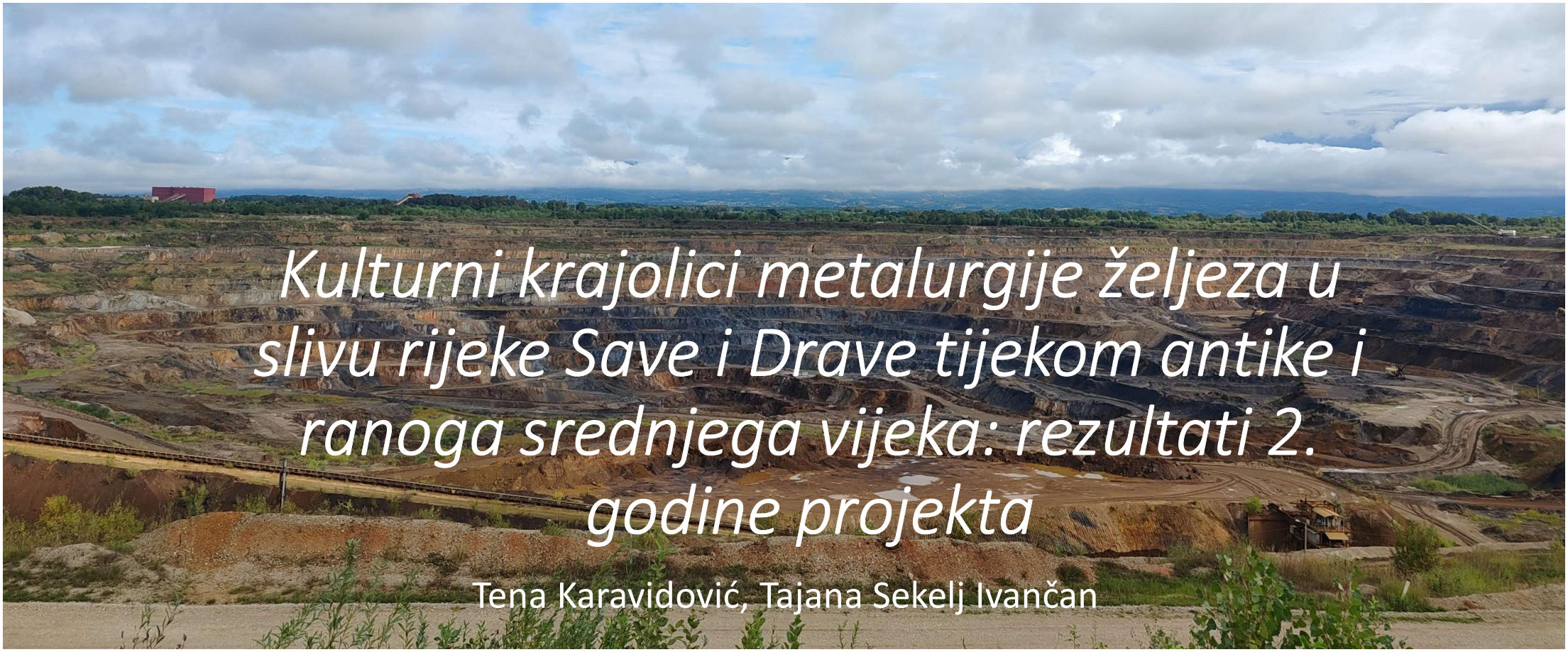
E-Okrugli stol, 19. prosinca 2025.



Kulturni krajolici metalurgije željeza u slivu rijeke Save i Drave tijekom antike i ranoga srednjega vijeka: rezultati 2. godine projekta

Tena Karavidović, Tajana Sekelj Ivančan

HrZZ Croatian Science Foundation

INSTITUTE OF ARCHAEOLOGY

KulturFER

KulturFER 2024. – 2028.

Cultural Landscapes of Iron Metallurgy During Antiquity and the Early Middle Ages in the Sava and Drava River Basin – KulturFER

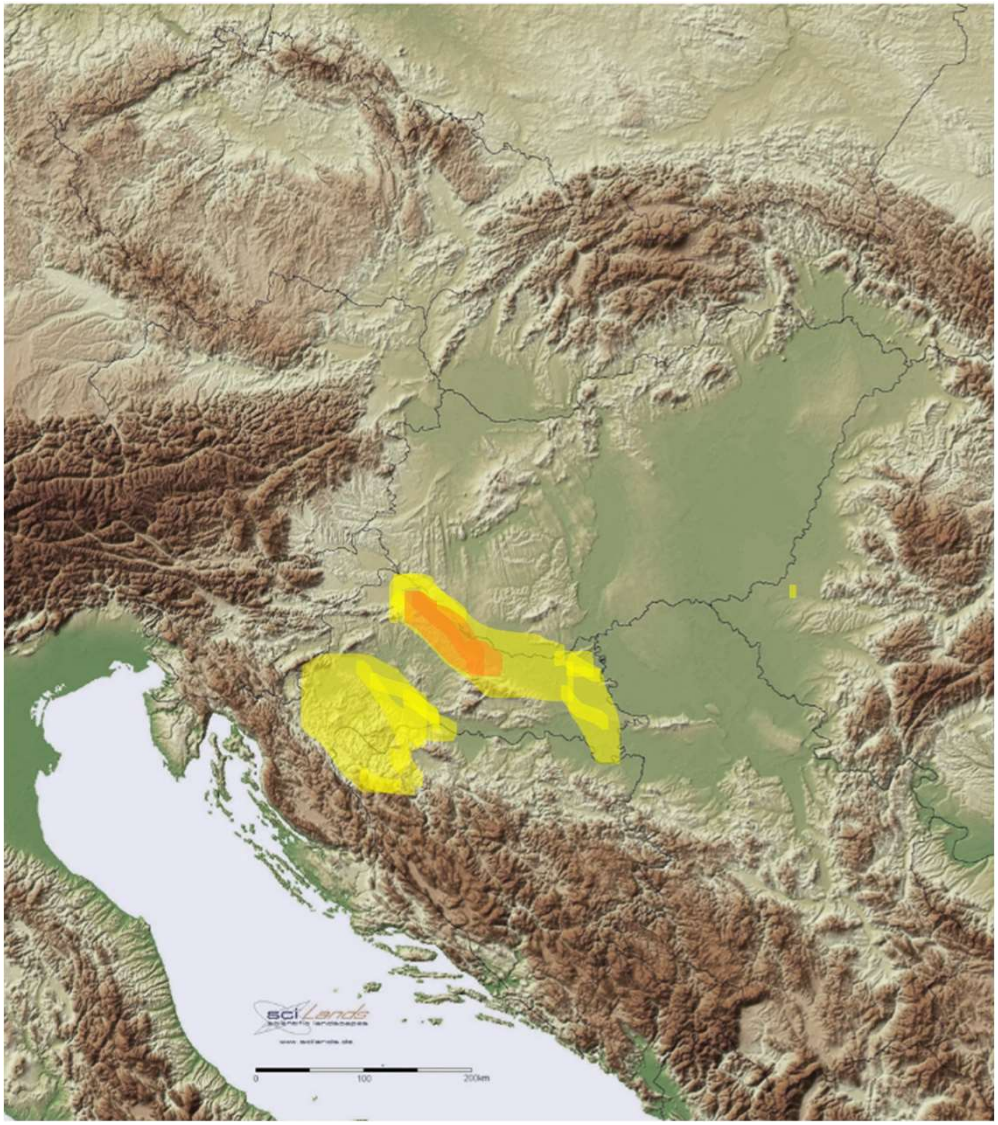
O1 Define the mineralogical composition and unique geochemical fingerprint of the Pannonian and Dinaric source raw materials (iron ore)

O2 Connect the source of raw materials with the archaeological remains of iron production (waste - slag) and (semi)products and to define the areas of exploitation in the area of the Sava and Drava River basins during archaeological periods

O3 Define and compare technological processes, similarities and differences in the methods of production and processing of iron and the degree of standardization of iron (semi)products during Antiquity and the Early Middle Ages in the observed area

O4 Establish the organization of production processes and the distribution of semi-finished products during Antiquity and the Early Middle Ages in the area of the Sava and Drava River basins

Research area

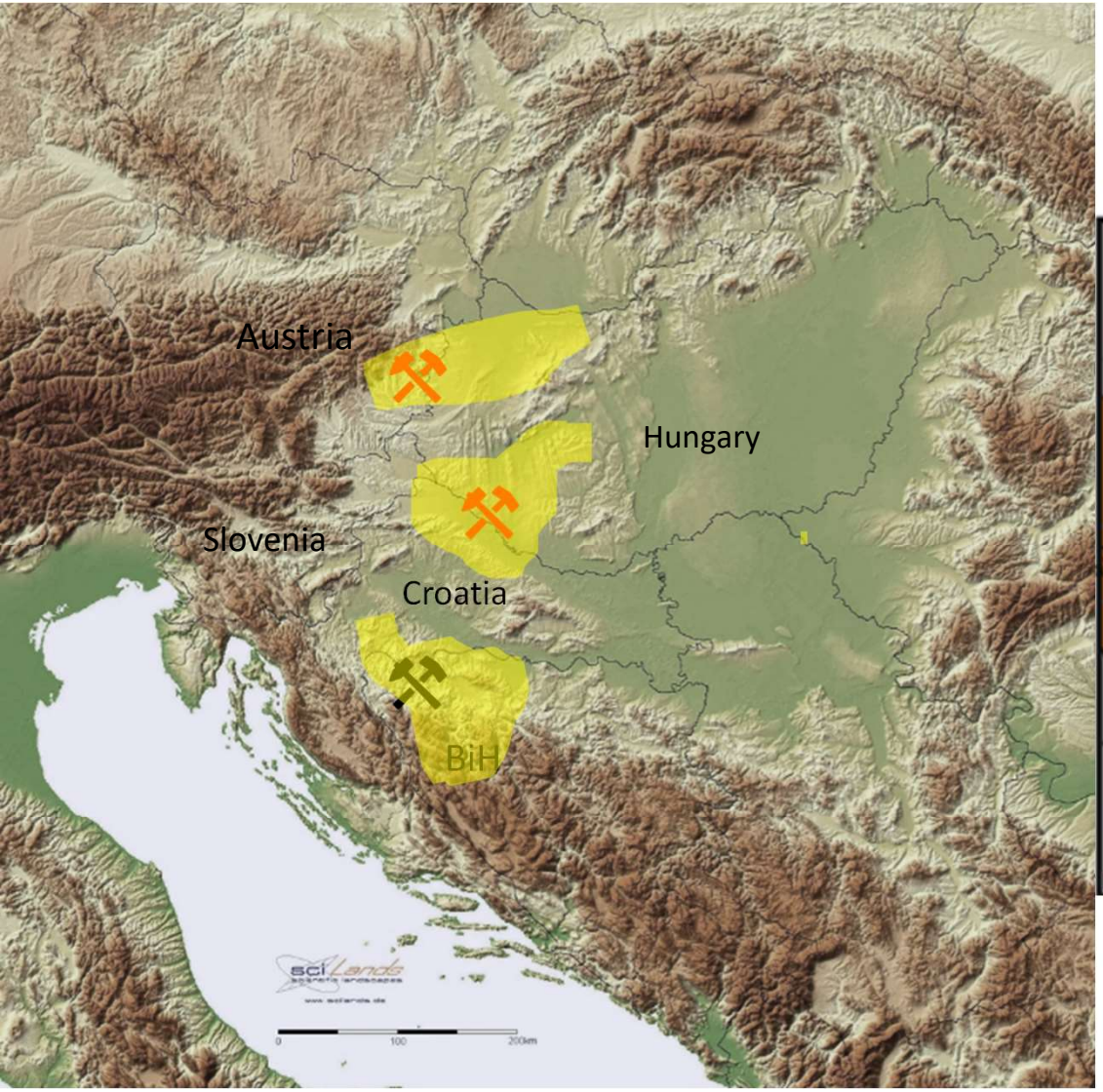


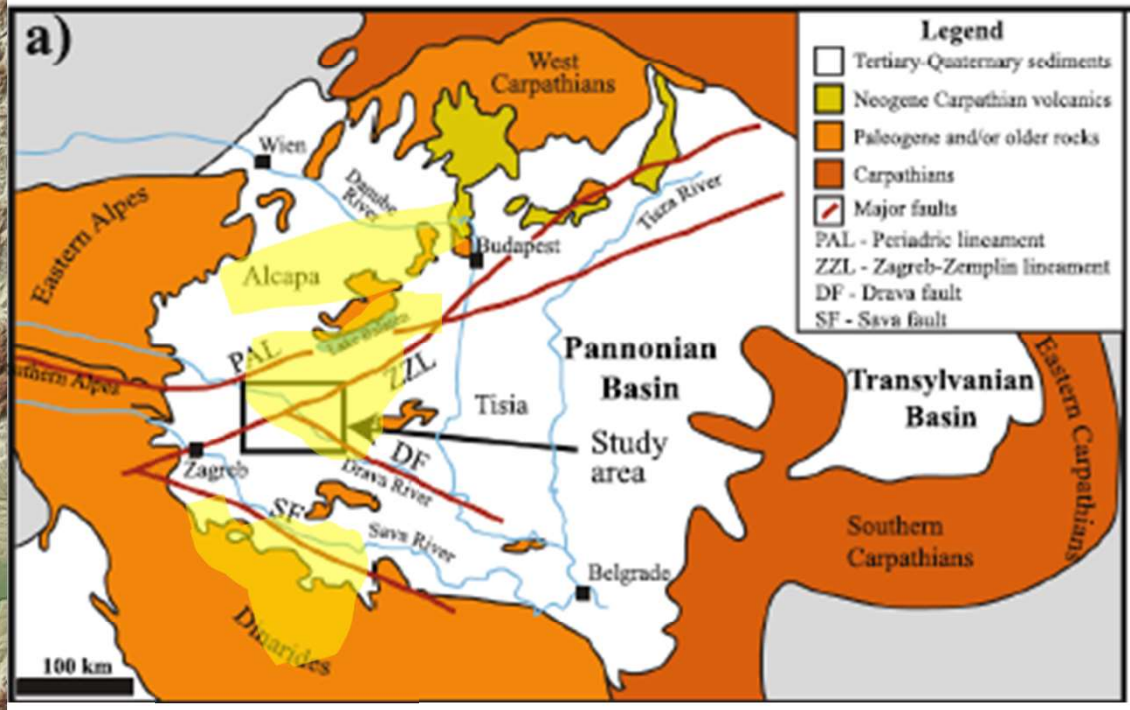
Sava and Drava river plains // mountanious outskirts

Pannonian and Dinaric ore resources

Antiquity and Early Middle ages + Iron age

rural and urban spaces





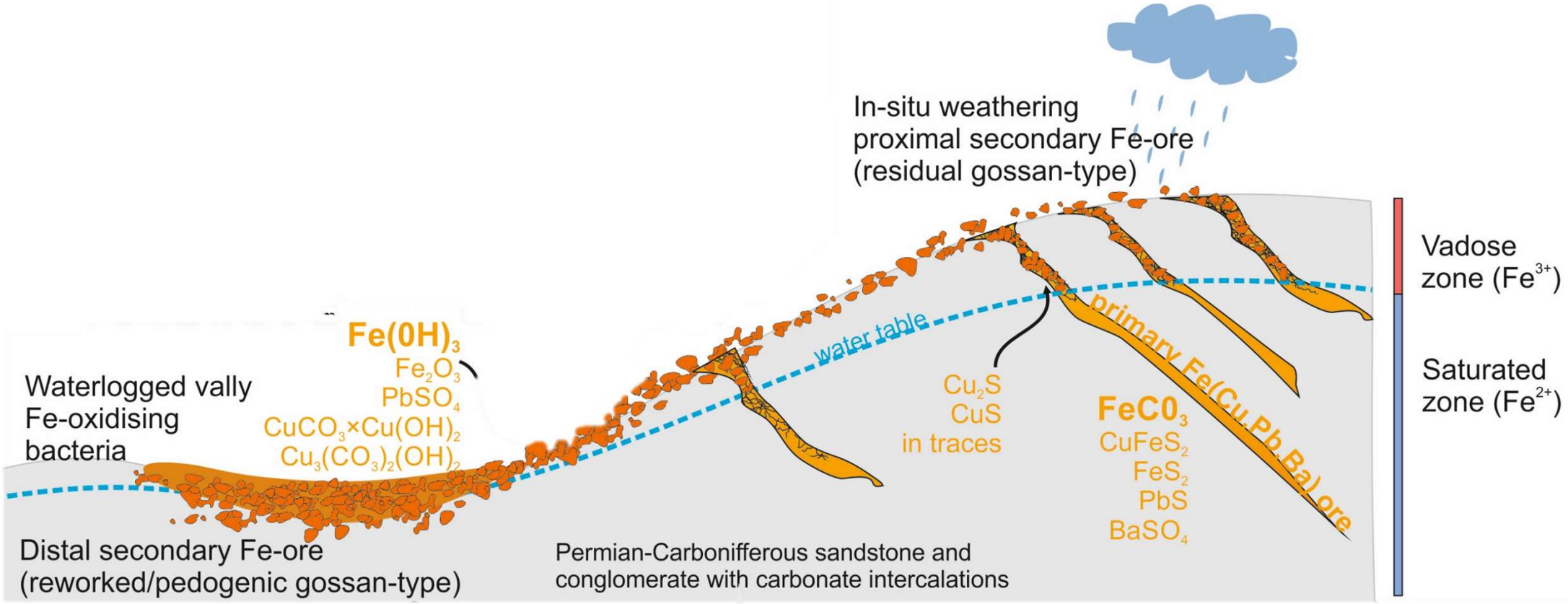
Digital relief model of the Carpathian basin.

Panonian and Dinaric ore resources

Alluvial plains – Sava and Drava – landscape and traces of bog iron ore mineralisation

Zrinska and Trgovska Gora/**Ljubija – Omarska** – traces of mining and presence of iron ore mineralisation – siderite/ankerite and limonite (primary, gossan – proximal and distal BIO mineralisation).

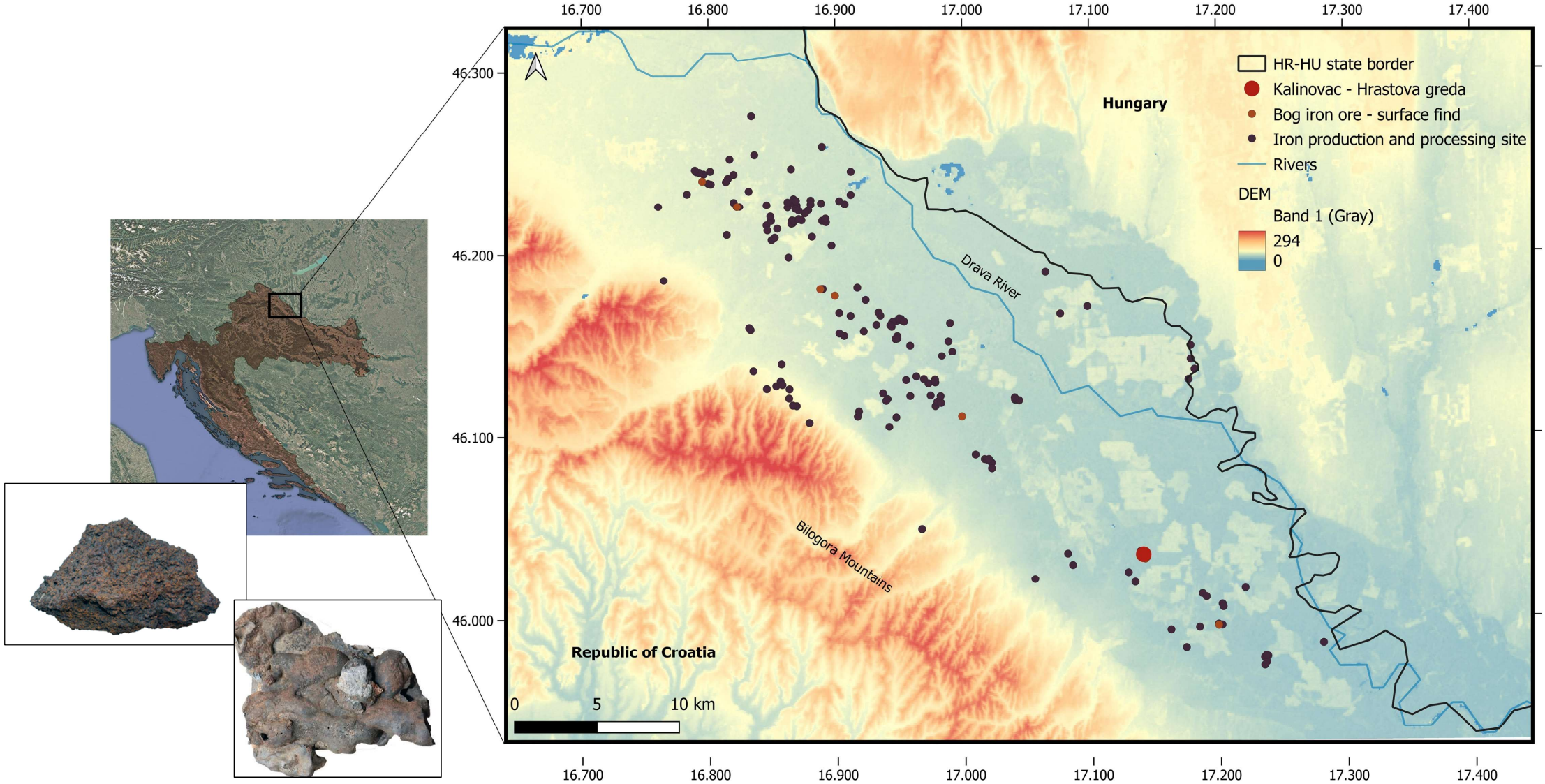
Ore evolution and geochemical characterisation of unique fingerprits – provenance



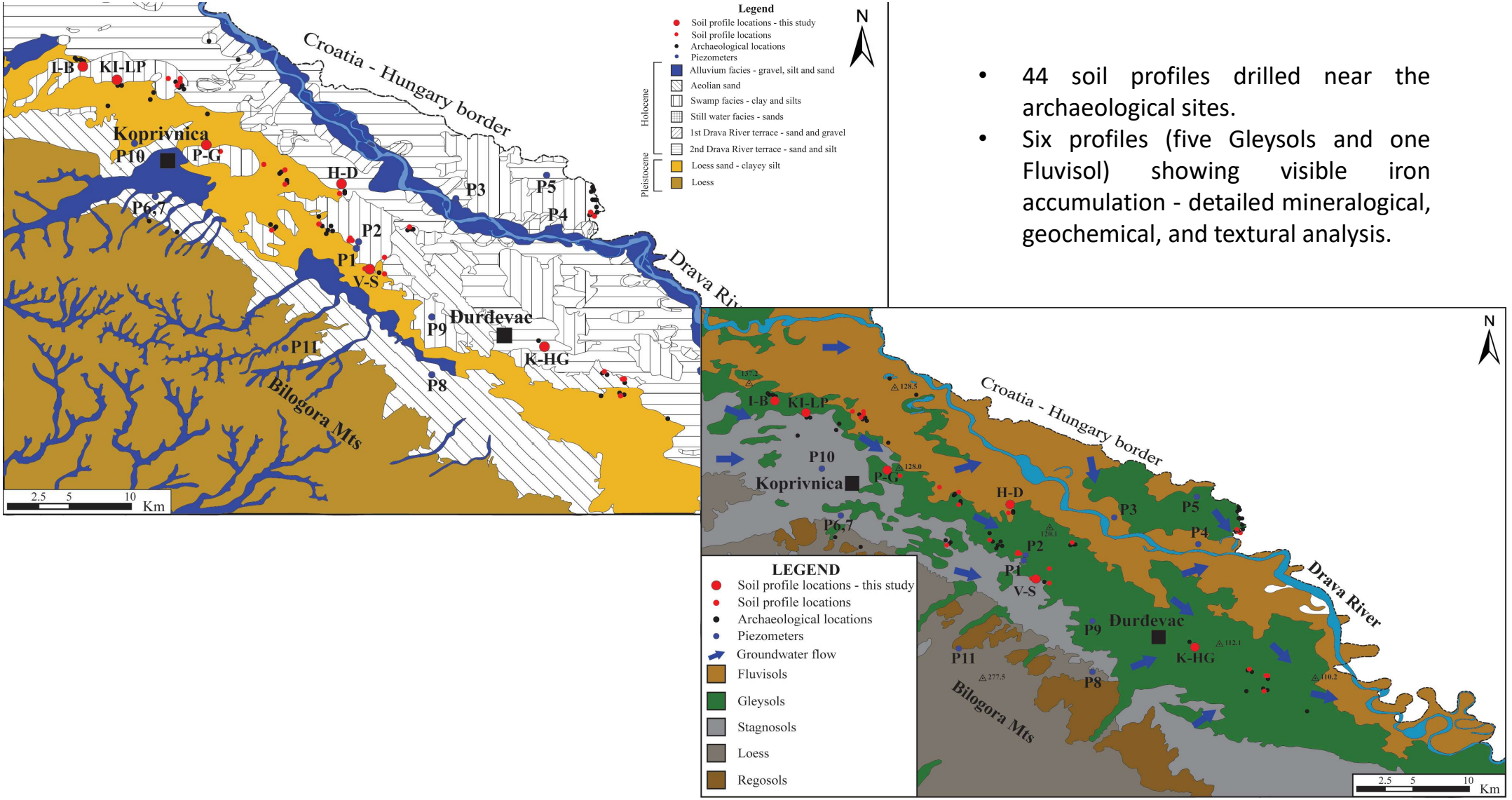
Ljubija and Omarska mine (NW BiH)

Panonnian lowlands : Drava – Sava – Danube alluvial plains

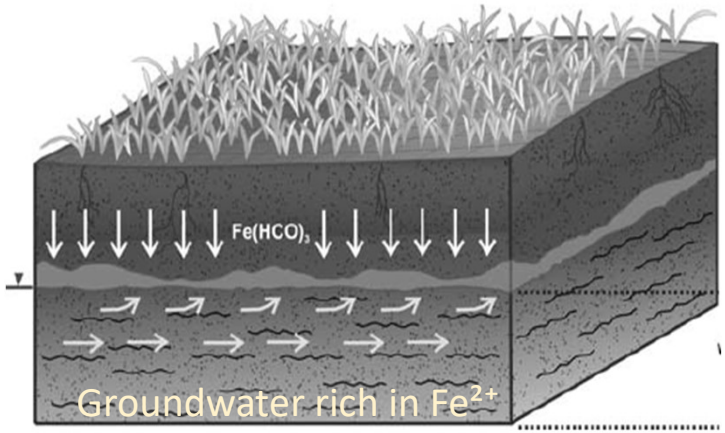
Lowlands : The Podravina region, NW Croatia



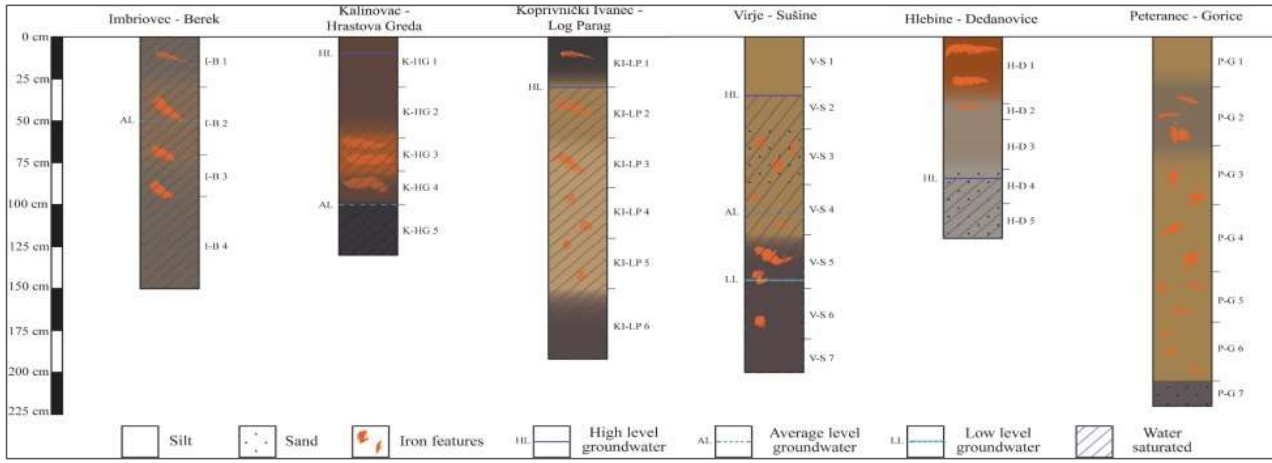
Deposit Formation Potential – Surface Survey and Soil Profile Sampling



- 44 soil profiles drilled near the archaeological sites.
- Six profiles (five Gleysols and one Fluvisol) showing visible iron accumulation - detailed mineralogical, geochemical, and textural analysis.



Horizon of bog iron ore deposition



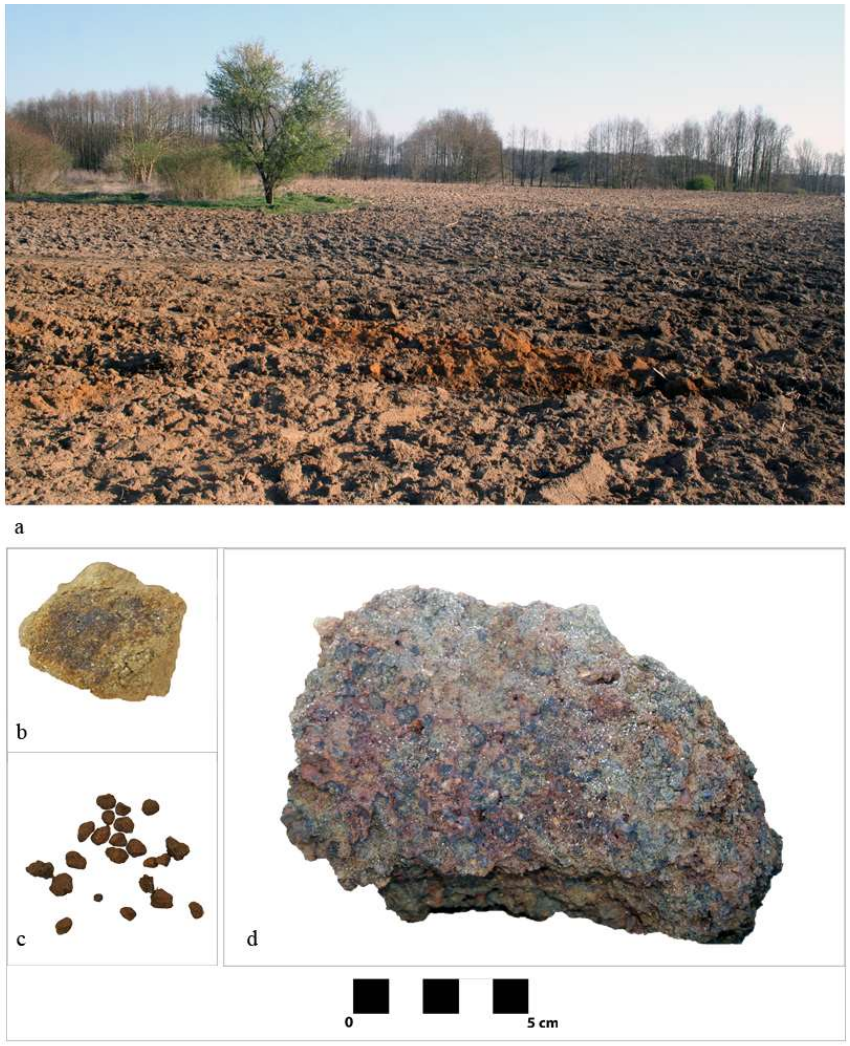
Schematic representation of the mechanism of bog iron ore deposition in relation to the groundwater level (after Werovska 2009)

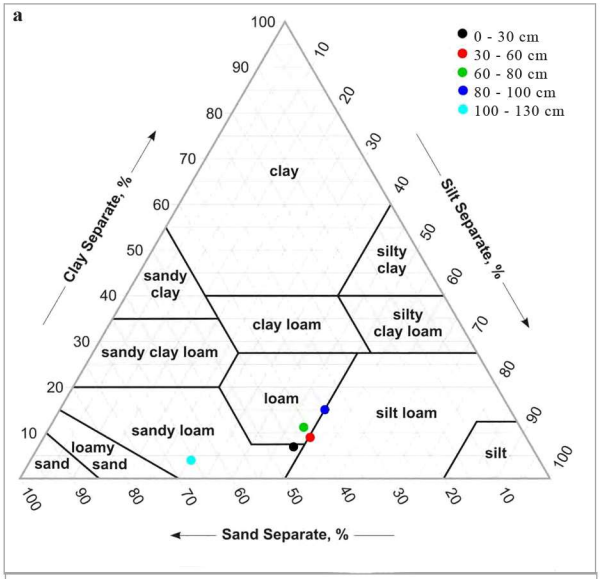
Surface occurrence and deposits

- presence of goethite, with elevated Fe, P, and As levels at depths of 30–80 cm ***– soft bog iron ore – 1st developmental phase***
- hardened goethite nodules (0.5–3 mm), likely brought up by ploughing – ***2nd developmental phase***
- cemented iron ore lumps and disrupted bog iron lenses in the subsoil layers – ***hard bog iron ore – 3rd developmental phase***

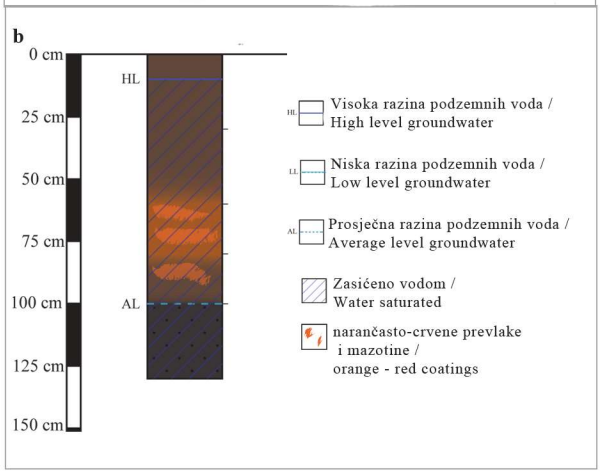
Podravina region is a suitable area for the formation of bog iron ore, although recent conditions inhibit the formation due to changes made by agriculture and melioration which are altering groundwater levels.

Case study: Kalinovac – Hrastova greda – archaeological site and bog iron deposit



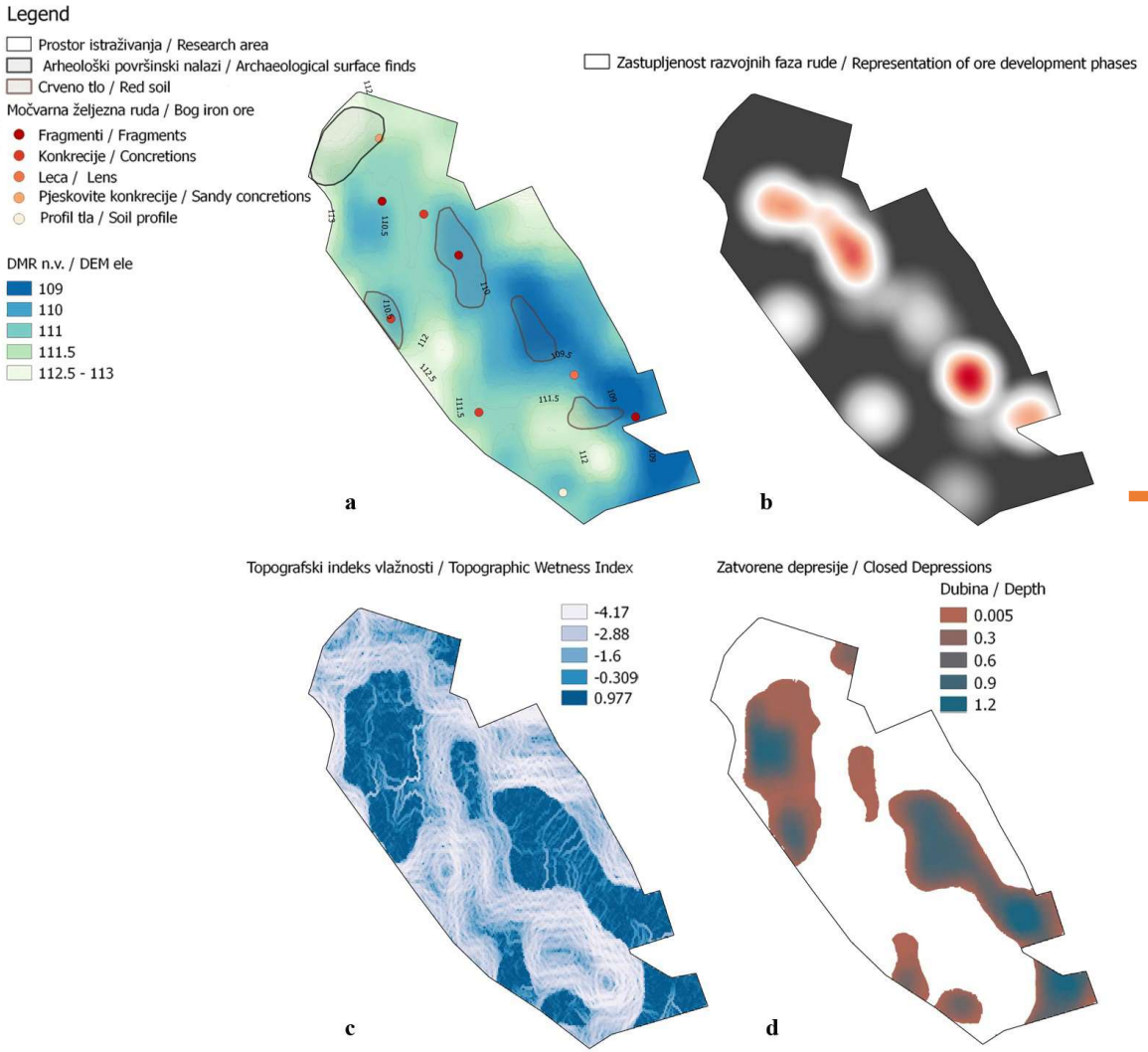


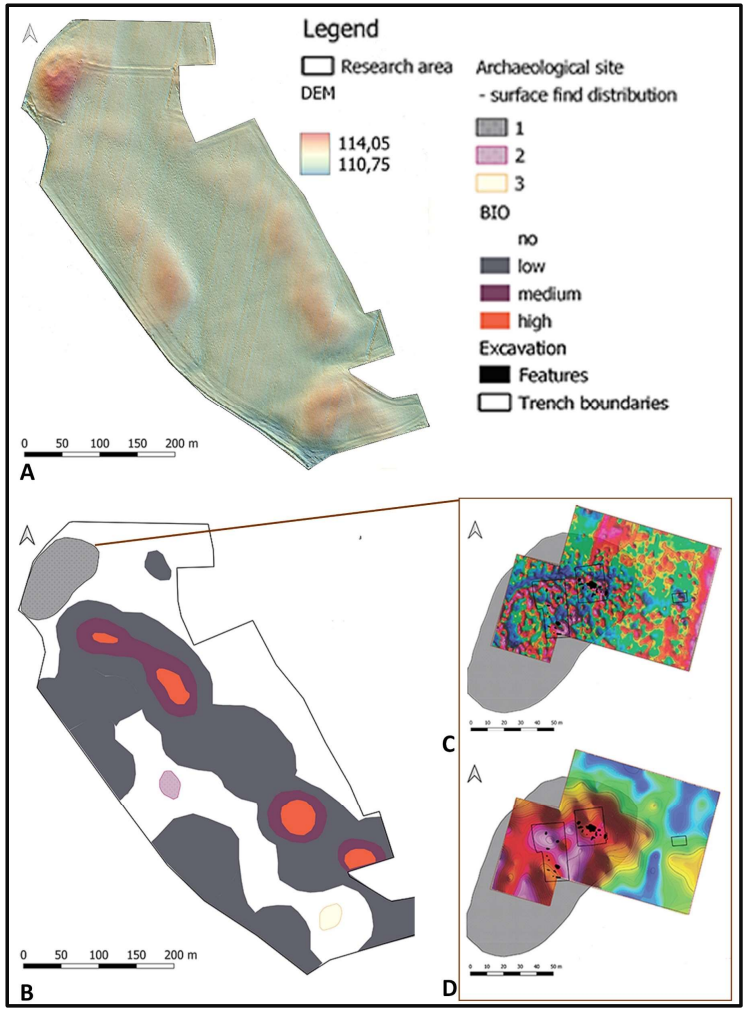
Kalinovac – Hrastova greda – indicative formations and bog iron ore: a) red ploughed surface soil; b) sandy concretion with iron matrix; c) globular concretions (nodules) d) fragment of bog iron ore collected from a destroyed deposit



Kalinovac – Hrastova greda – soil profile: a) granulometric classification of the soil profile, (classification of the USDA); b) schematic representation of the soil profile

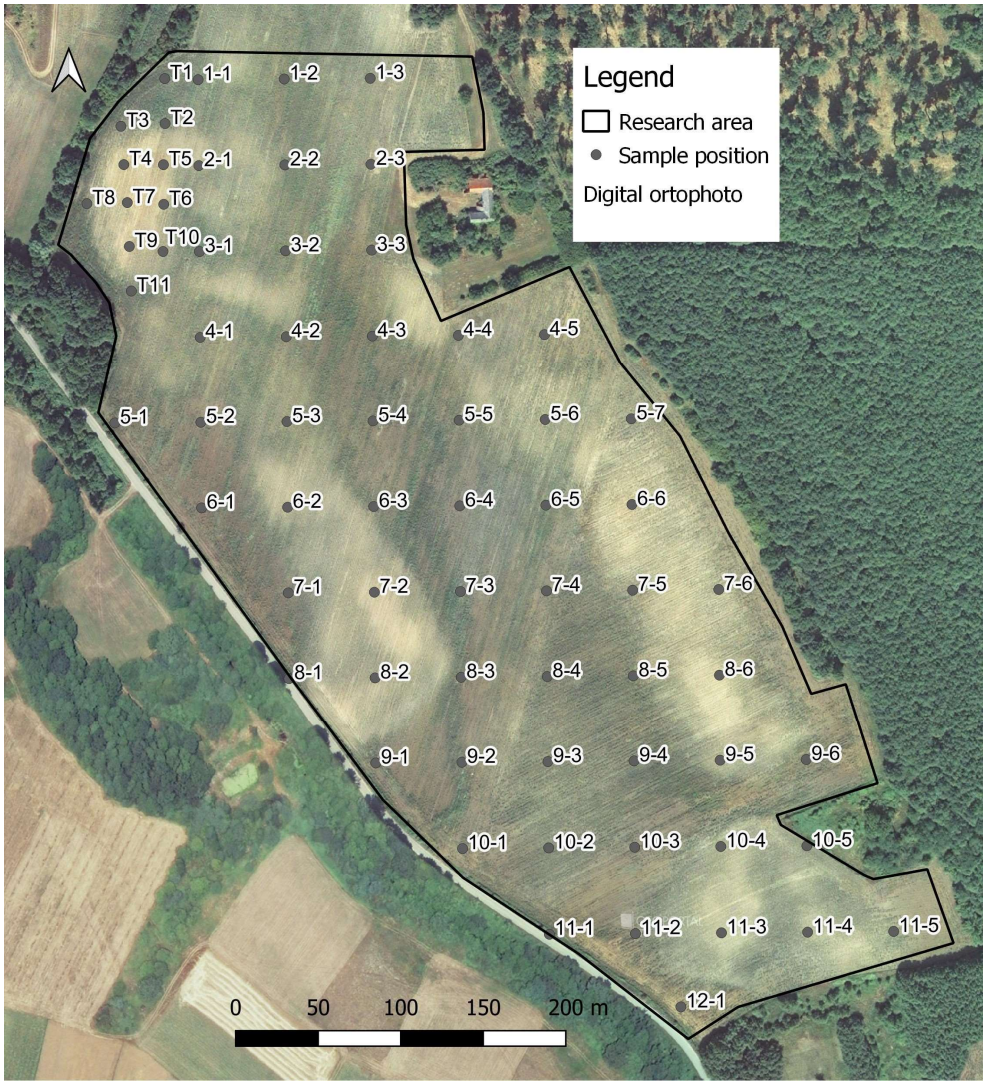
Predictive modelling of BIO occurance potential: Kalinovac – Hrastova Greda

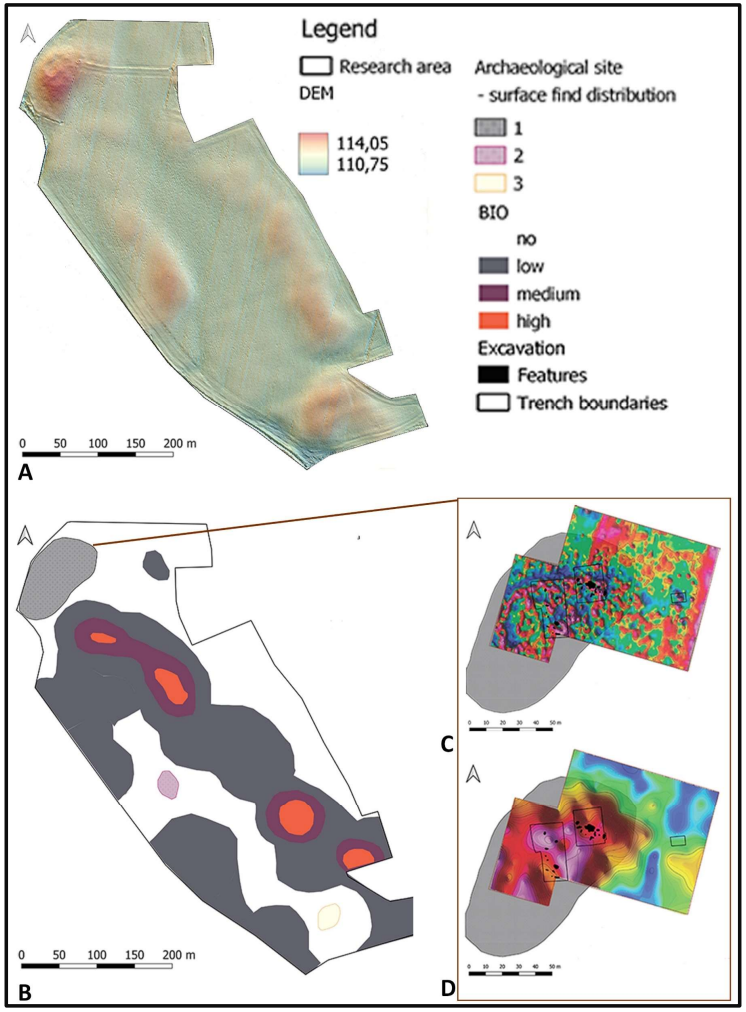




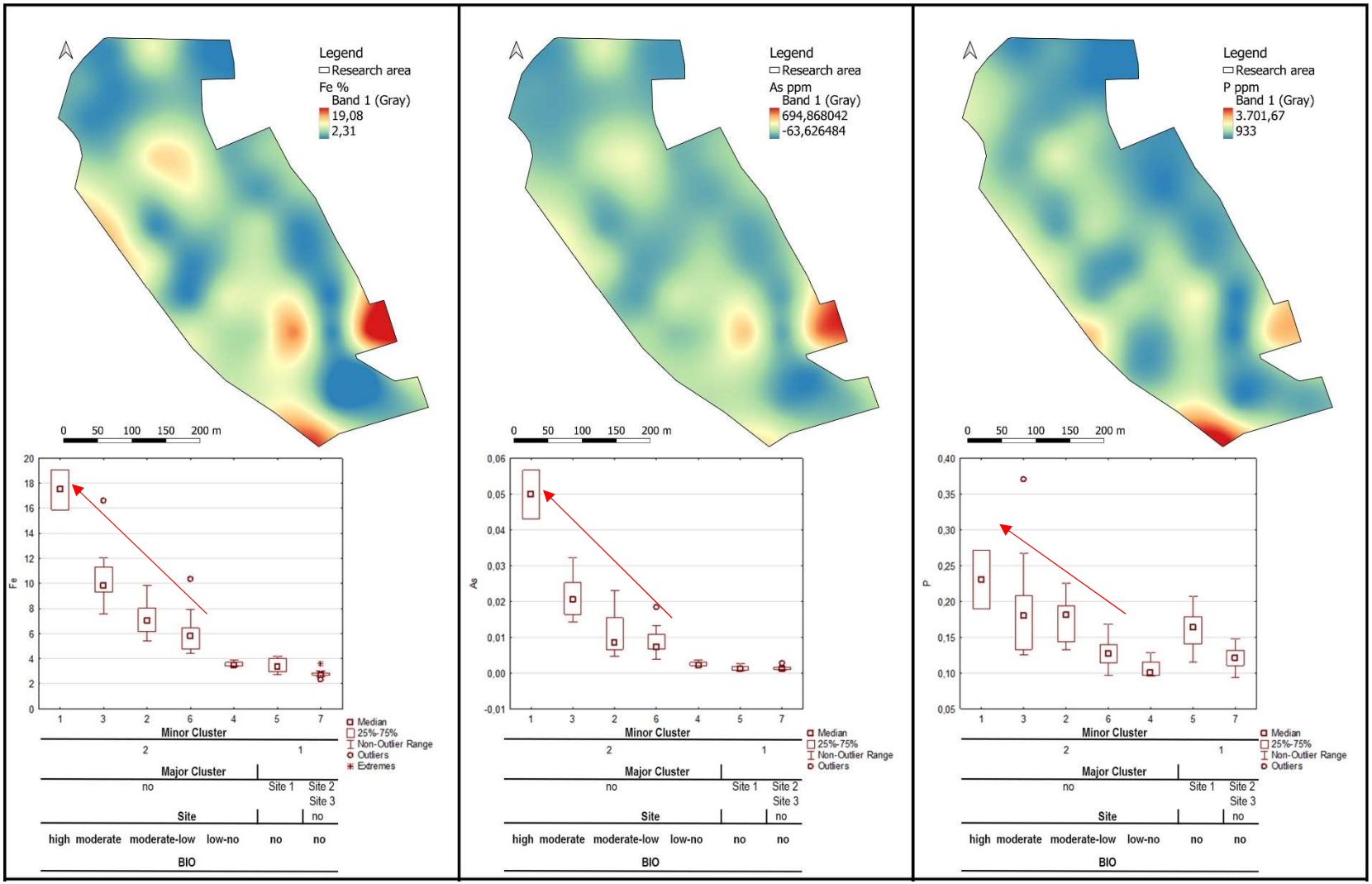
Bog iron ore potential occurrence and archaeological sites – spatial distribution

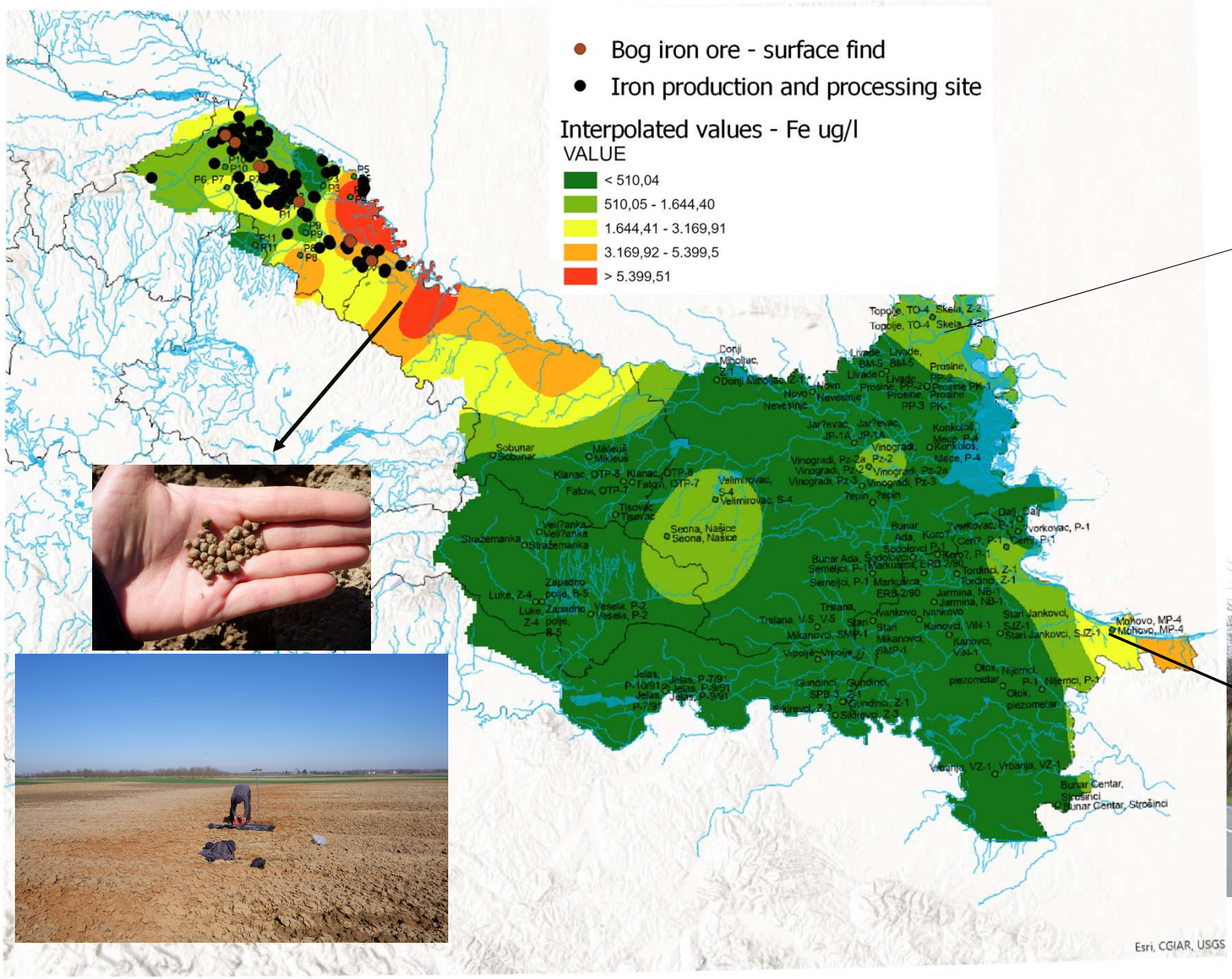
Topsoil properties and geochemical fingerprint of the iron production environment

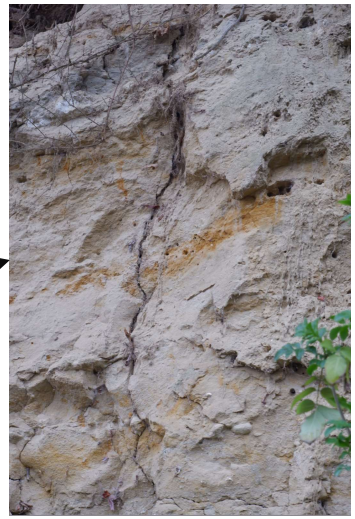




Interpolated spatial distribution of original values of elements and boxplot diagrams by cluster membership




Bog iron ore - surface find
Iron production and processing site
Interpolated values - Fe ug/l
VALUE
< 510,04
510,05 - 1.644,40
1.644,41 - 3.169,91
3.169,92 - 5.399,5
> 5.399,51
Esri, CGIAR, USGS



Technology of iron production and processing

Methods

- Morphological / morphometric analisys
- Mineralogical analisys – XRD
- Chemical analisys – pXRF (main elements) & ICP-MS/AES (main, trace, REE)
- Metallographic analisys – optical microscopy, SEM-EDS
- Statistical treatment of data
- Experimental testing

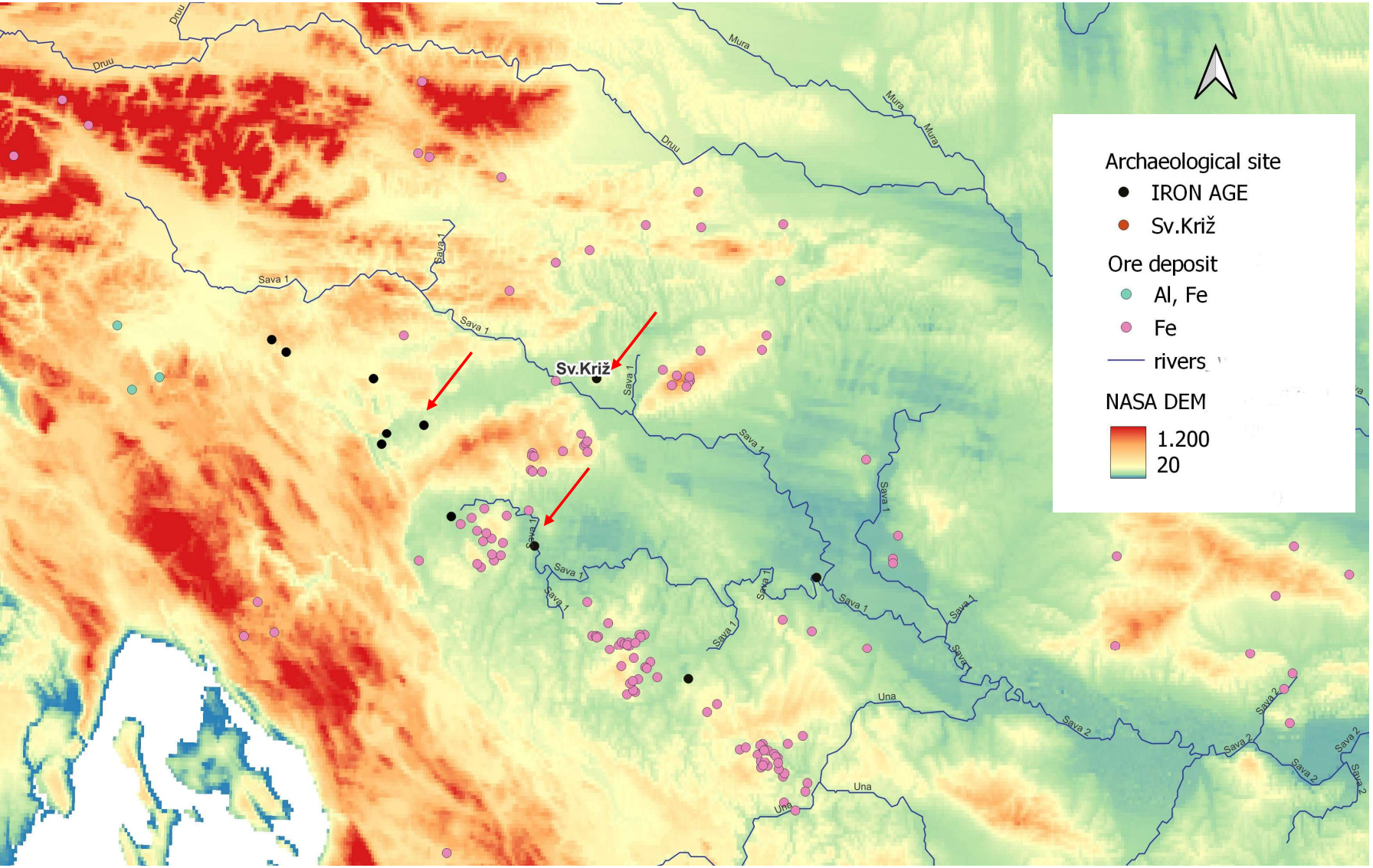
Objectives

Type of process, technology used and technological choices made, quantification of production

Iron characteristics

Ore and slag provenance

Case study : Sveti Križ (North-West Croatia) - Evidence from the Late Hallstatt Settlement



- Technology applied
- Resource availability, comunication, trade and exchange routes

Ore

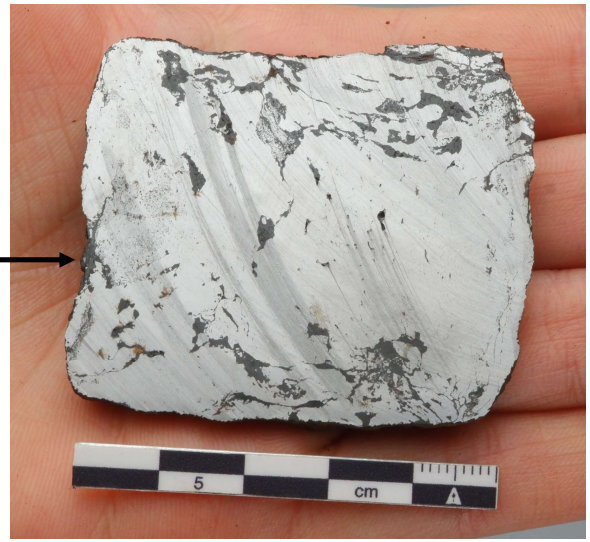
Semi-products

Slag

Objects

- Diversified and spatially organised workspace (structures) for various metallurgical activities – bronze and iron = binding two metalworking practices, a versatile know-how
- Primary production (?) and secondary processing – multiple steps of smithing practices
- Standardised operating routines – repetability - one/few smiths with stable habits – specialisation

Case study : Hrvatska Dubica hoard (Croatia) - technical traditions and standardisation in Roman iron semi-products: morphometric and metallographic evidence from the

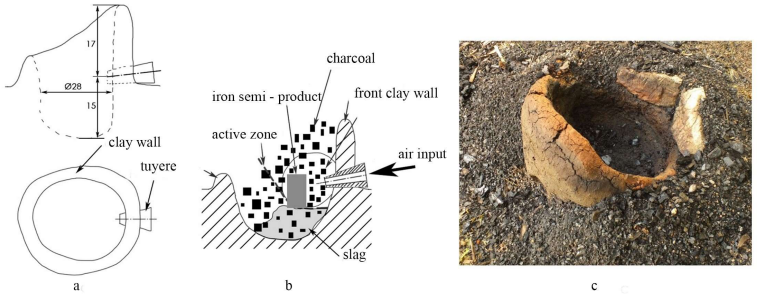


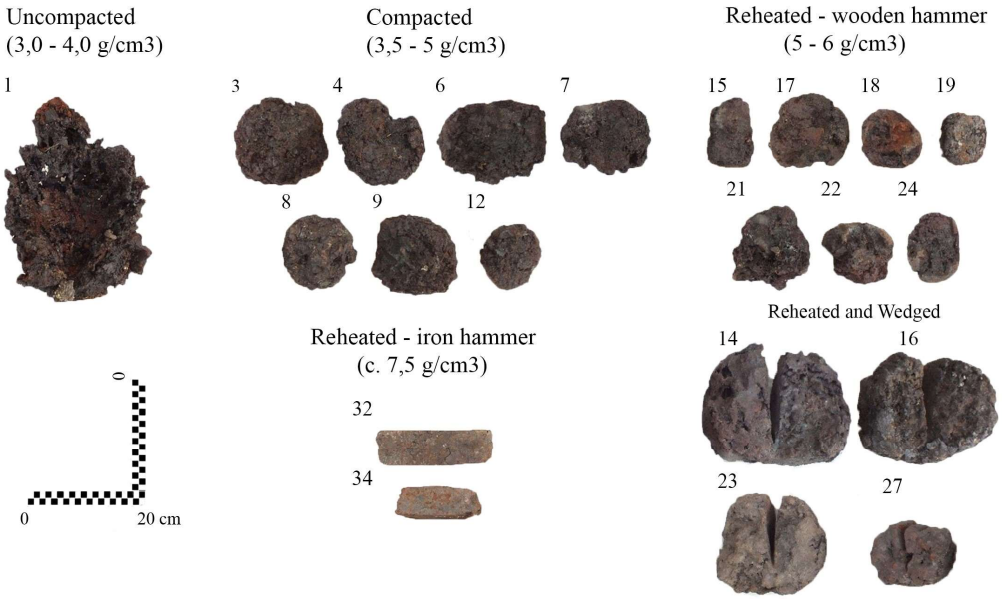
- standardised groups of semi-products in terms of basic shape and weight, comprising mainly quadrangular bars weighing 2,650–5,316 g (equivalent to c. 8–16 Roman *librae*)

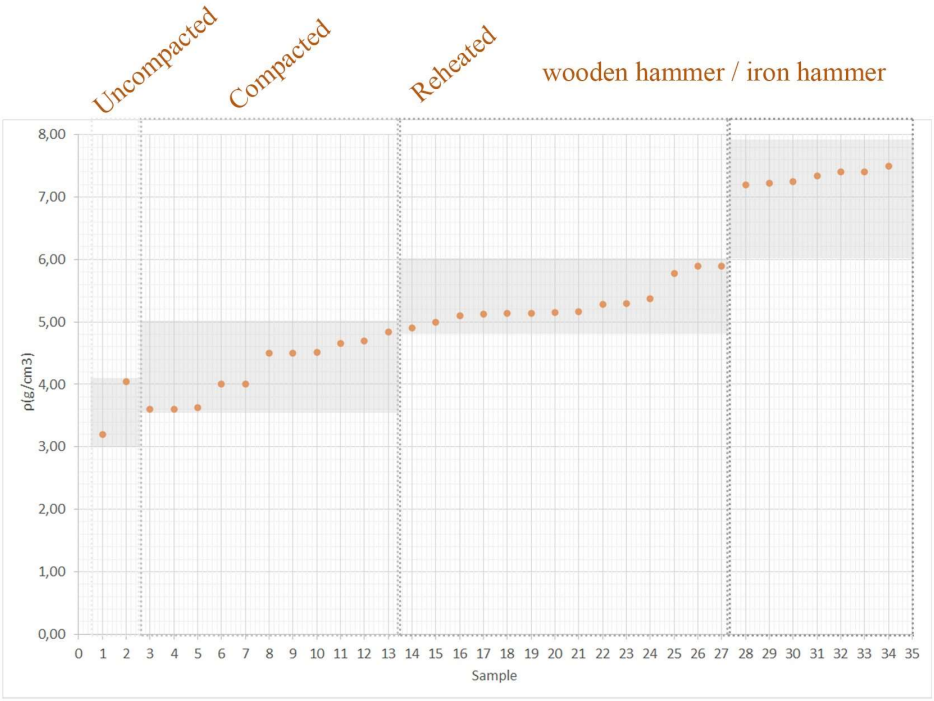
OM, SEM-EDS, ICP-MS = technological traist, provenance + datation

- ? variation in production techniques and in handling during the smithing stage, reflecting distinct technical traditions

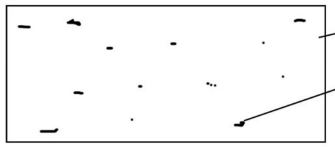
Methodological experimental study:
Density-Based Classification and Iron Content Estimation of Bloomery Iron Semi-Products: An Experimental Approach to Post-Reduction Technological Characterization



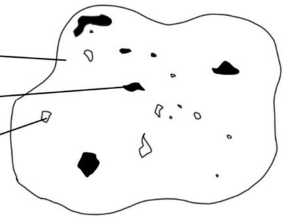




Cross-section of an iron bar



Cross-section of an iron bloom



Mass of the iron semi-product

$$m_{sp} = m_{\mathrm{Fe}} + m_{\mathrm{slag}} \quad (1)$$

Iron content of the semi-product by mass

$$\mathrm{Fe}\% = \frac{m_{\mathrm{sp}} - m_{\mathrm{slag}}}{m_{\mathrm{sp}}} \quad (2)$$

Volume of the iron bar (excluding voids)

$$V_{\mathrm{sp}} = V_{\mathrm{Fe}} + V_{\mathrm{slag}} \quad (3)$$

Volume of the iron bloom (including voids)

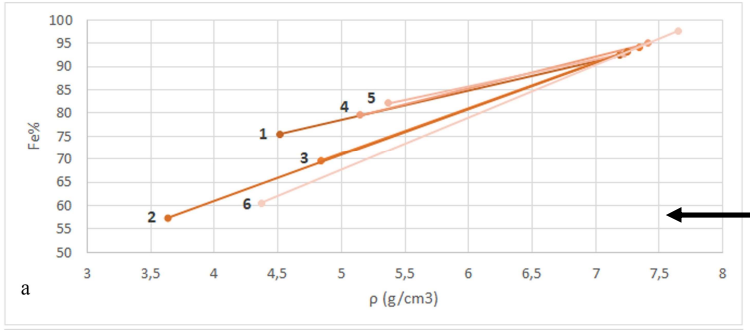
$$V_{\mathrm{sp}} = V_{\mathrm{Fe}} + V_{\mathrm{slag}} + V_{\mathrm{voids}} \quad (4)$$

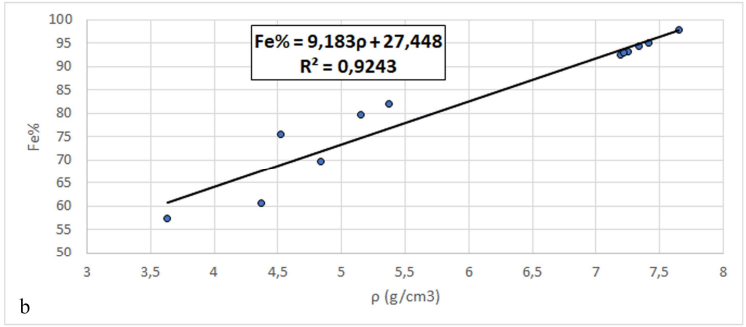
From this follows:

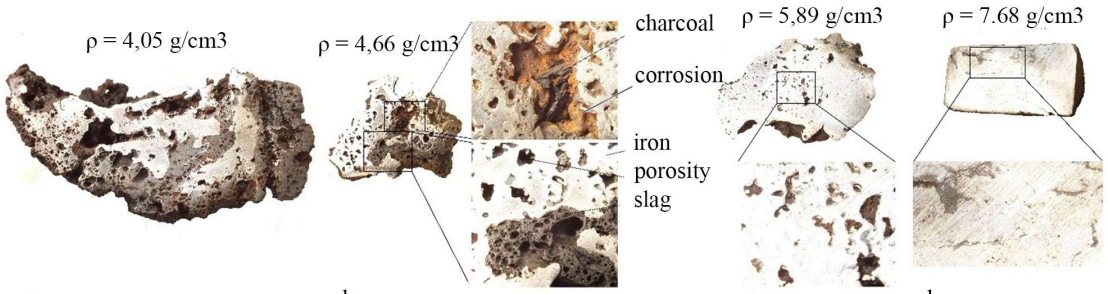
$$\frac{m_{sp}}{\rho_{sp}} = \frac{m_{\mathrm{Fe}}}{\rho_{\mathrm{Fe}}} + \frac{m_s}{\rho_s} \quad \Rightarrow \quad m_s = \frac{\rho_{\mathrm{Fe}}\rho_s \frac{m_{sp}}{\rho_{sp}} - \rho_s m_{sp}}{\rho_{\mathrm{Fe}} - \rho_s} \quad (5)$$

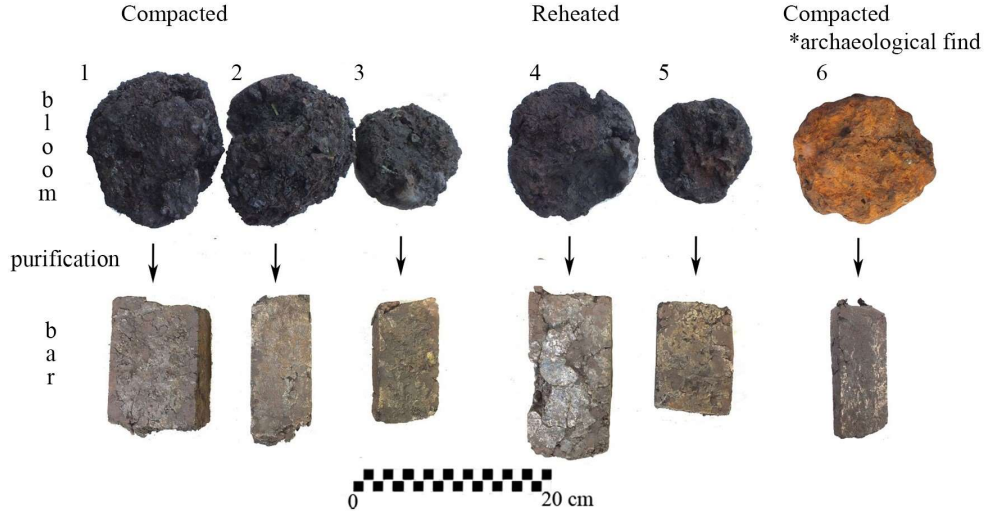
Porosity

$$P\% = \frac{V_{\mathrm{void}}}{V_{\mathrm{sp}}} = \frac{\frac{m_{sp}}{\rho_{sp}} - \frac{m_s}{\rho_s} - \frac{m_{sp} - m_s}{\rho_{\mathrm{Fe}}}}{\frac{m_{sp}}{\rho_{sp}}} \quad (6)$$

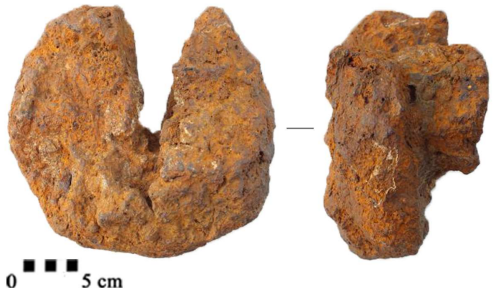


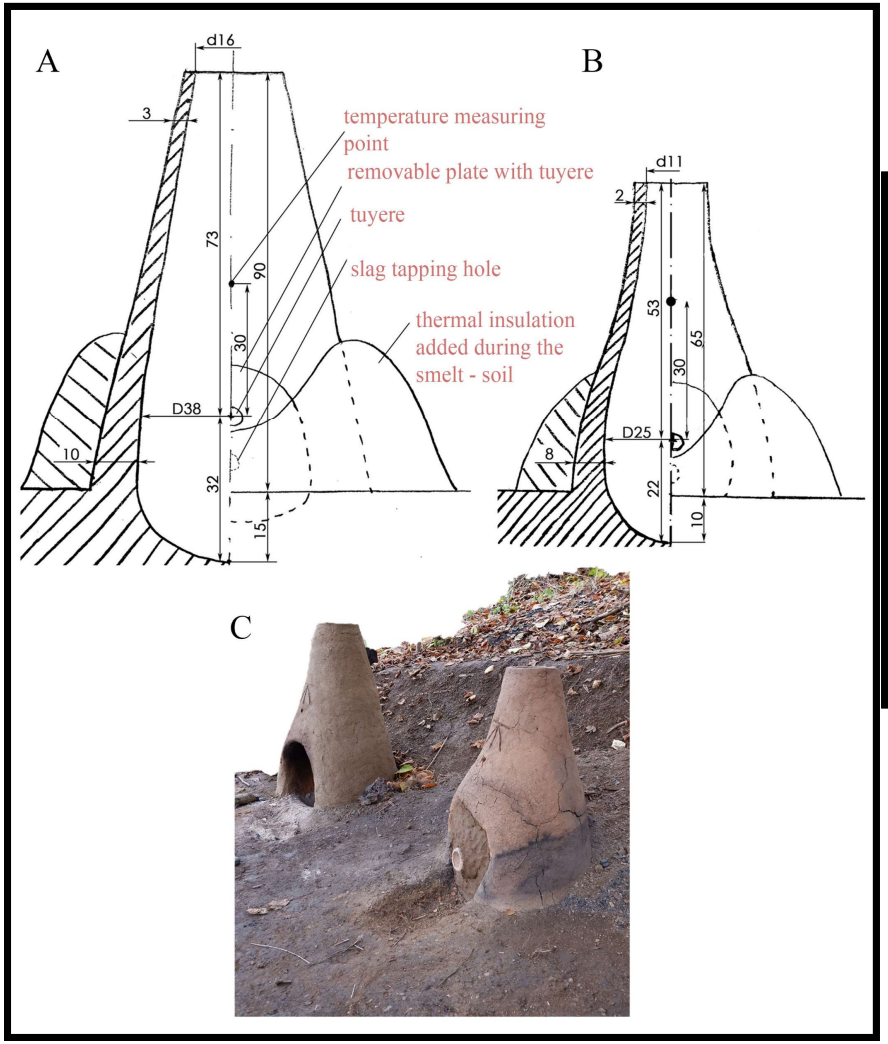


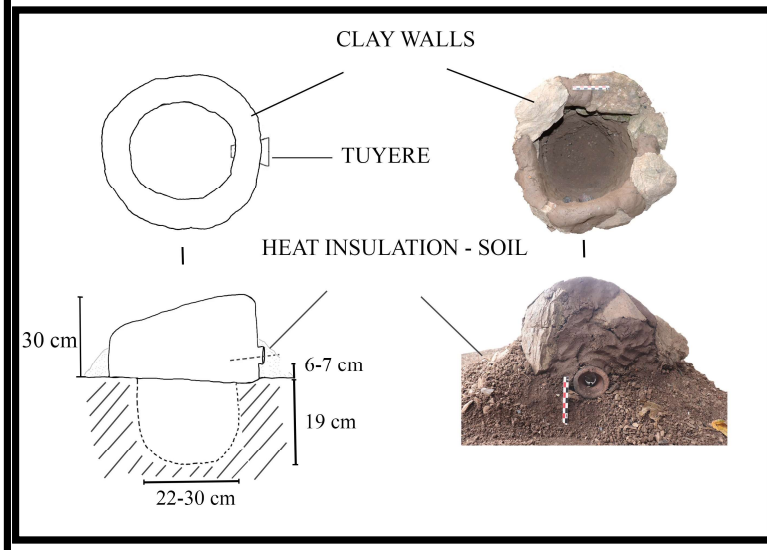


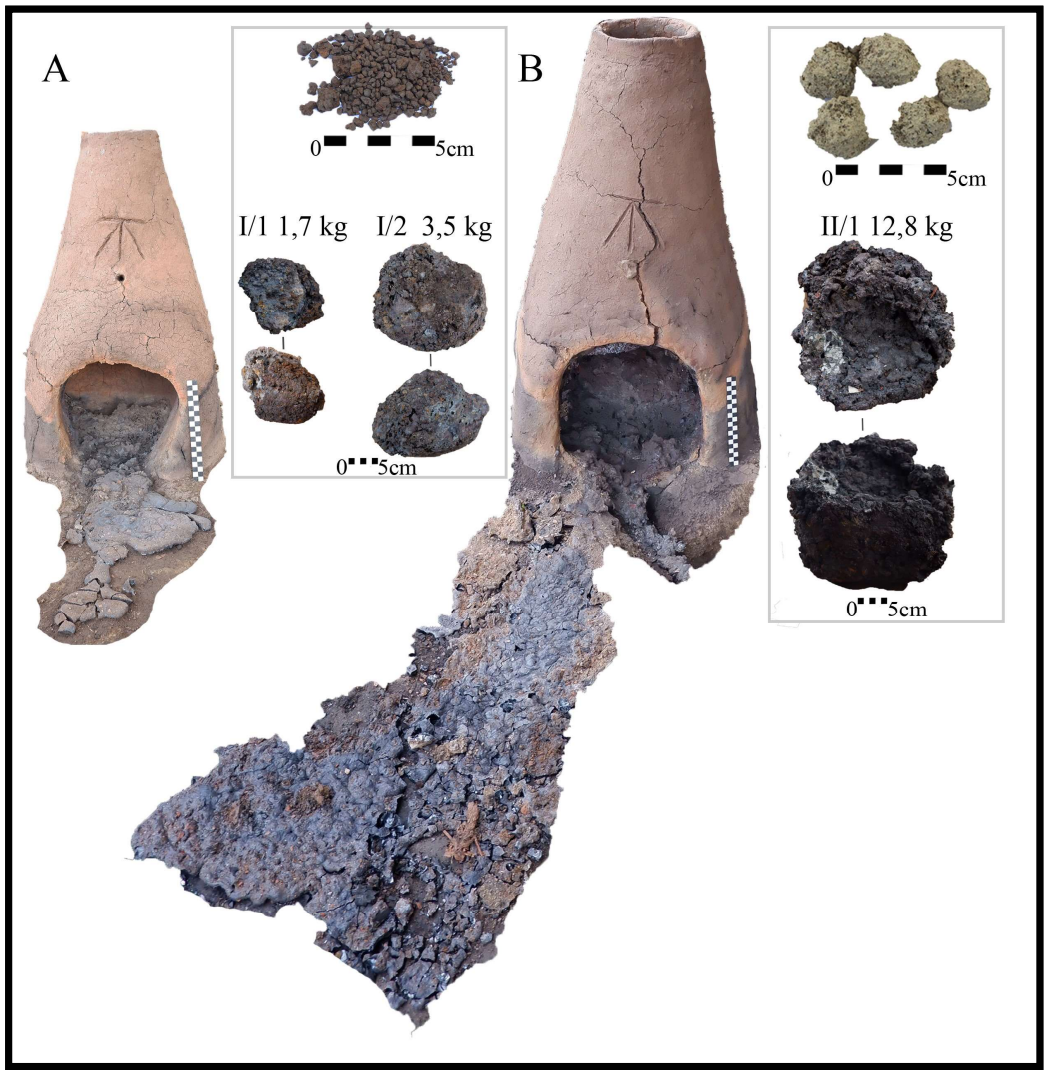


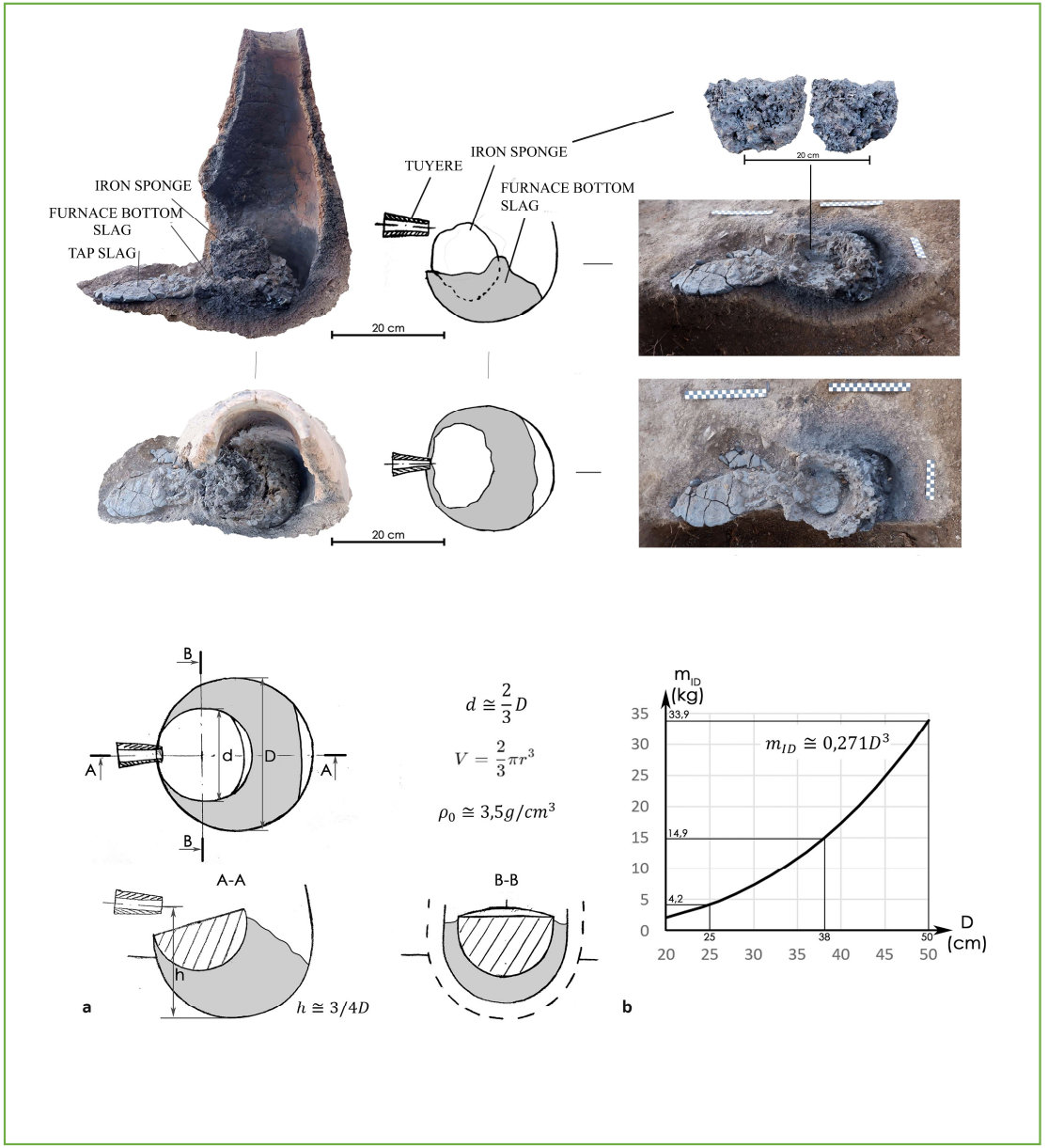
Technology and economic implications of massive iron bloom production in the Early Middle Ages within Carpathian basin - smelting and diffusion welding

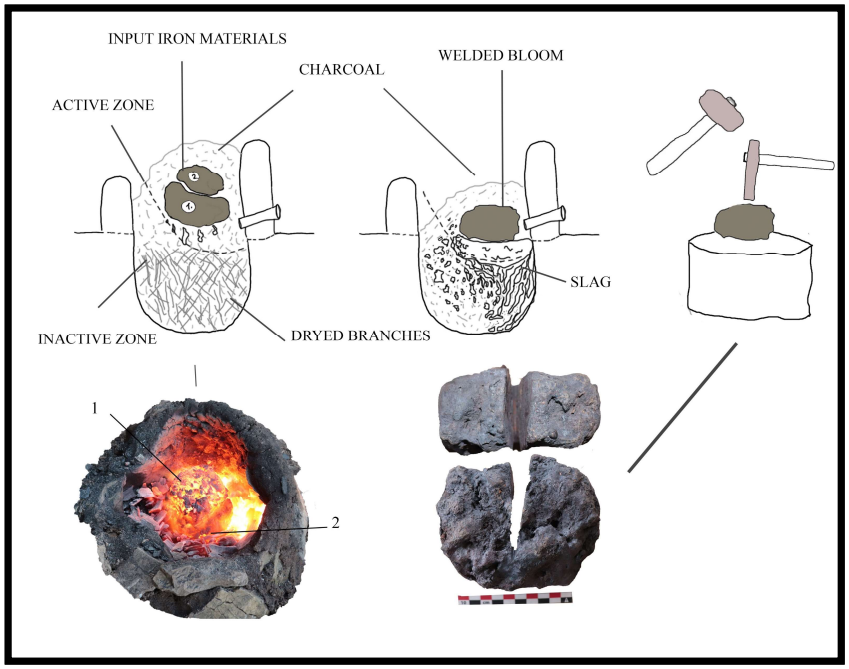


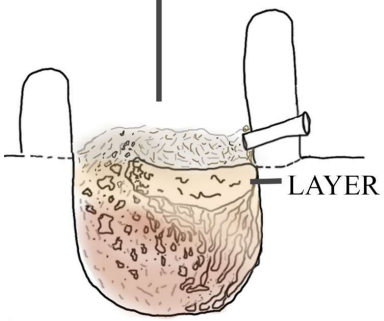




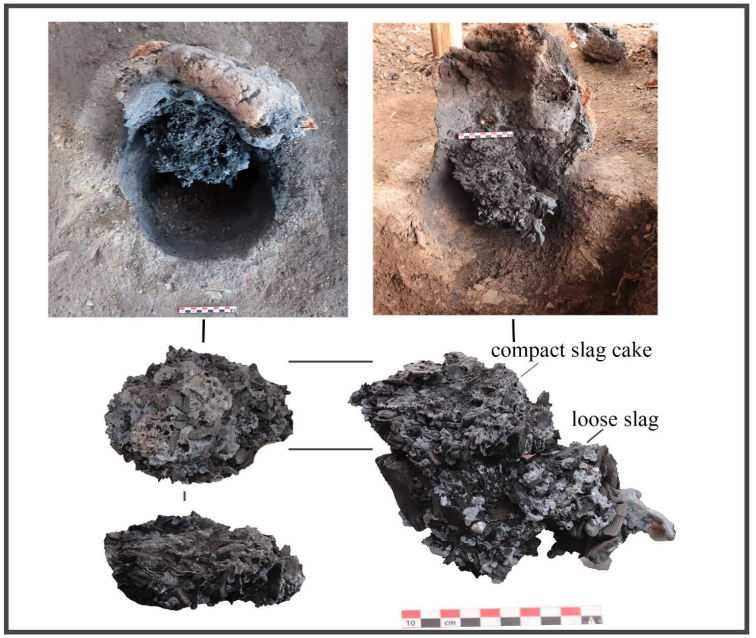

A
B
0 5cm
I/1 1,7 kg
I/2 3,5 kg
0 5cm
0 5cm
II/1 12,8 kg
0 5cm


IRON SPONGE
FURNACE BOTTOM SLAG
TAP SLAG
20 cm
TUYERE
IRON SPONGE
FURNACE BOTTOM SLAG
20 cm
20 cm
B
A
d
D
A
B
A-A
h
a
$h \cong 3/4D$
$d \cong \frac{2}{3}D$
$V = \frac{2}{3}\pi r^3$
$\rho_0 \cong 3{,}5 g/cm^3$
B-B
m_{ID} (kg)
33,9
14,9
4,2
$m_{ID} \cong 0{,}271D^3$
35
30
25
20
15
10
5
0
20 25 30 35 40 45 50
D (cm)
b


INPUT IRON MATERIALS
CHARCOAL
WELDED BLOOM
ACTIVE ZONE
SLAG
INACTIVE ZONE
DRYED BRANCHES
1
2


LAYER 1
A
LAYER 2
LAYER 3


B


compact slag cake
loose slag

Thank you !