Examination of the environmental impact of UXO and weapon residues detected using drone-based and ground-based magnetometer surveys and quantified with laboratory magnetic and geochemical methods

Kseniia Bondar

Dr. Sci. (Geophysics), Assistant Professor

Department of Magnetism

Institute of Geophysics Polish Academy of Sciences
ul. Księcia Janusza 64, 01-452 Warsaw, Poland
e-mail: kbondar@igf.edu.pl, phone (office): +48 22 6915 773

KYIV | May 2024

Specialization

NEAR-SURFACE GEOPHYSICS, SOIL MAGNETISM, ENVIRONMENTAL MAGNETISM, GEOPHYSICAL PROSPECTION IN ARCHAEOLOGY,

Education

SPECIALIST (GEOPHYSICS), 2001, TARAS SHEVCHENKO NATIONAL UNIVERSITY OF KYIV

CANDIDATE OF GEOLOGICAL SCIENCE, 2004, TARAS SHEVCHENKO NATIONAL UNIVERSITY OF KYIV

DOCTOR OF GEOLOGICAL SCIENCES, 2022, TARAS SHEVCHENKO NATIONAL UNIVERSITY OF KYIV

MBA IN MANAGEMENT OF RESEARCH INFRACTRUCTURES, 2024, UNIVERSITY OF MILANO-BICOCCA

Career/Employment

2004-2022 – JUNIOR TO SENIOR RESEARCHER IN THE LABORATORY OF THEORETICAL AND APPLIED GEOPHYSICS, ESI "INSTITUTE OF GEOLOGY", TARAS SHEVCHENKO NATIONAL UNIVERSITY OF KYIV

Since October 2023 – ASSISTANT PROFESSOR, DEPARTMENT OF MAGNETISM, INSTITUTE OF GEOPHYSICS PAS (WARSAW, POLAND)

- Kseniia Bondar
- Institute of Geophysics of Polish Academy of Sciences

Quantifying magnetic properties of soils to evaluate sustainable hazards from heavy metal pollution due to military activities in Ukraine (USA-PAN)

Volodymyr Bakhmutov

Dr. habil.

Institute of Geophysics of the NAS of Ukraine

Oleksandr Menshov

Dr. habil.

Taras Shevchenko National University of Kyiv

Ievhen Poliachenko

PhD

Institute of Geophysics of the NAS of Ukraine

Dmytro Hlavatskyi

PhD

Institute of Geophysics of the NAS of Ukraine

Principal Investigator

- Kseniia Bondar
- Institute of Geophysics of Polish Academy of Sciences

USA-PAN
Quantifying magnetic properties of soils to evaluate sustainable hazards from heavy metal pollution due to military activities in Ukraine
Kseniia Bondar
Volodymyr Bakhmutov
Ievhen Poliachenko
Dmytro Hlavatskyi
Olexandr Menshov

NATO SPS
MinesEye –
UXO (unexploded ordnance) identification and classification in de occupied territories of Ukraine

Volodymyr Bakhmutov – Partner Country Director
Institute of Geophysics NASU

- **magnetometer surveys**
- magnetic susceptibility mapping
- soil sampling
- laboratory magnetic and geochemical measurements

Eurizone Fellowship Programme
Development and implementation of multitask magnetometer survey methodology

Sergyi Popov - PI
Taras Shevchenko National University of Kyiv

Institute of Environmental Engineering and Biotechnology of Opole University (Opole, Poland)
Microbial biodegradation of weapon residue with the purpose to monitor the process of transformation and accumulation of iron oxides and toxic heavy metals in soil.

Olexandr Tashyrev - PI

Map of Ukrainian territories affected by the war (https://mine.dsns.gov.ua/),

The project is focused on quantitative assessment of soil pollution with HMs due military-related activities through in-situ and laboratory measurements of soil magnetic properties and establishing their links with HM contents.

Main goals to achieve :

- **elaborate novel strategy for the assessment of military-related soil pollution, based on a combination of magnetic and geochemical methods;**
- **quantify iron and heavy metals emissions deposited in the topsoil**
- **assess by geoinformation modelling of spatial distribution of heavy metals associated with weapon residues and small size particulate matter**

Sustainability **2020**, 12, 9002; doi:10.3390/su12219002

Table 3. Concentrations of common PTEs (mg kg^{-1}) in military-impacted soils in reviewed studies conducted on military base areas (MBA) and war-impacted areas (WIA).

Reference	Site	Activity	Soil pH	Ag	As	Ba	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Sb	Ti	V	Zn	Zr
[9]	Bosnia Herzegovina	MBA	9.2–9.9	-	-	-	0.8–6.1	-	-	23.6–443	-	-	40.4–73.6	27.7–40.9	-	-	-	91.7–238	-
[69]	Switzerland	MBA	6.1–8.2	-	-	-	-	-	-	63–66	-	480–860	55–61	500–620	17–21	-	-	100–110	-
[21]	Korea	MBA	6–6.8	-	-	-	7.45–8.11	-	-	318–562	-	-	- *	3918–18,609	26–108	-	-	104–123	-
[17]	Norway	MBA	4.8–6.5	-	-	-	-	-	-	41–88	-	-	-	356–1112	40–123	-	-	-	-
[19]	Spain	MBA	3.72–6.75	-	-	-	-	-	40–79	19–98	-	-	11–33	55–6309	-	-	-	34–264	-
[29]	Korea	MBA	8	-	-	-	-	-	-	1168	-	-	-	17,468	164	-	-	-	-
[28]	Czech Republic	MBA	5.6–7.7	-	5.33	-	0.235	3.81	18.4	6.91	-	-	10.7	15.5	3.33	-	-	34.3	-
[27]	Canada	MBA	-	-	-	-	-	-	-	245	-	-	-	3368	73	-	-	177	-
[65]	U.S.	MBA	4.9	-	2.47–2.67	-	-	-	36.27–38.4	65.67–118.77	-	91.57–107.33	33.777–57.33	17.85–19.30	0.08–0.12	-	-	54.8–58.27	-
[26]	Canada	MBA	5.9–8.1	-	-	-	-	-	-	1760	-	-	-	43,300	780	-	-	355	-
[68]	Australia	MBA	5.3–6.4	-	0.25–9.55	-	-	-	-	0.43–1250	-	-	0.48–8.97	1.18–10,403	1–252	-	-	0.99–179	-
[67]	U.S.	MBA	6.11–6.72	-	-	-	-	-	-	-	-	-	-	10,068–70,350	-	-	-	-	-
[66]	Canada	MBA	-	-	-	-	-	-	-	1830–7720	-	-	-	14,400–27,100	150–570	-	-	260–1080	-
[63]	U.S.	MBA	4.4–8.19	-	2.8–27.9	-	-	-	-	223–2936	-	83–930	3–33	4549–24,484	7–91	-	-	102–284	-
[13]	Canada	MBA	-	-	0.8–10	24.2–75	0.1–15.2	-	4–24.1	2.5–154	-	-	3–21	5–53.8	-	-	6.9–35.5	11.9–120	-
[6]	Korea	MBA	-	-	-	-	0.0735–0.22	-	-	3.12- 83	-	-	-	3.48–16.9	-	-	-	-	-
[15]	Switzerland	MBA	3.2–3.6	-	-	-	-	-	-	32–552.3	-	-	21.3–114.7	429–80,935	6.2–4022.4	-	-	60.3–128.3	-
[64]	Iran (Iran-Iraq War, 1980–1988)	WIA	8	-	3.9	93	-	13	156	40	2.25	443	110	36	8	3000	63	4420	100
[24]	Spain (WWII, 1939–1945)	WIA	-	1.4–42	-	-	15–23	-	60–115	1403–11,860	0.142–0.624	960–2492	19–96	1555–2000	-	-	-	2805–9019	-
[7]	Poland (WWI, 1914–1918; WWII, 1939–1945)	WIA	5.3–5.9	-	-	-	-	-	-	-	0.4162	-	-	-	-	-	-	-	-
[22]	Croatia, (War of Independence, 1991–1995)	WIA	4.8–7.2	-	-	-	0.13	-	32	13	0.07	506	19	17	-	-	-	53	-
[70]	France (WWI, 1914–1918)	WIA	5.3–5.9	-	1937–72,820	-	-	-	-	1451–9113	-	-	-	968–5777	-	-	-	10,660–90,190	-
[16]	Belgium, (WWI, 1914–1918)	WIA	-	-	-	-	-	-	-	23.3	-	-	-	47.6	-	-	-	-	-
[20]	Belgium (WWI, 1914–1918)	WIA	-	-	-	-	-	-	-	26.9	-	-	-	-	-	-	-	-	-
[23]	France (WWI, 1914–1918)	WIA	4.4–5.8	-	59–136,770	-	-	5–7	22–39	20–15,755	-	99–840	8–17	766–26,398	-	-	-	399–133,237	-

* -: Not available.

Sources of PTE (in particular, HM) in soils of regions affected by war

- UXO
- Weapon residues
- Small size particulate matter

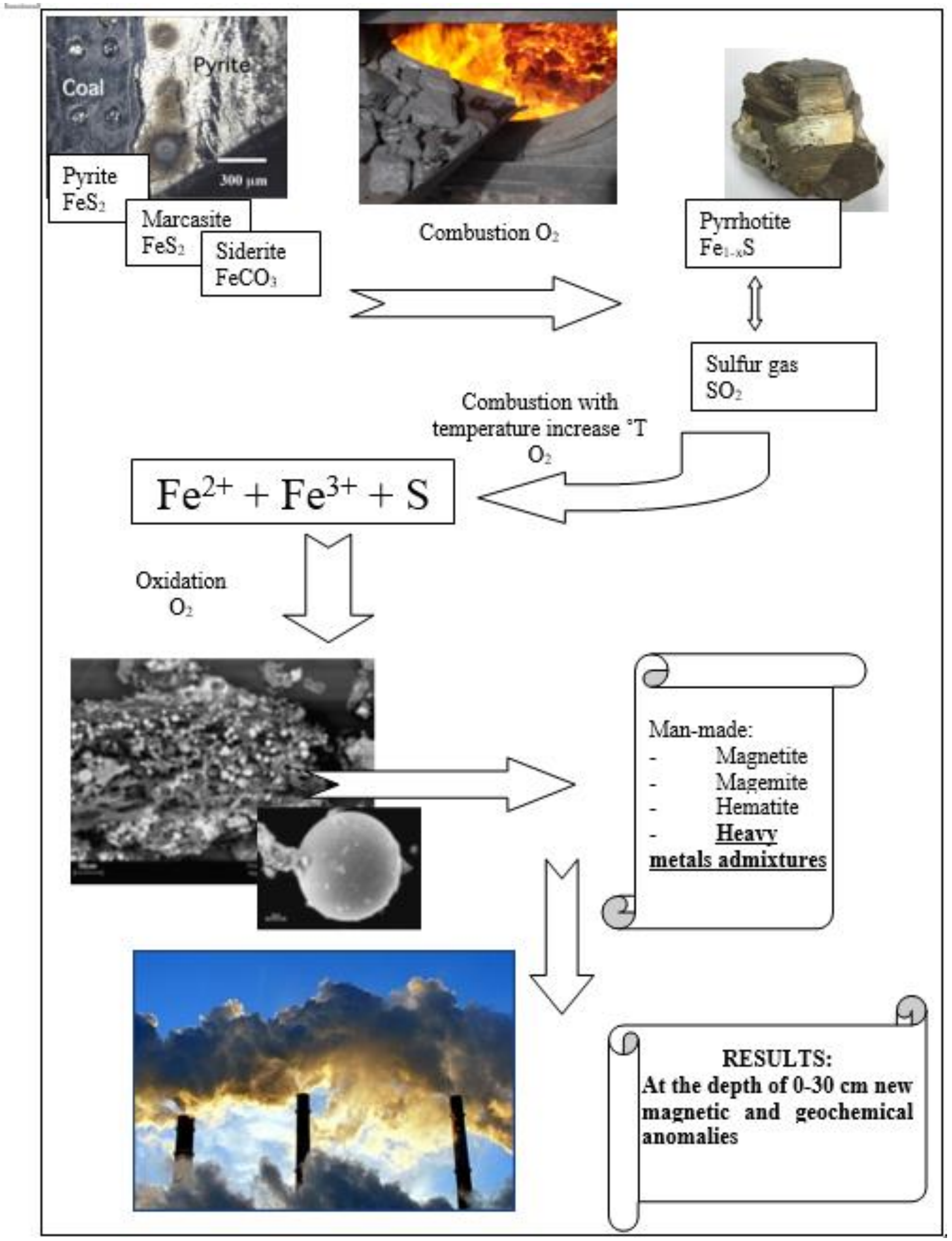
We propose to use the magnetic method as a tool for quantification of soil pollution with military-related HM emissions

Industry

Road traffic

Coal burning

WAR



Methodology

Field measurements

- high-resolution magnetometer survey
- magnetic susceptibility mapping

Sampling of soils, tree bark, collecting aerosol on air filters

Laboratory magnetic studies →

Elemental analysis and microscopy

- XRF
- ICP
- SEM-EDS observations

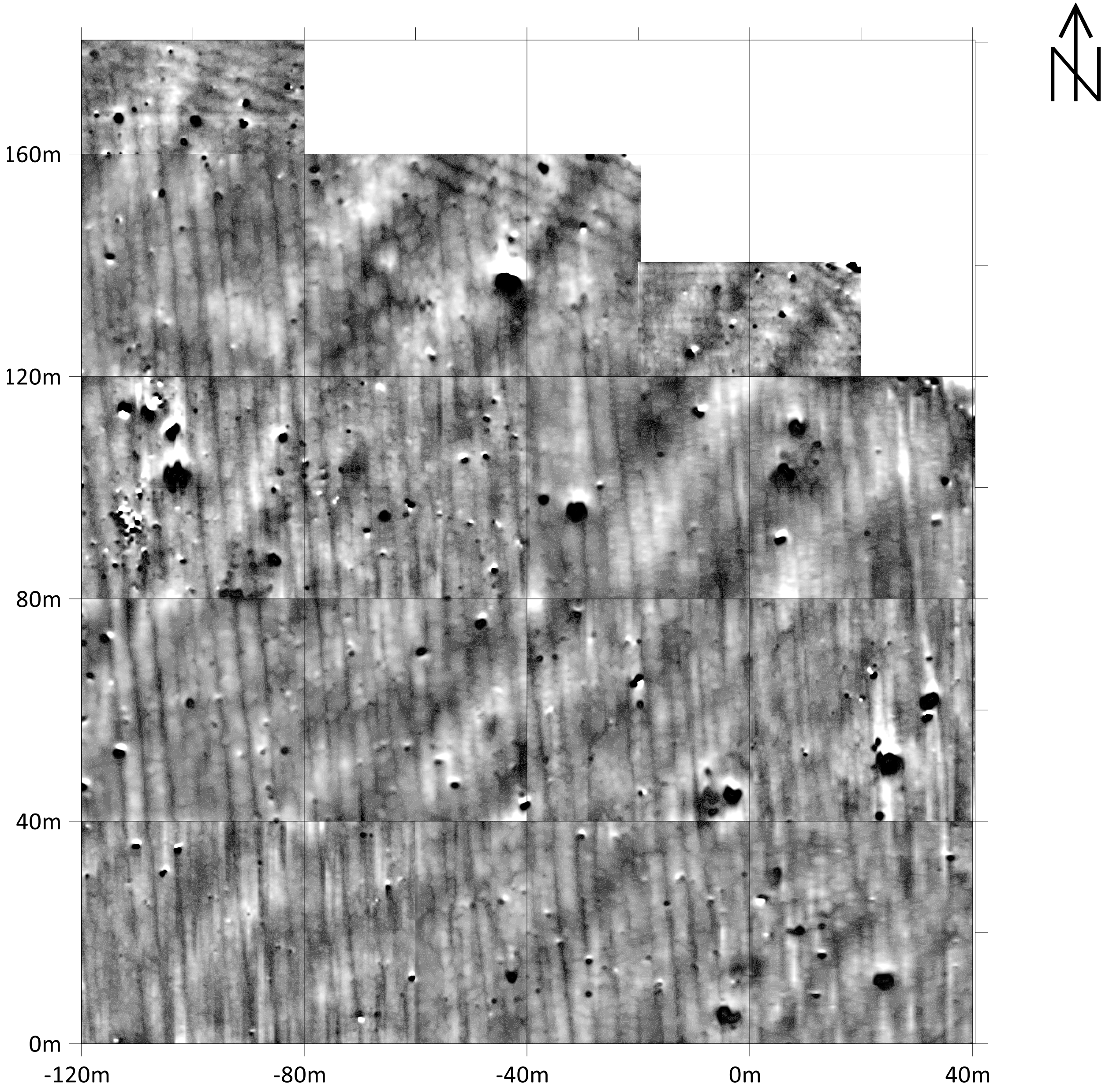
Multivariate statistical analyses

Geoinformation modelling

Rock magnetic parameters and their bivariate ratios

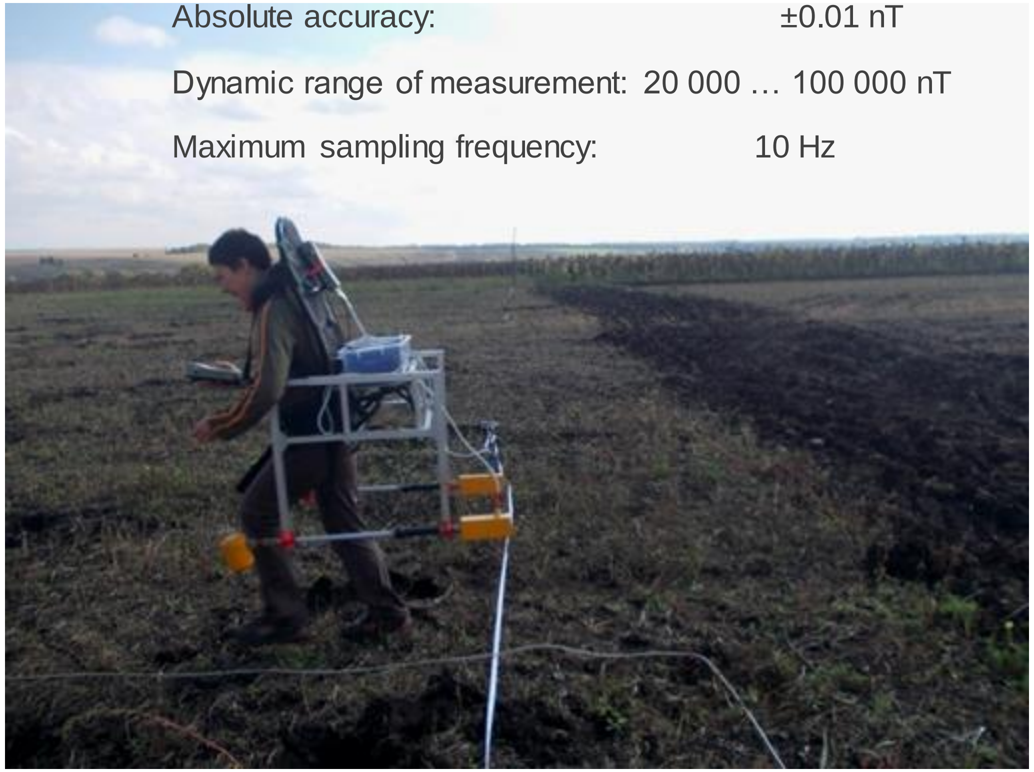
Magnetic parameters	**Symbol**	**Magnetic quantities**	**Description**
Group 1. Concentration-dependent parameters - represent the concentration of magnetic minerals	κ	10^{-6} SI	Volume magnetic susceptibility (dimensionless)
	χ_{lf}	m^3/kg	Mass-specific magnetic susceptibility measured in low frequency
	χ_{hf}	m^3/kg	Mass-specific magnetic susceptibility measured in high frequency
	χ_{ferri}	m^3/kg	Ferrimagnetic susceptibility
	M_s or J_s	Am^2/kg	Saturation magnetization (mass normalized)
	M_{rs} or J_{rs}	Am^2/kg	Saturation remanent magnetization (SIRM)
	M_i or J_i	Am^2/kg	Isothermal remanent magnetization (IRM)
	M_{ri} or J_{ri}	Am^2/kg	Anhysteretic remanent magnetization (ARM): subject to a small amount of single domain particles
	M_n or J_n	mA/m	Natural remanent magnetization (NRM): subject to the constant composition of the magnetic fraction
Group 2. Magnetic-mineralogical parameters – represent the composition of the magnetic fraction (relative content in the magnetic fraction)	Q-ratio	–	Koenigsberger ratio
	S-ratio	–	Relative amounts of high coercivity ("hard", like magnetite/maghemite) to low coercivity ("soft", like goethite/hematite) remanence
	H_s	mT	Saturation field or field, in which 90% of the saturation magnetization is acquired
	B_c or H_c	mT	Coercive force
	B_{cr} or H_{cr}	mT	Remanence coercivity
	Curie temperatures T_c (by χ (T), M_s (T)); unblocking temperatures T_{ub}, (by SIRM (T), NRM (T)); median destructive AF field MDF (by AF demagnetization of remanent magnetization NRM, SIRM, ARM), residual magnetization after maximum demagnetization M/M_{max}; hard isothermal remanent magnetization HIRM		
Group 3. Granulometric paerameters –particle size of magnetic minerals and the associated domain state of ferromagnetic (structurally sensitive)	$FD_{\%}$	%	Frequency-dependent factor; $FD_{\%} = 100 \cdot (\chi_{lf} - \chi_{hf})/\chi_{lf}$
	M_{ri} or J_{ri}	Am^2/kg	Anhysteretic remanent magnetization (ARM): subject to a small amount of single domain particles
	Ratios χ/SIRM, χ/ARM, SIRM/ARM (proportional to the grain size); bivariate plots of hysteresis parameters M_{rs}/M_s, B_{cr}/B_c		

Using magnetometer survey for detecting explosion craters, iron debris clusters and hit sites



Technical characteristics of magnetometer PKM-1

Sensitivity - not less than:	±0.001 nT
Absolute accuracy:	±0.01 nT
Dynamic range of measurement:	20 000 … 100 000 nT
Maximum sampling frequency:	10 Hz



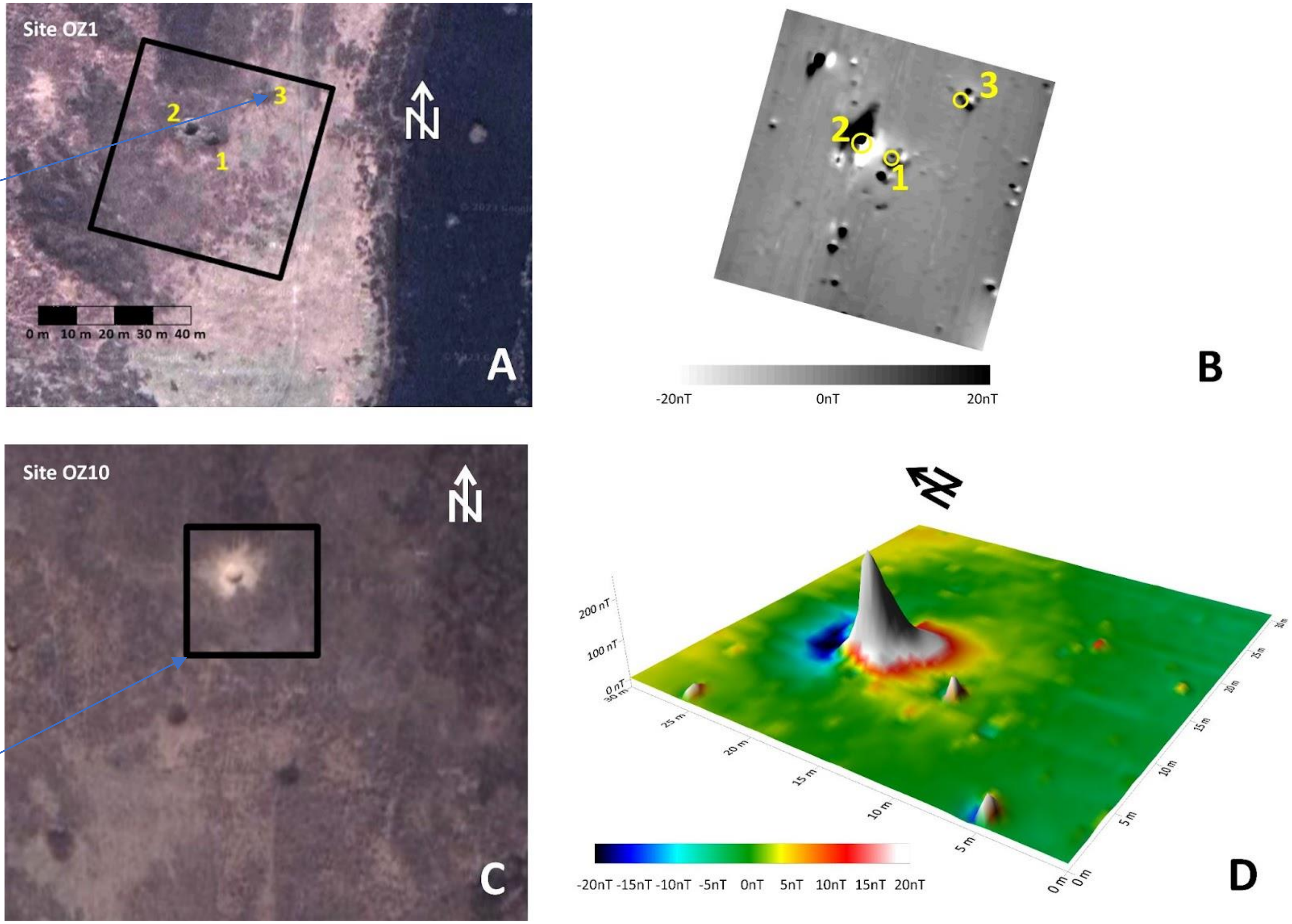
The instrument is switched to 10 measurements per second, which gave a spatial resolution of about 10 cm on the line.

In that mode, the magnetometer has an accuracy of +/-0.01nT.

A traverse interval is usually chosen with 0.5 m or 1 m.

Distance triggering is made manually every line (0.5 or 1 m), using start and stop buttons on the controller.

Using **magnetometer survey** for detecting explosion craters, iron debris clusters and hit sites



Battlefield of spring 2022 near Kyiv: (a) satellite image of the OZ1 site, impact craters are marked with yellow; (b) results of the magnetometer survey in greyscale; (c) satellite image of the OZ10 site; (d) 3D representation of magnetic map of OZ10 site.

Eurizone Fellowship Programme
Development and implementation of multitask magnetometer survey methodology

Sergyi Popov - PI
Taras Shevchenko National University of Kyiv

GEM GSMP Potassium Magnetometer for High Precision and Accuracy

Mineral Exploration, UXO, Archaeology

GSMP-25

Sensitivity: 0.022nT @ 1Hz
Resolution: 0.0001 nT
Absolute Accuracy: +/- 0.05 nT
Dynamic Range: 15,000 to 120,000 nT, (250,000 optional)
Gradient Tolerance: 50,000 nT/m
Sampling Rate: 1, 2, 5, 10, 20 Hz
Operating Temperature: -40°C to +55°C

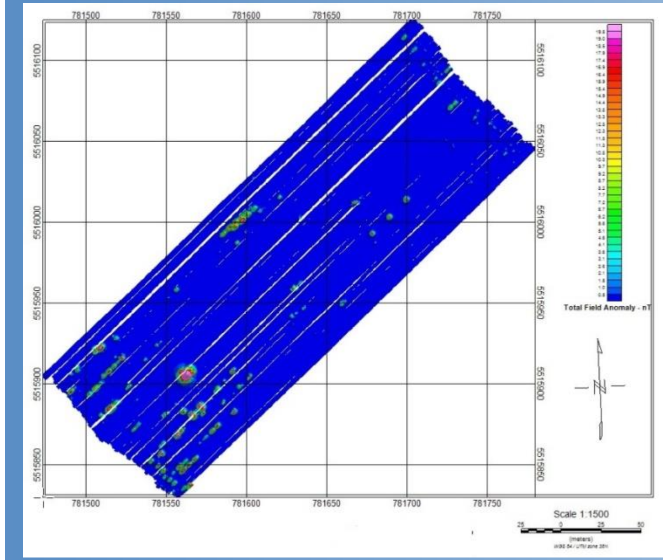
NATO OTAN

This project is supported by: The NATO Science for Peace and Security Programme

MinesEye - UXO (unexploded ordnance) identification and classification in de occupied territories of Ukraine

Project goal:

Design multi sensor system for UXO detection and identification, measure its effectiveness in testing ranges and real world (% detection, identification precision)

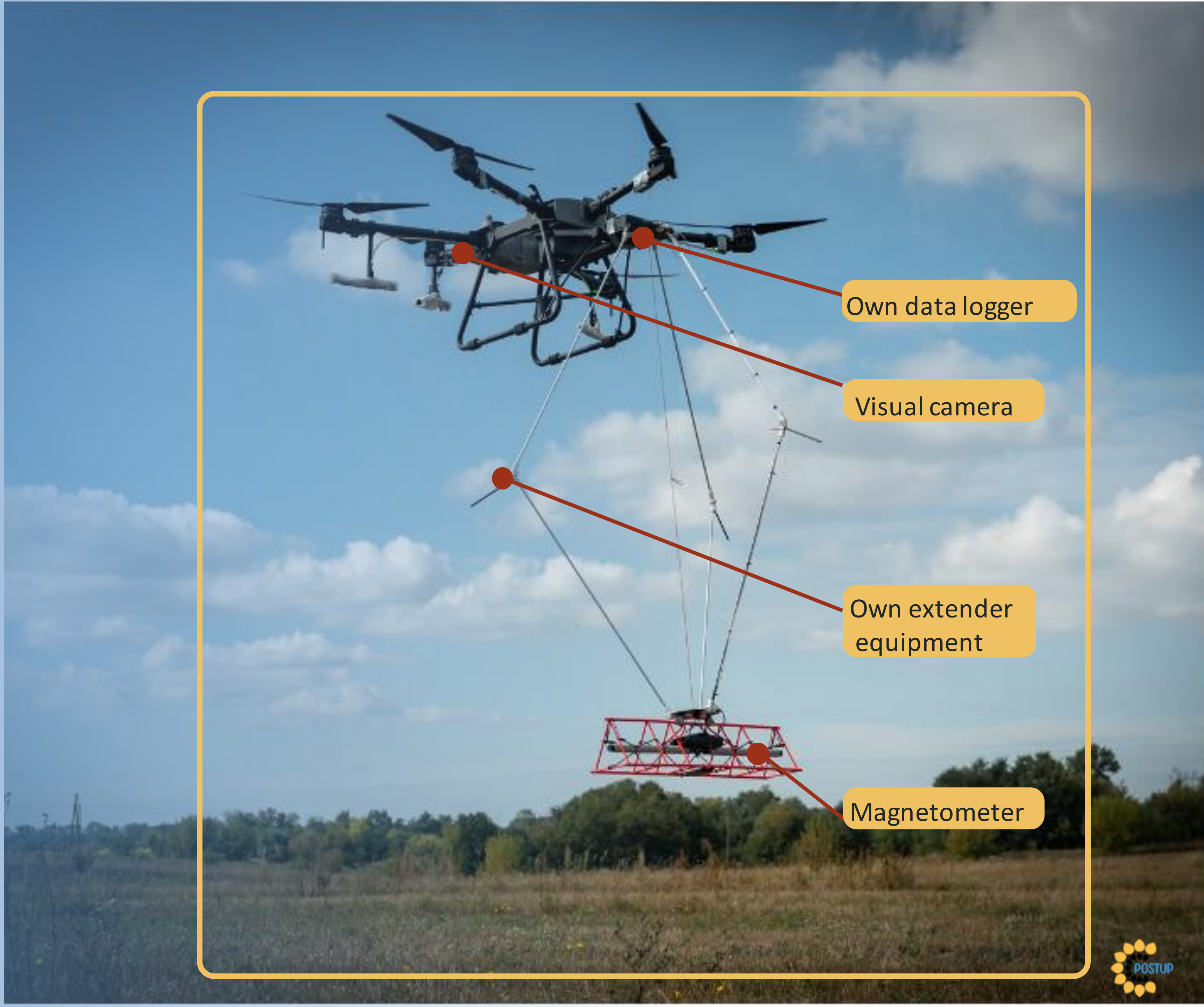


Consortium structure	Country	Role
“Postup” Foundation	Poland	Project leader (NPD)
The Institute of Geophysics (NASU)	Ukraine	Partner country leader
Institute of Aviation Lukasiewicz ILOT	Poland	Co-director
Wroclaw University of Science and Technology	Poland	Co-director
Lviv National Polytechnic University	Ukraine	Co-director

Solution - scalable system for UAV scanning

Combine agricultural drones broadly available in Ukraine

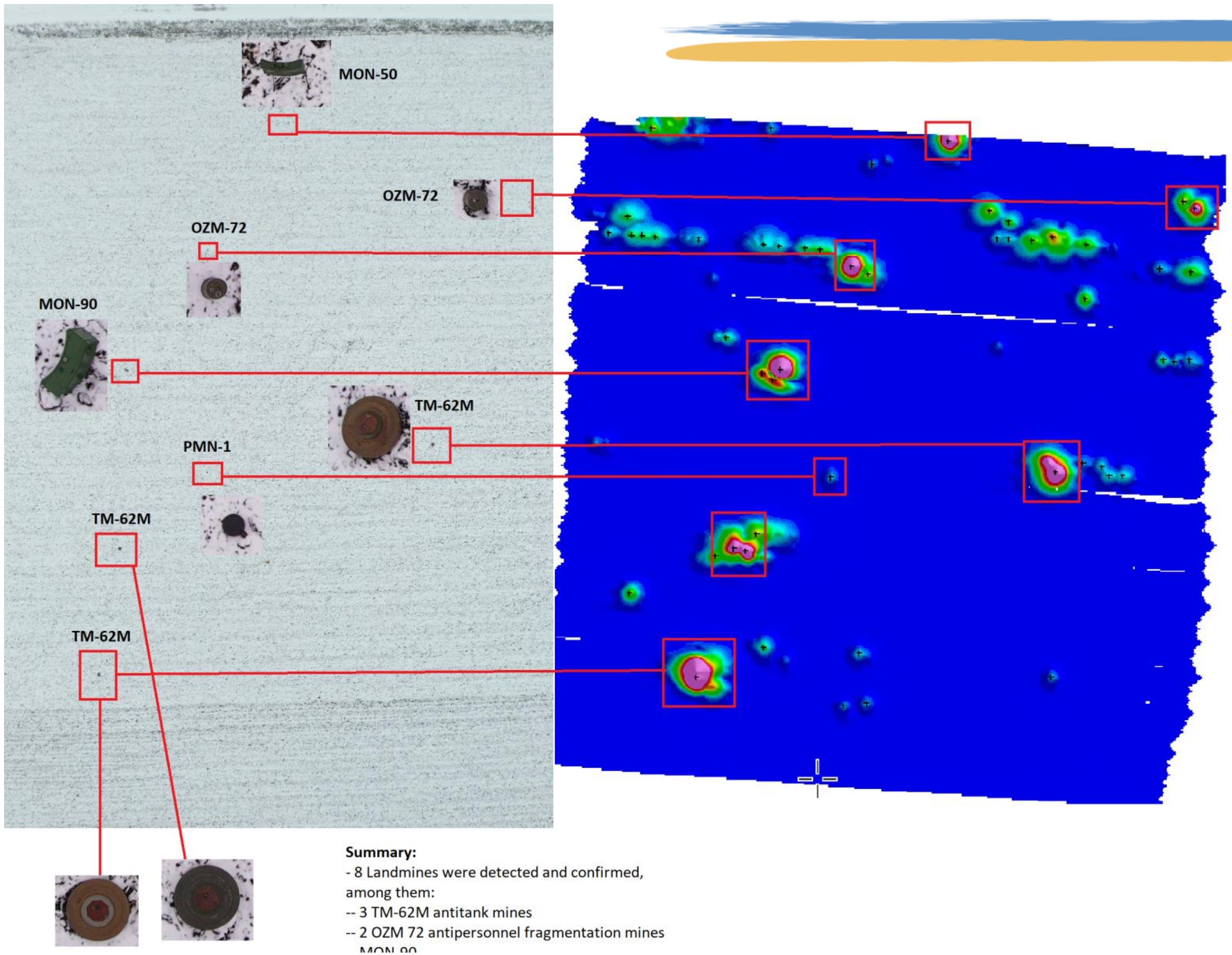
With a smart system to scan territories in search for landmines



Technical specifications of Sensys MagDrone R3 magnetometer

Operating Temperature	**-20°C to +50°C**
Weight / with Li-Ion battery	750 g / 884 g
Overall power consumption	500 mA
Sensor tube dimensions (W x D x H)	1,070 x 22 mm
Specified measurement range	±75,000 nT (higher ranges available on request)
Number of sensor axis	3
Distance between sensor centre points	1,000 mm
Sampling rate	200 Hz (higher rates available on request)
Internal memory	2 GB
Survey pre-processing software	MagDrone DataTool

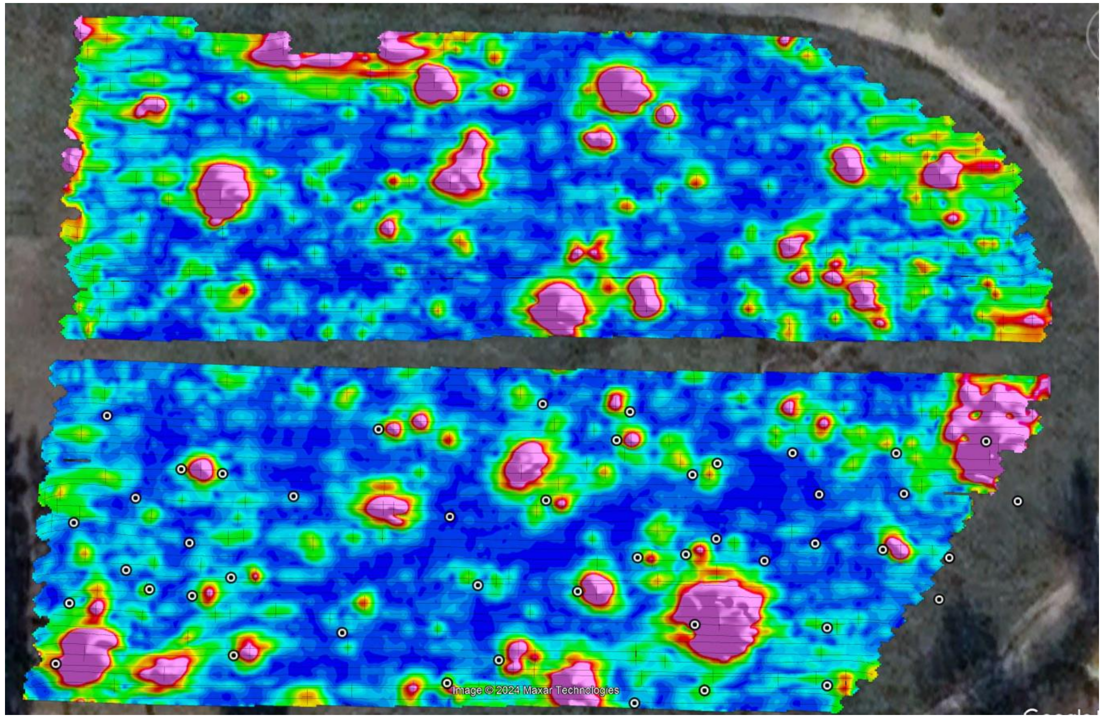
Executed: December 2023

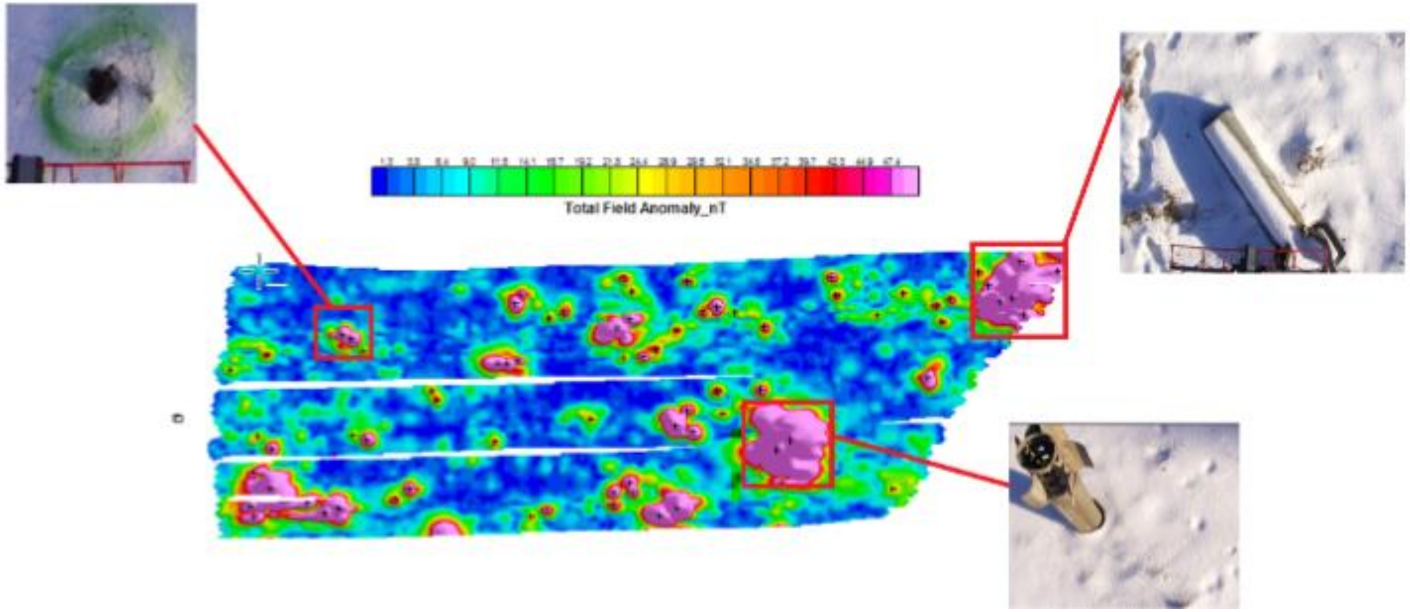


Summary:

- 8 Landmines were detected and confirmed, among them:
-- 3 TM-62M antitank mines
-- 2 OZM 72 antipersonnel fragmentation mines
-- MON-90
-- PMN-1
--MON-50
- Area covered = 70*70 m ~ 0.5 hectare
- Instrument noise <2 nT (picture attached)
- Largest anomaly: peak-to-peak 495 nT, range 3.66 m
- average instrument altitude = 0.7m above the soil
- Number of targets detected (several targets have to be merged, cutoff point 10 nT for analytic

Kharkiv region - February 2024
ICHDRR SESU





Details:

Inputs:

Number of ERW replica – 46 (various types)
Test range size: 100 x 90 m

Magnetic:

- **Detection rate – 59%**
- **Detection rate (target objects) – 89%**
- **Replicability – 88%**
- **Replicability (target objects) – 100%**

Visual:

- **Detection rate – 18%**

Coordinate error:

- **0.96 m**

Soil sampling and laboratory magnetic measurements

Crater from ballistic missile near Kyiv

Destroyed russian position in Mykolaiv region

Magnetic laboratory Demydiv

Laboratory equipment for study the magnetic properties of rocks and minerals in IGF NASU, Kyiv

Sampling equipments

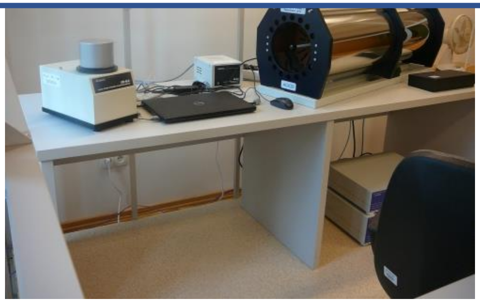
Dual speed spinner magnetometer JR-6

Shielded room MMLFC with high precision thermal demagnetizer MMTD and spinner magnetometer JR-6 inside the coils

AF Demagnetizer LDA 3A with AMU-1A modul

Three frequency Kappabrdige MFK-1B

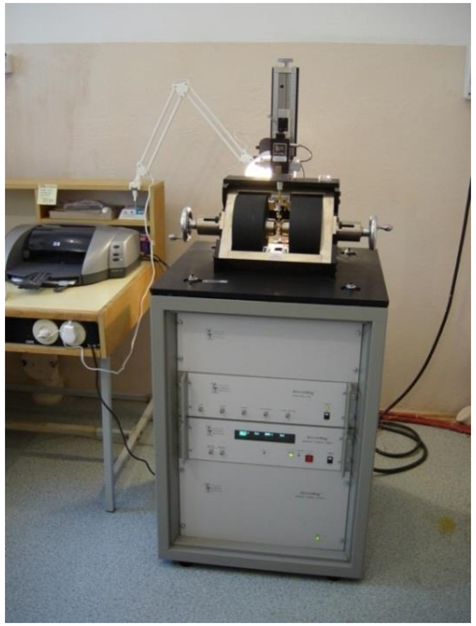
Equipment for study the magnetic properties of rocks and minerals in Department of Magnetism, Institute of Geophysics Polish Academy of Science, Warsaw



JR6A dual speed spinner magnetometer with LDA5/PAM1 demagnetizer

2G Enterprises cryogenic magnetometer DC SQUID

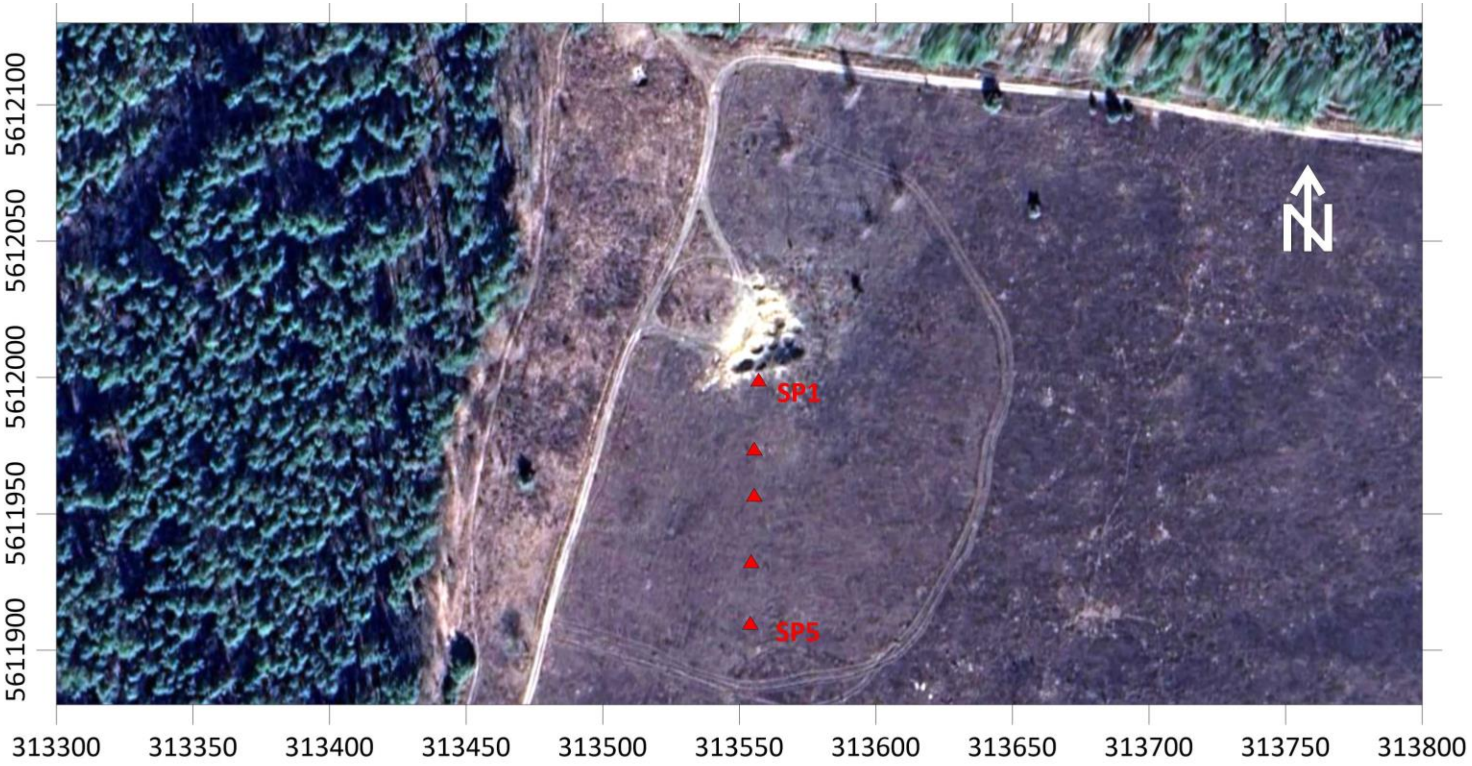
MMTD1 Nonmagnetic furnace for thermal demagnetization



Micromag AGFM 2900-02 Alternating gradient force magnetometer

MFK1-FA Susceptibility bridge

UXO destruction site Stari Petrivtsi (Kyiv region)



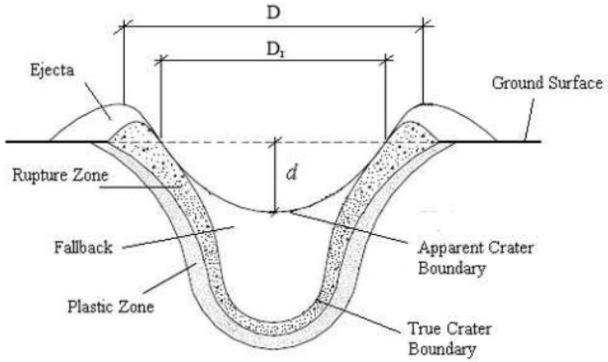
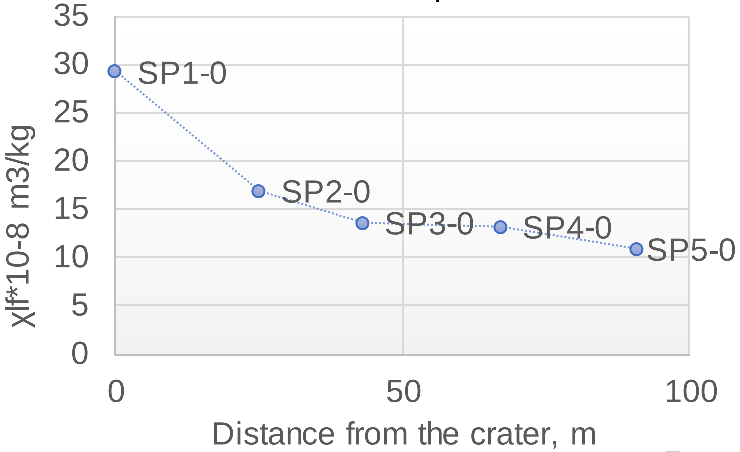
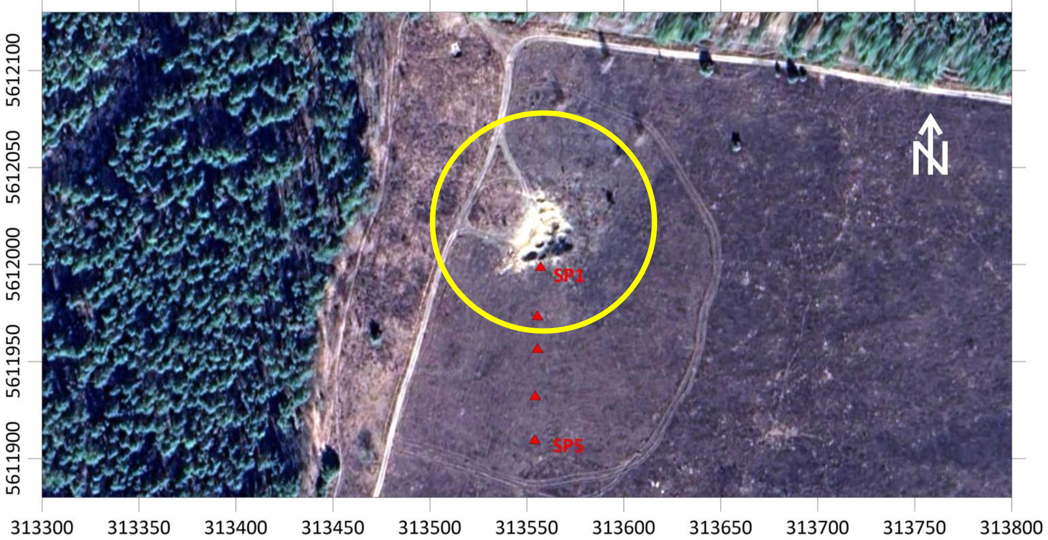


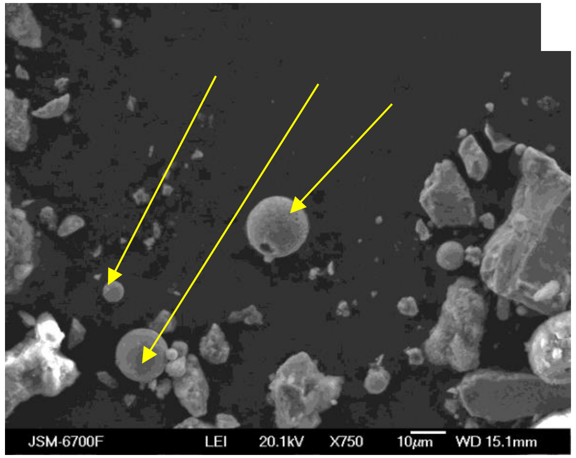
Fig. 1. Cross sectional dimensions of a typical crater.

UXO destruction site Stari Petrivtsi (Kyiv region)

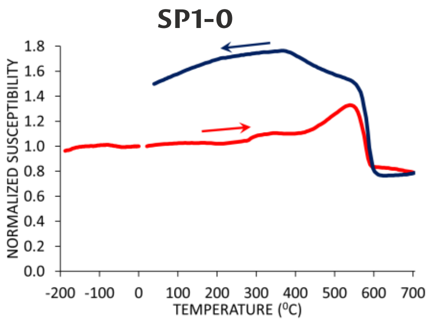
Variation of the topsoil magnetic susceptibility from the distance to the explosion crater

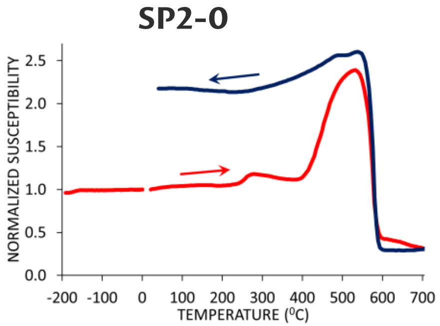


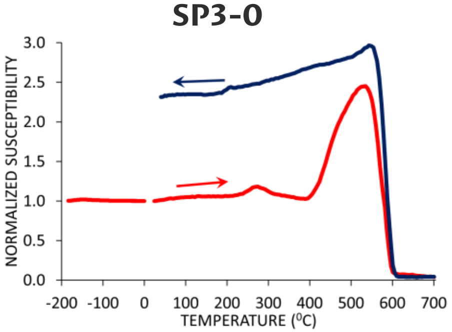




Temperature dependence of the magnetic susceptibility of magnetic material extracted from the topsoil samples from the UXO landfill site







	Distance from the crater, m	χ_{lf} (976 Hz)*10-8 m3/kg	Fe, мкг/кг	Zn, мкг/кг	Pb, мкг/кг	Y, мкг/кг
SP1-0	0	29.26	8409	48	37	10
SP2-0	25	16.96	6733	37	27	10
SP3-0	43	13.65	4523	n/s	n/s	2
SP4-0	67	13.23	5089	14	8	2
SP5-0	91	10.93	4262	17	n/s	2

MAGNETIC, GEOCHEMICAL AND MICROSCOPY CHARACTERIZATION OF SOIL POLLUTION IN UKRAINIAN CITIES – BASELINE TO TRACK FUTURE CHANGES RESULTING FROM THE WAR SITUATION

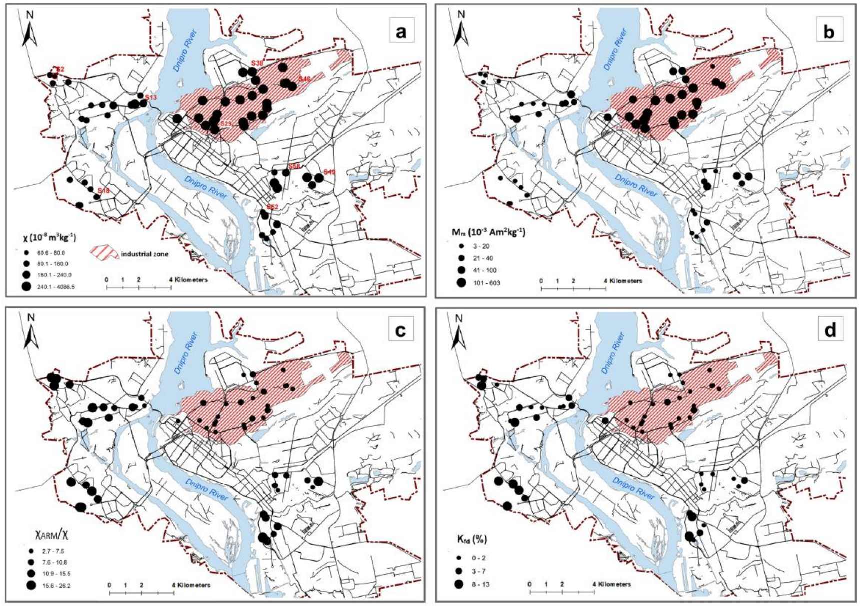
Acta Geophysica
https://doi.org/10.1007/s11600-024-01297-4

RESEARCH ARTICLE - SPECIAL ISSUE

Pre-war situation with soil pollution in the city of Zaporizhzhia: metallurgical industry center in Ukraine—characterized by magnetic, geochemical and microscopy methods

Ksenila M. Bondar[1,2] · Iryna V. Tsiupa[2] · Anastasia V. Sachko[3] · Ievhen I. Nasiedkin[4]

Received: 24 July 2023 / Accepted: 8 January 2024



Various magnetic post classed maps of urban topsoil: **a** magnetic susceptibility (χ), **b** saturation remanence (Mrs), **c** anhysteretic ratio (χARM/χ), **d** frequency dependence of magnetic susceptibility (kfd)

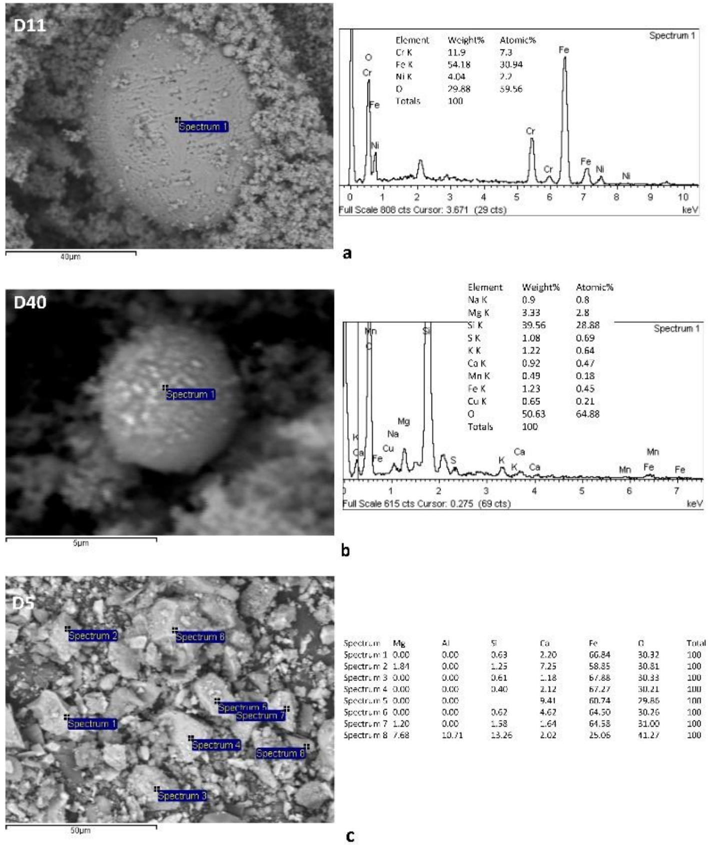


Table 6 Correlation matrix showing linkage between magnetic parameters, content of heavy metals, PLI index and pH

	M_{rs}	χ	k_{fd}	χ_{ARM}/χ	pH	Mn	Ni	Cu	Zn	Pb	PLI
M_{rs}	*1*										
χ	**0.947**	*1*									
k_{fd}	0.159	0.113	*1*								
χ_{ARM}/χ	**0.758**	**0.820**	**0.682**	*1*							
pH	**0.440**	**0.591**	**−0.332**	**−0.678**	*1*						
Mn	**0.670**	**0.800**	**−0.510**	**−0.630**	**0.386**	*1*					
Ni	**0.340**	**0.610**	**−0.590**	−0.287	**0.510**	**0.527**	*1*				
Cu	**0.550**	**0.660**	**−0.460**	**−0.629**	0.302	0.049	**0.414**	*1*			
Zn	**0.380**	**0.620**	**−0.540**	**−0.614**	0.307	**0.847**	**0.753**	**0.381**	*1*		
Pb	**0.570**	**0.730**	**−0.560**	**−0.512**	**0.434**	0.049	**0.597**	**0.707**	**0.489**	*1*	
PLI	**0.797**	**0.860**	0.025	**−0.701**	**0.649**	**0.795**	**0.756**	**0.817**	**0.624**	**0.817**	1

Number of samples $n=60$. R_s correlations significant at the 0.01 level are printed in bold type

Table 7 Components extracted by PCA characterized by their significant correlations with variables

	PC1 Eigenvalue 4.492 Explained variability 44.922%	PC2 Eigenvalue 1.332 Explained variability 13.323%	PC3 Eigenvalue 1.163 Explained variability 11.633%	Communality
k_{fd}	−0.819			0.627
Zn	0.809			0.709
χ_{ARM}/χ	−0.738			0.903
Pb	0.674			0.639
pH	0.650			0.542
χ		0.916		0.947
M_{rs}		0.904		0.923
Mn		0.770		0.570
Ni			0.862	0.740
Cu			0.686	0.564

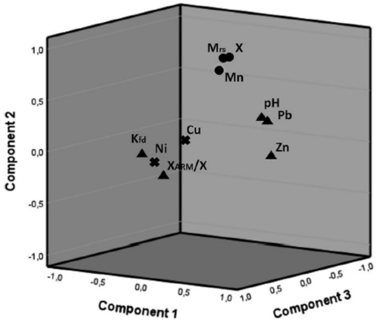
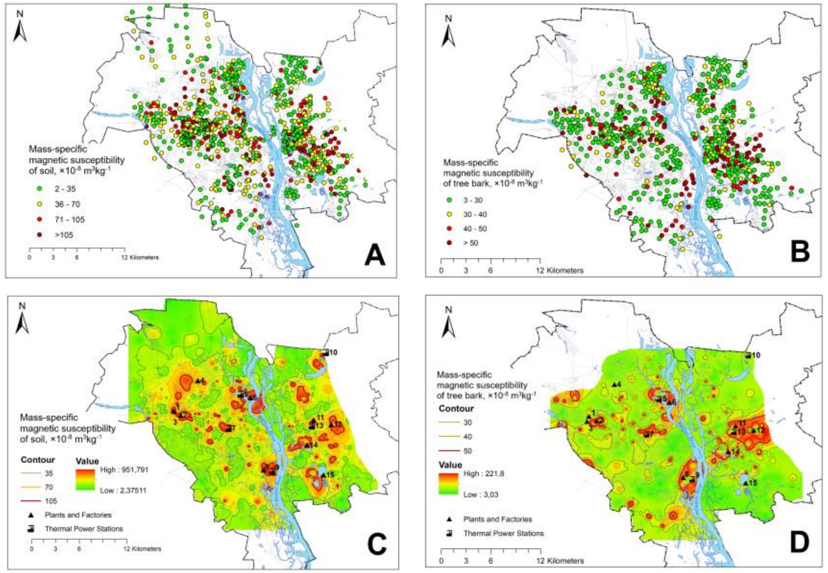


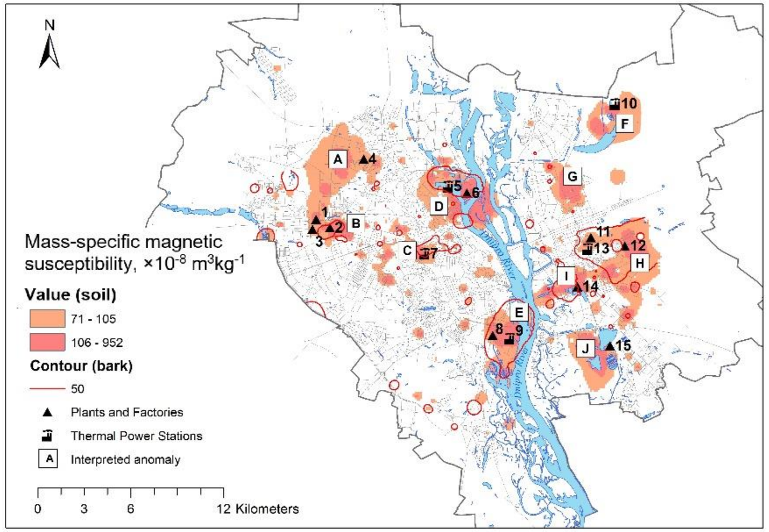
Fig. 12 PCA results: 3D representation of loadings of the three principal components (circles—PC1; triangles—PC2, crosses—PC3)

LONG AND SHORT-TERM POLLUTION EFFECT IN KYIV MEGAPOLIS ASSESSED FROM MAGNETIC AND GEOCHEMICAL MEASUREMENTS ON SOILS, TREE TRUNK BARK AND AIR FILTERS

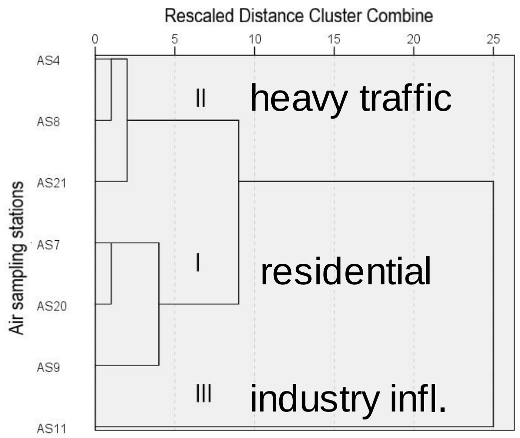
Magnetic susceptibility maps of Kyiv: post-classed map of measured soils χ_S, (a); post-classed map of measured tree bark χ_B (b), IDW interpolated χ_S (c); IDW interpolated χ_B (d)



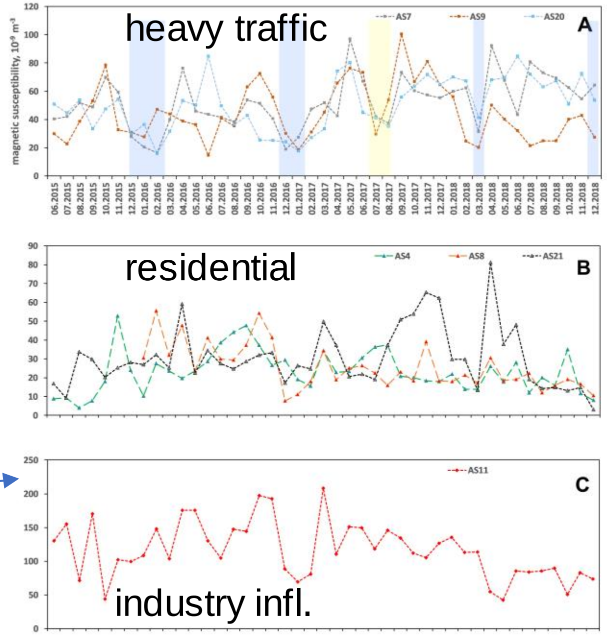
Geographical distribution of magnetic susceptibility χ_S and χ_B anomalies in relation to polluting industries. Industries shown on the map: 1 – aviation plant; 2 – machine tool factory; 3 – machinery plant (closed); 4 – electrical equipment factory; 5 - TPS-2; 6 - metalworking and ship construction plant; 7 - TPS-1; 8 – asphalt and concrete factory; 9 – TPS-5; 10 – TPS-6; 11 – chemical factory (closed); 12 – railway car repair factory; 13 - Darnytska TPS; 14 – ash landfill of Darnytska TPS; 15 – municipal waste incineration plant.



Cluster analysis results: dendrogram of air sampling sites classified by k_V temporal variation pattern



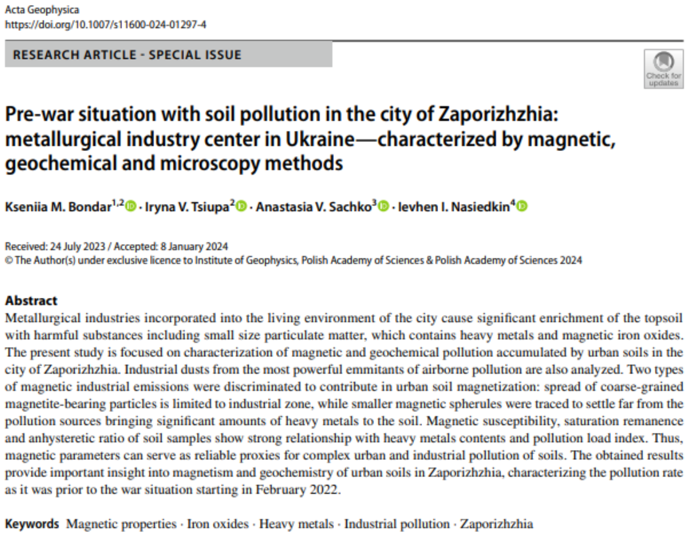
Temporal variation of magnetic susceptibility of PM collected on air filters at air sampling sites of cluster 1 (a), cluster 2(b), cluster 3 (c)



OUTLOOK

The application of the results to the environmental pollution assessment, military hazard evaluation and quantification of soil degradation will accelerate the development of Ukraine's post-war recovery strategy.

Our publications


Acta Geophysica
https://doi.org/10.1007/s11600-024-01297-4

RESEARCH ARTICLE - SPECIAL ISSUE

Pre-war situation with soil pollution in the city of Zaporizhzhia: metallurgical industry center in Ukraine—characterized by magnetic, geochemical and microscopy methods

Kseniia M. Bondar[1,2] · Iryna V. Tsiupa[2] · Anastasia V. Sachko[3] · Ievhen I. Nasiedkin[4]

Received: 24 July 2023 / Accepted: 8 January 2024

Abstract
Metallurgical industries incorporated into the living environment of the city cause significant enrichment of the topsoil with harmful substances including small size particulate matter, which contains heavy metals and magnetic iron oxides. The present study is focused on characterization of magnetic and geochemical pollution accumulated by urban soils in the city of Zaporizhzhia. Industrial dusts from the most powerful emmitants of airborne pollution are also analyzed. Two types of magnetic industrial emissions were discriminated to contribute in urban soil magnetization: spread of coarse-grained magnetite-bearing particles is limited to industrial zone, while smaller magnetic spherules were traced to settle far from the pollution sources bringing significant amounts of heavy metals to the soil. Magnetic susceptibility, saturation remanence and anhysteretic ratio of soil samples show strong relationship with heavy metals contents and pollution load index. Thus, magnetic parameters can serve as reliable proxies for complex urban and industrial pollution of soils. The obtained results provide important insight into magnetism and geochemistry of urban soils in Zaporizhzhia, characterizing the pollution rate as it was prior to the war situation starting in February 2022.

Keywords Magnetic properties · Iron oxides · Heavy metals · Industrial pollution · Zaporizhzhia

Journal paper

Bondar, K.M., Tsiupa, I.V., Sachko, A.V. *et al.* Pre-war situation with soil pollution in the city of Zaporizhzhia: metallurgical industry center in Ukraine—characterized by magnetic, geochemical and microscopy methods. *Acta Geophys.* (2024). https://doi.org/10.1007/s11600-024-01297-4

Conference materials

Bondar, K., Bakhmutov, V., Menshov, O., Poliachenko, I., Hlavatskyi, D., (2023). Detecting war-related pollution of soils using magnetic and geochemical methods. First results from recaptured outskirts of Kyiv. EAGE XVII International Scientific Conference «Monitoring of Geological Processes and Ecological Condition of the Environment», 7–10 November 2023, Kyiv, Ukraine, Mon23-209. https://www.earthdoc.org/content/papers/10.3997/2214-4609.2023520209?crawler=true

Hlavatskyi, D., Menshov, O., Bakhmutov, V., Poliachenko, I., Bondar, K. (2023). Magnetic properties of soils from the areas of former military operations in Ukraine. First results. AGU Fall Meeting 2023, 11–15 December 2023, San Francisco, USA, AGU23-1262726. https://agu.confex.com/agu/fm23/meetingapp.cgi/Paper/1262726

Thanks for your attention!