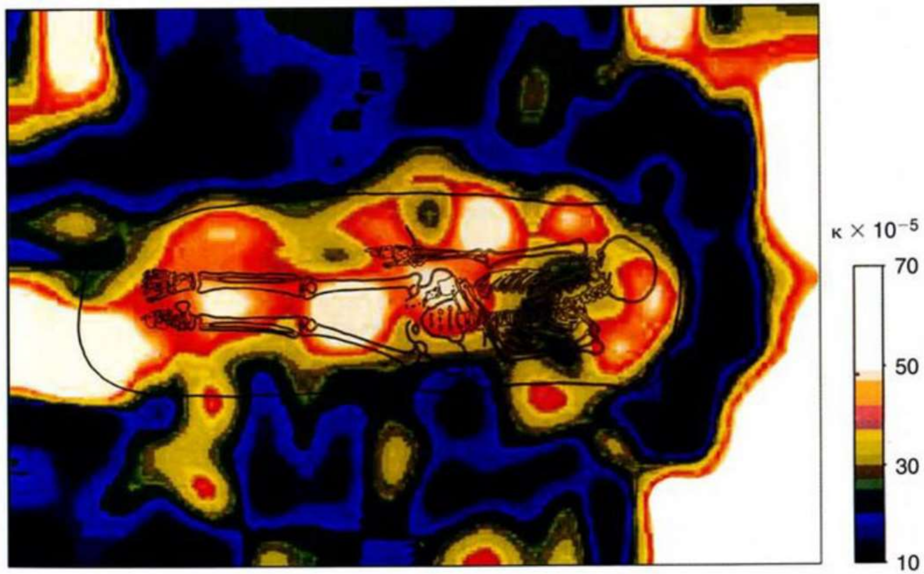


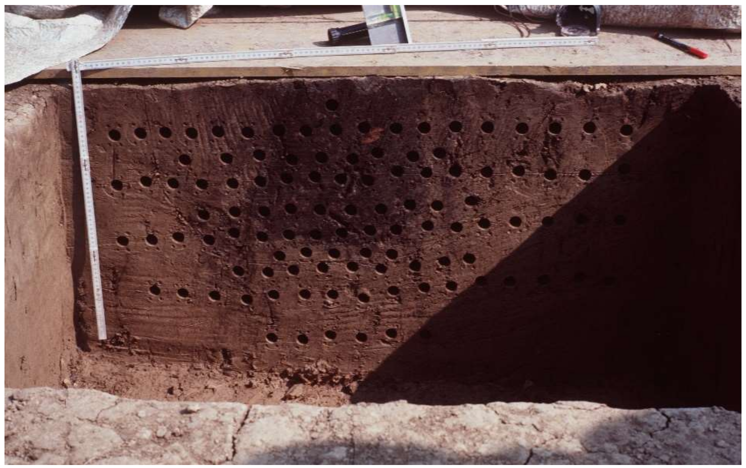
Рис. 152. Місцезнаходження «Утюг» (Бюк-Карасу XIX):

а — схематичний план; *ключ*: *1* — шурф, *2* — рештки млина, *3* — колодязь, *4* — знахідки обробленого кременю, *5* — яблуневі дерева, *6* — ділянки із рештками татарських будівель, *7* — надзаплавні тераси, *8* — безіменний струмок; *б* — вид на шурф після закінчення розкопок; *в* — стратиграфія південно-за-
— стратиграфічний горизонт, 2 — черепашки
— кераміка епохи бронзи, 6 — кістки

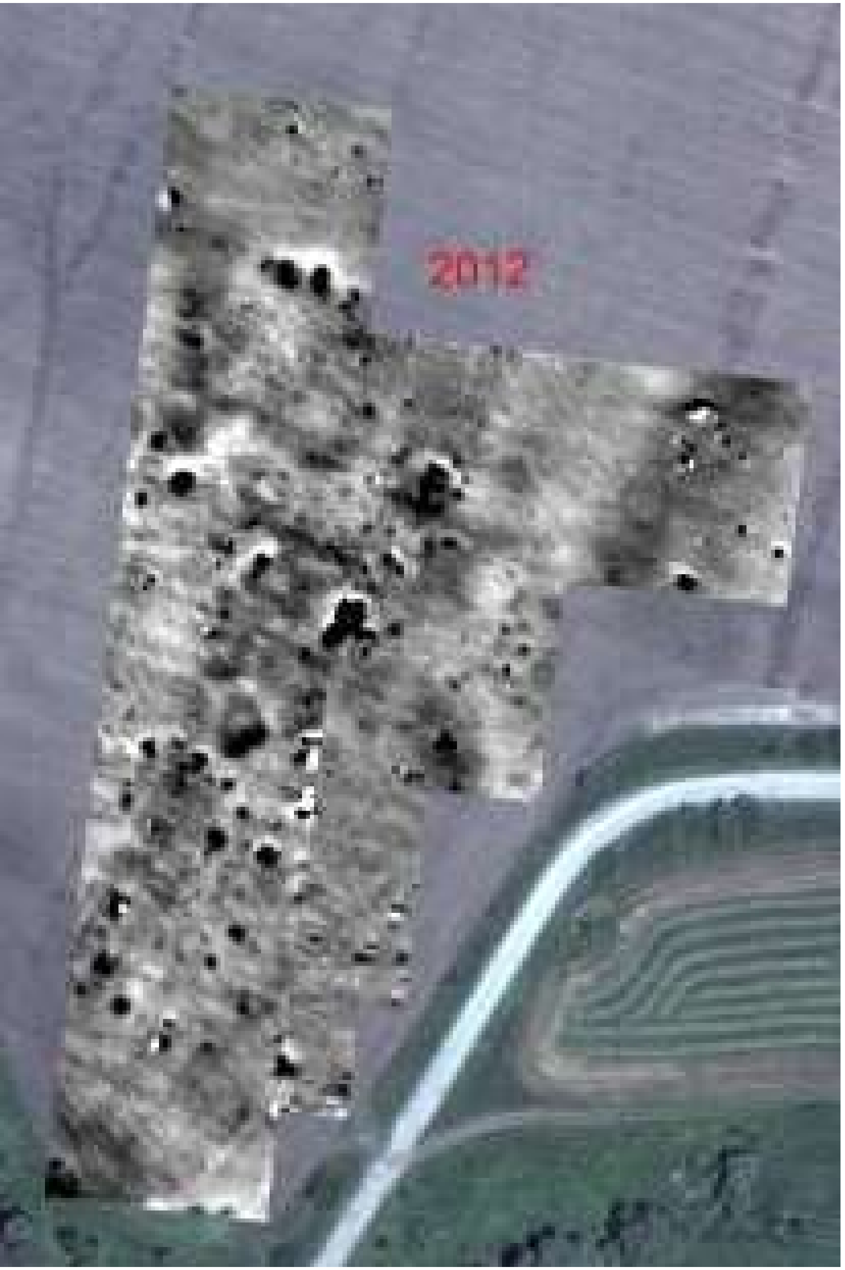




(Linford, 2002)



(Fassbinder & Stanjek, 1993)

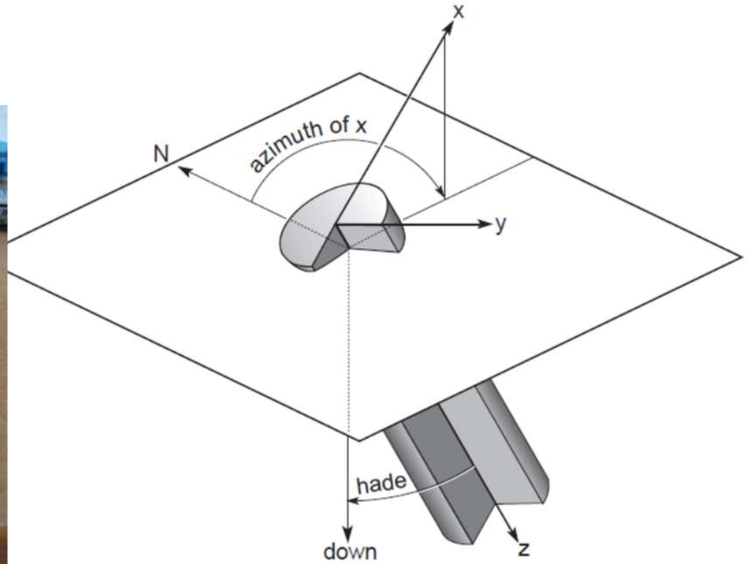


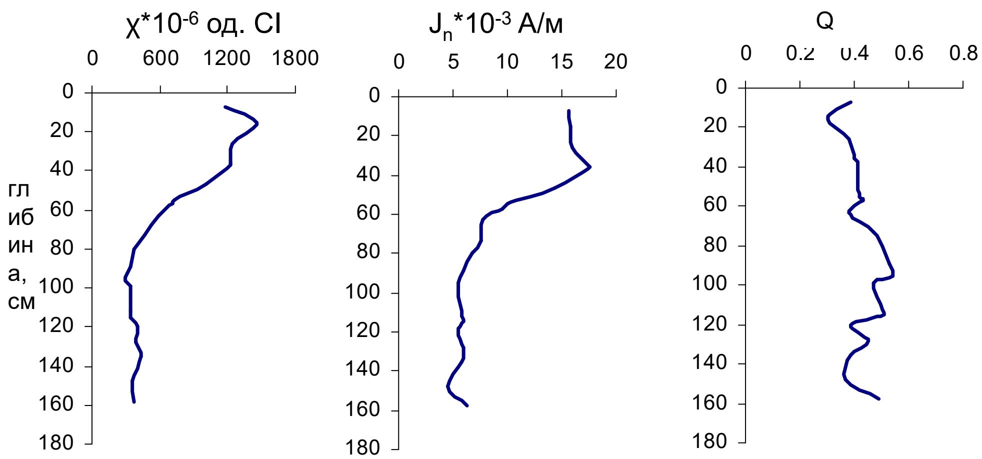
Origin of magnetic anomalies in archaeological sites:

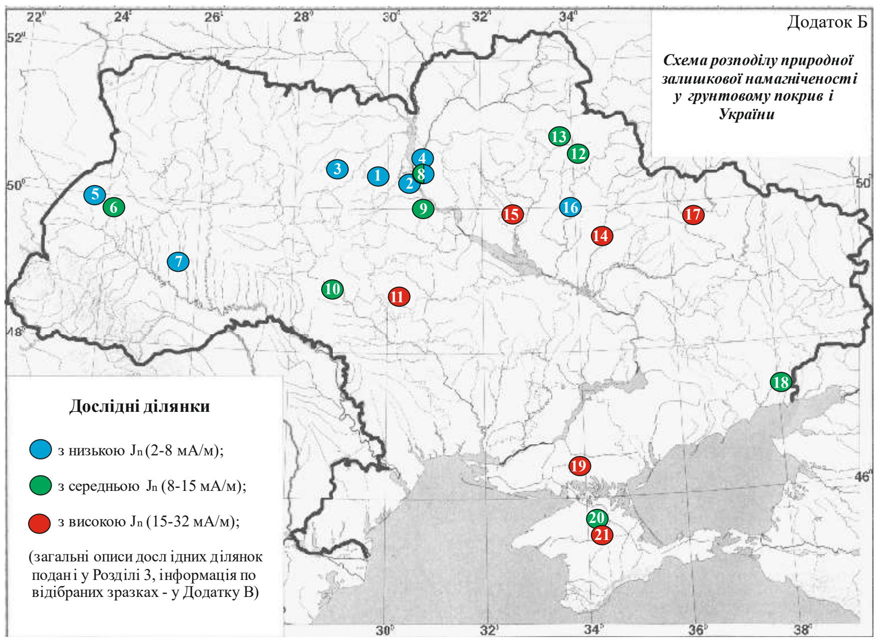
a) enrichment of magnetic minerals
e.g. magnetite and maghemite
in the archaeological structure

b) natural remanent
magnetization NRM
of the sediment (object)
in the archaeological structure

Natural remanent magnetization

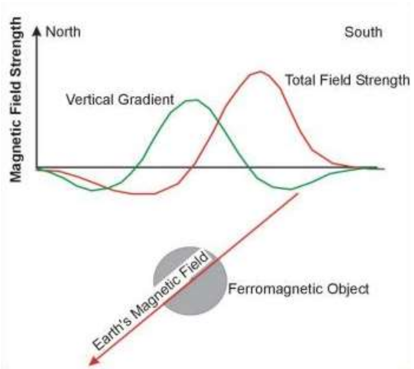


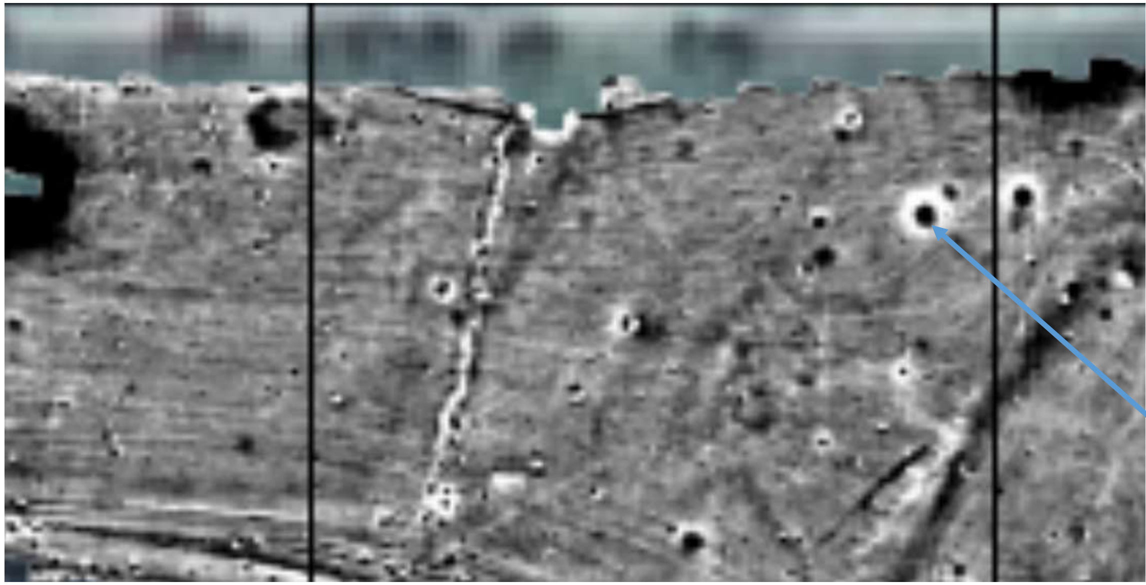


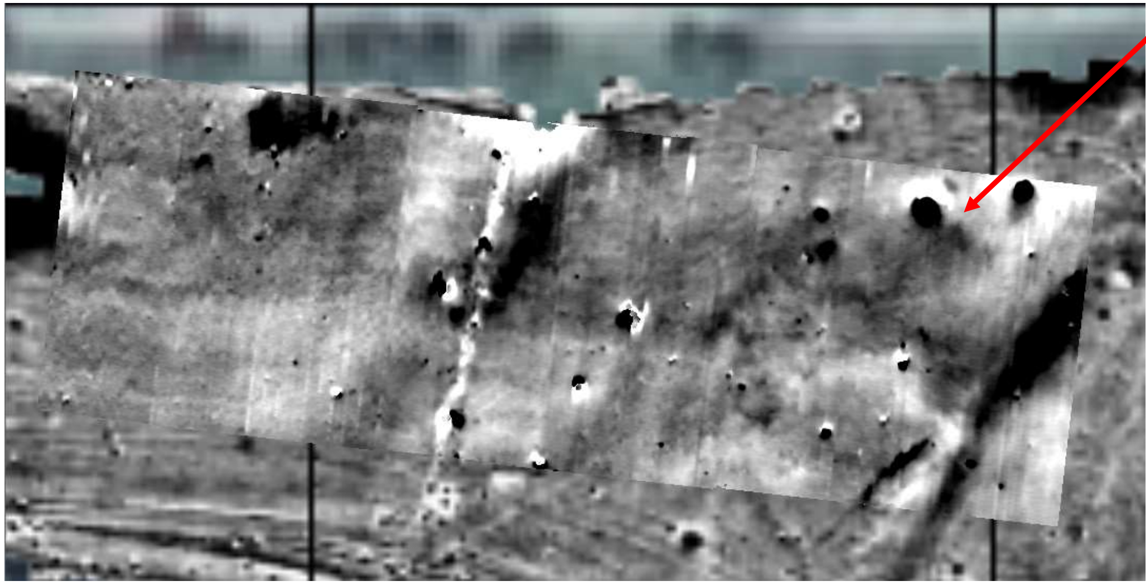


Contribution of NRM into total magnetization of soils in Ukraine

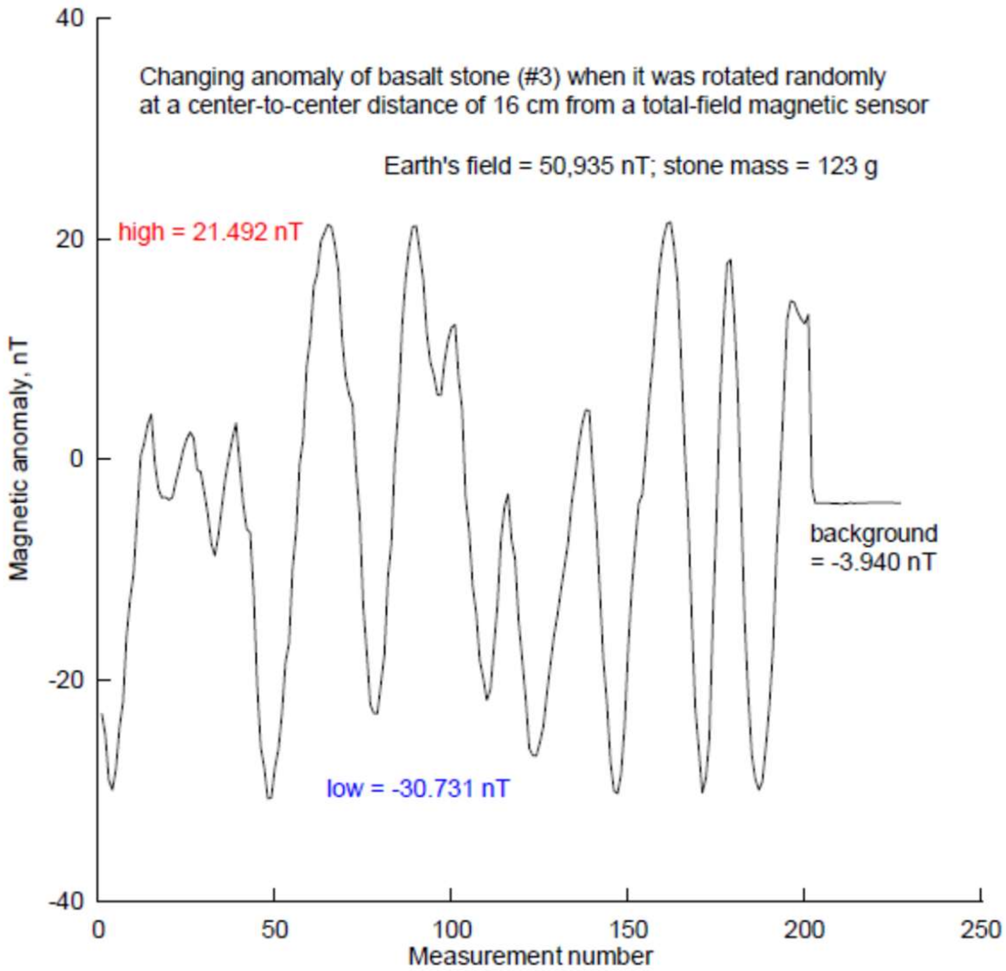
Тип ґрунту	Шифр зразка			Магнітні параметри						
	Об`єкт	Пункт	Глибина, см	J_n*10^-3 А/м	$Q=J_n/J_i$	Кути J_n		$J_{сум}$*10^-3 А/м	Кути $J_{сум}$	
						I	D		I	D
Дерновий	Жуків	1	0-8	9.979	1.04	74.8	31.5	19.93	68.5	13.0
		-"-	10-18	11.254	1.16	73.3	16.8	21.39	67.6	8.6
		2	0-8	8.802	1.05	68.5	26.5	17.55	65.3	13.2
		-"-	10-18	11.506	1.17	67.6	0.94	21.90	64.5	2.2
		3	0-8	14.145	1.2	58.0	343.83	26.55	59.9	352.4
Лучний	Університетський сад	1	0-10	3.94	0.72	70.8	353.7	9.71	65.2	0.2
		6	10	4.85	0.73	52.6	334.5	11.81	58.5	350.0
		-"-	20	2.92	0.53	59.8	329.3	8.72	61.7	351.8
		-"-	30	3.83	0.69	74.7	33.6	9.59	67.1	11.1
		7	10	5.47	0.82	79.7	17.9	12.37	69.4	6.5
Дерново-підзолистий		29	20	17.07	1.43	81.2	353.5	29.31	72.8	0.4
		-"-	30	18.12	1.63	68.6	13.6	29.87	65.8	8.8
		38	10	12.14	0.78	54.2	343.5	28.41	58.6	354.0
		-"-	20	9.64	0.59	53.9	344.4	26.83	58.9	355.7
		39	10	6.71	0.73	75.8	328.7	16.22	67.9	354.5
Сірий лісовий	Умань	1	0-5	8.22	0.54	60.5	351.4	24.41	61.1	359.2
		-"-	0-5	11.11	1.06	60.5	339.3	22.08	61.4	351.1
		2	0-5	11.32	0.55	53.8	14.4	33.06	58.8	7.6
		-"-	0-5	12.51	0.74	59.4	18.8	30.49	60.7	9.8
		4	0-5	11.65	0.35	70.2	27.6	46.67	63.8	7.8
Чорнозем типовий	Халеп`є	1	10	17.55	0.75	77.6	328.7	41.83	68.6	355.2
		-"-	20	15.00	0.61	68.6	22.2	40.79	64.2	9.0
		-"-	30	17.43	0.75	65.0	28.4	41.94	63.3	12.8
		5	16-21	5.74	0.48	63.3	334.3	18.21	62.5	354.7
		-"-	22-27	13.12	0.75	58.0	333.1	31.55	60.7	350.2
Чорнозем звичайний	Вовчий Яр	1(11)	0-5	26.63	0.56	66.9	353.1	77.40	63.2	0.23
		1(12)	-"-	25.08	0.57	65.8	349.8	72.06	62.9	359.08
		1(13)	-"-	17.36	0.47	68.5	344.3	56.47	63.7	358.54
		1(14)	-"-	23.05	0.50	67.9	350.3	71.56	63.5	359.78
		1(15)	-"-	25.16	0.51	61.6	1.8	77.38	61.4	2.81
Темно-каштановийй	Асканія-Нова	3	28-33	15.24	0.28	81.0	320.2	72.40	65.7	0.1
		-"-	20-25	32.02	0.57	61.5	344.4	91.18	61.6	356.7
		-"-	44-49	18.54	0.41	68.1	353.9	66.17	63.2	1.1
		4	0-4	34.01	0.77	67.1	0.4	81.03	63.7	2.2
		-"-	6-10	19.99	0.44	74.8	337.2	67.73	65.5	358.6


Magnetic Field Strength
North
South
Total Field Strength
Vertical Gradient
Earth's Magnetic Field
Ferromagnetic Object






reference sensor
measuring sensor
sample in sphere
control unit
battery


Changing anomaly of basalt stone (#3) when it was rotated randomly at a center-to-center distance of 16 cm from a total-field magnetic sensor
Earth's field = 50,935 nT; stone mass = 123 g
high = 21.492 nT
low = -30.731 nT
background = -3.940 nT
Magnetic anomaly, nT
Measurement number
40
20
0
-20
-40
0
50
100
150
200
250

(Bewan, 2016)

Forward magnetic models

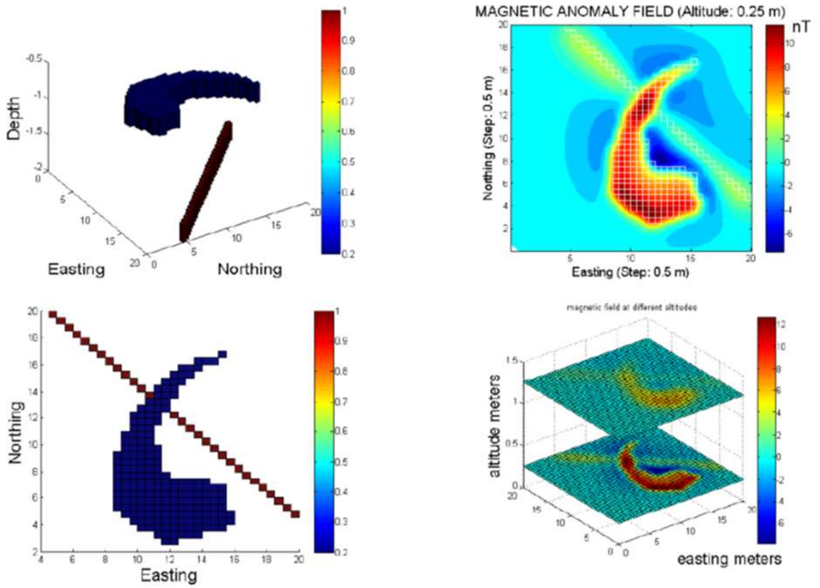
A forward magnetic model is created in order to calculate the magnetic map of an actual or assumed object.

This calculation may have several benefits:

1: Predict whether a feature might be detectable with a magnetic survey.

2: Verify if a feature found in an excavation caused the anomaly that was measured.

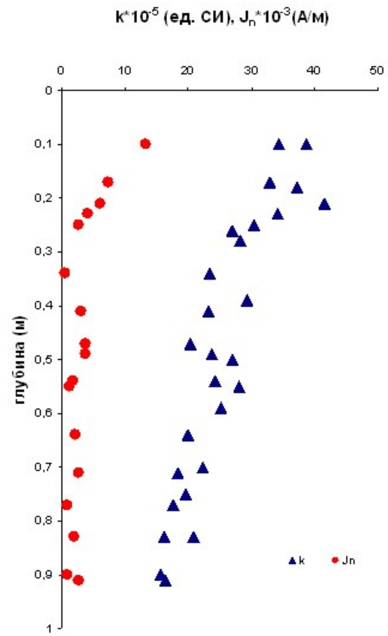
3: Discriminate the relative effects of different parts of a feature.

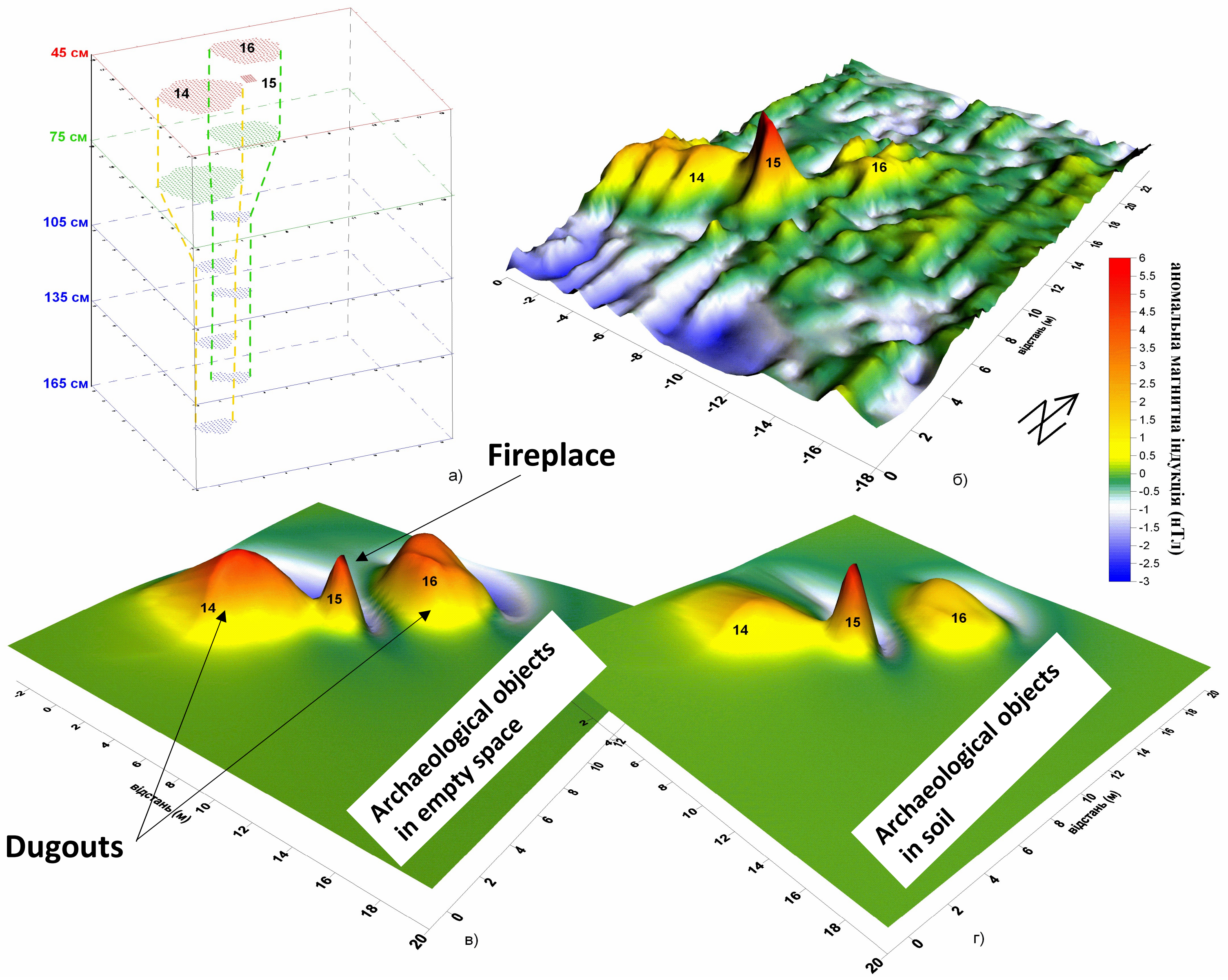


Magnetic properties needed for the forward modelling of magnetic anomalies in archaeological sites

M=Mi+**NRM**

Mi=**κ**H




45 см
75 см
105 см
135 см
165 см
14
15
16
а)
б)
в)
г)
відстань (м)
аномальна магнитна індукція (нТл)
Fireplace
Dugouts
Archaeological objects in empty space
Archaeological objects in soil

Various aspects and possibilities for application of soil and mineral magnetism in archeology open many new opportunities for reinforcement of multidisciplinary approach in archaeological investigations and for obtaining new and probably underestimated information that can give clues for unexpected valuable knowledge (Jordanova, 2016)