SAGA

The Soil Science & Archaeo-Geophysics Alliance

Training School 1

Geophysical methods 3: Electromagnetic induction

GHENT UNIVERSITY

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cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

HORIZON 2020

NTNU

FORTH Foundation for Research & Technology - Hellas

GeoSat ReSeArch Lab of Geophysical-Satellite Remote Sensing and Archaeoenvironment

What is electromagnetism?

What is electromagnetism?

Ampère-Maxwell law

An electrical current (or electrical field) induces circulating magnetic fields

$$\vec{\nabla} \times \vec{\boldsymbol{H}} = \sigma \vec{\boldsymbol{E}} + \varepsilon \frac{\partial \vec{\boldsymbol{E}}}{\partial t}$$

Faraday's law

An alternating magnetic field induces a circulating electrical field

$$\vec{\nabla} \times \vec{\boldsymbol{E}} = -\mu \frac{\partial \vec{\boldsymbol{H}}}{\partial t}$$

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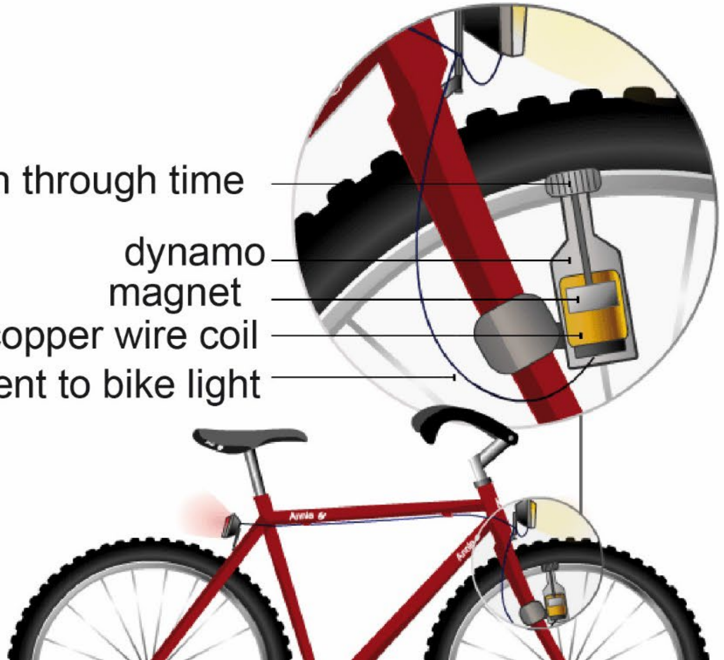

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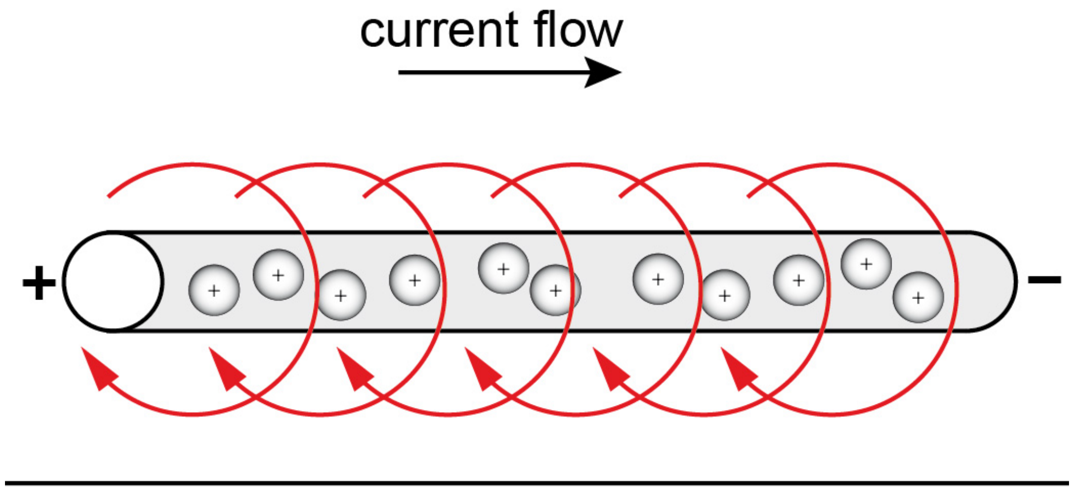
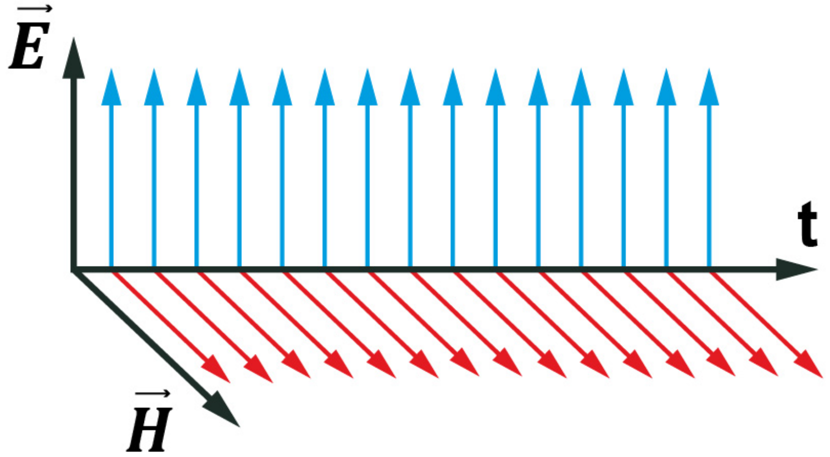
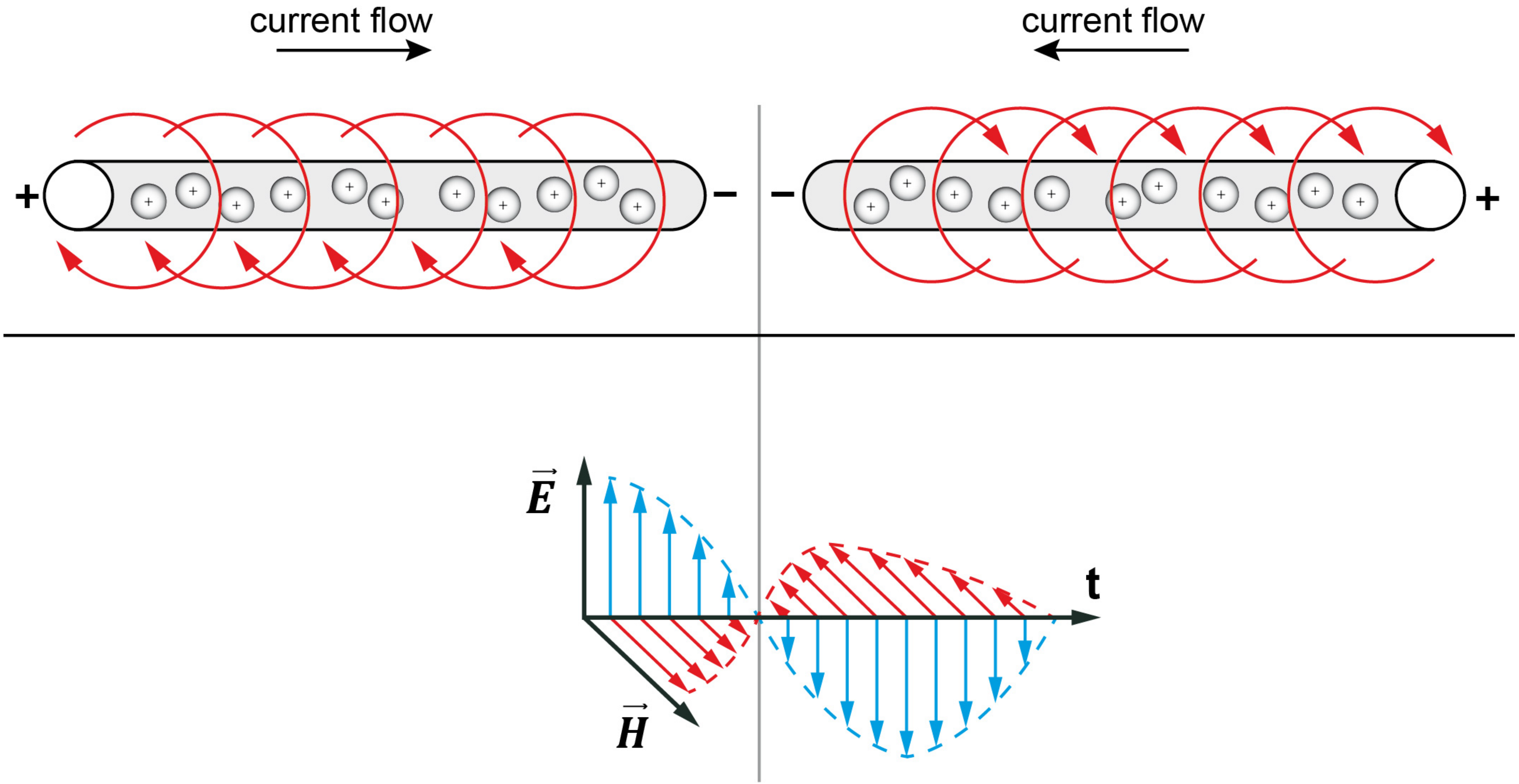
Uniform and time-varying electromagnetic fields



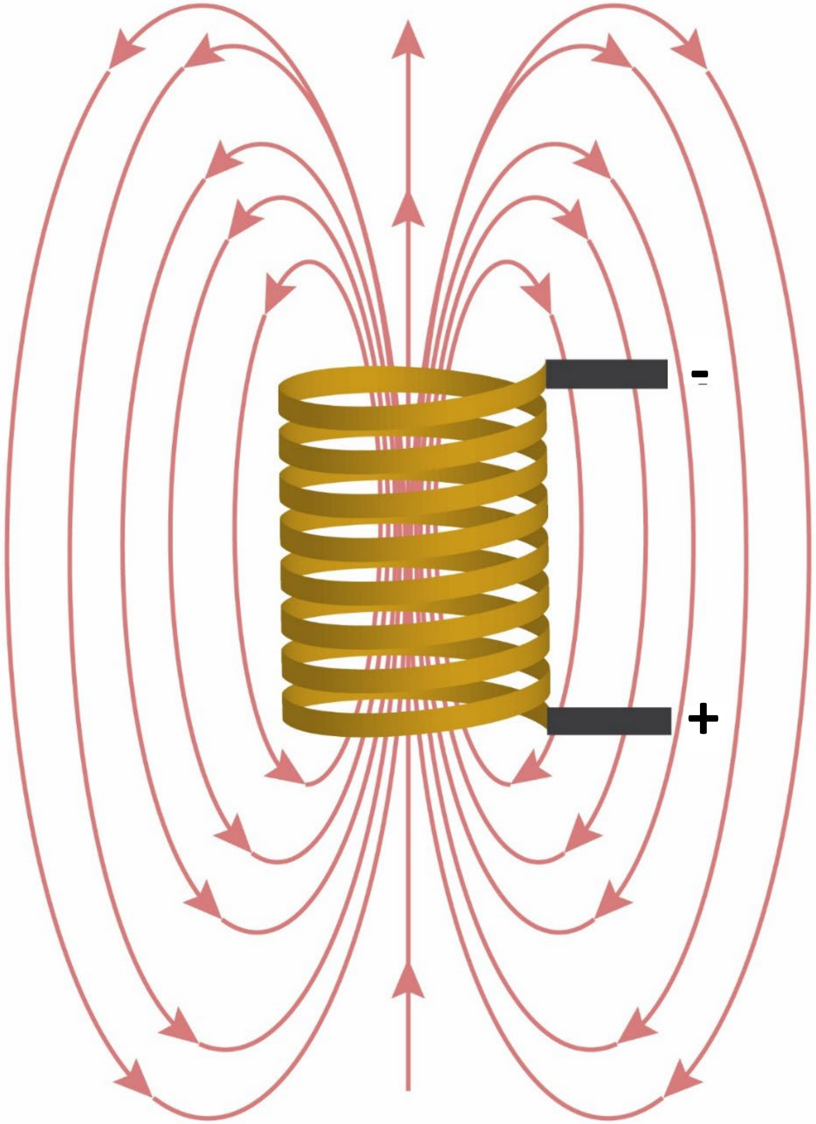


Uniform and time-varying electromagnetic fields



Properties of time-varying electromagnetic fields

A magnetic field is induced around a wire coil by an alternating current, varying at frequency *f*. As a result, the induced magnetic field oscillates at the same frequency *f*.



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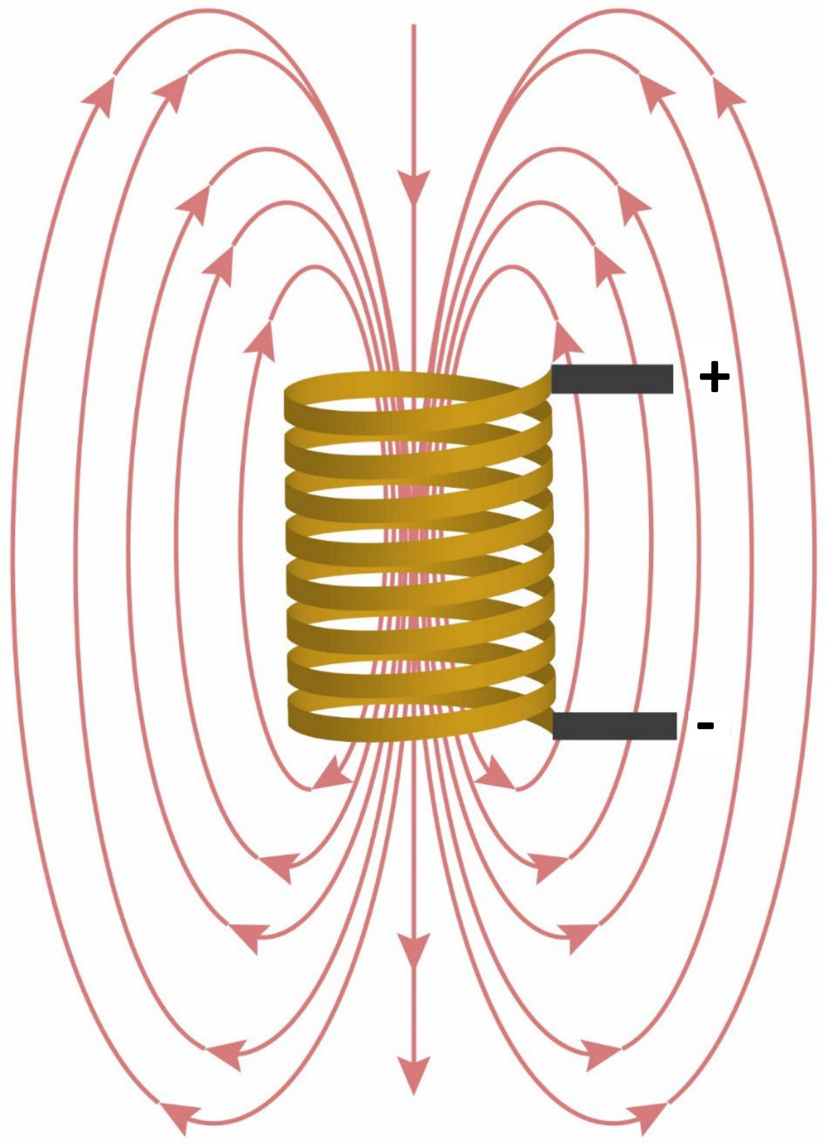
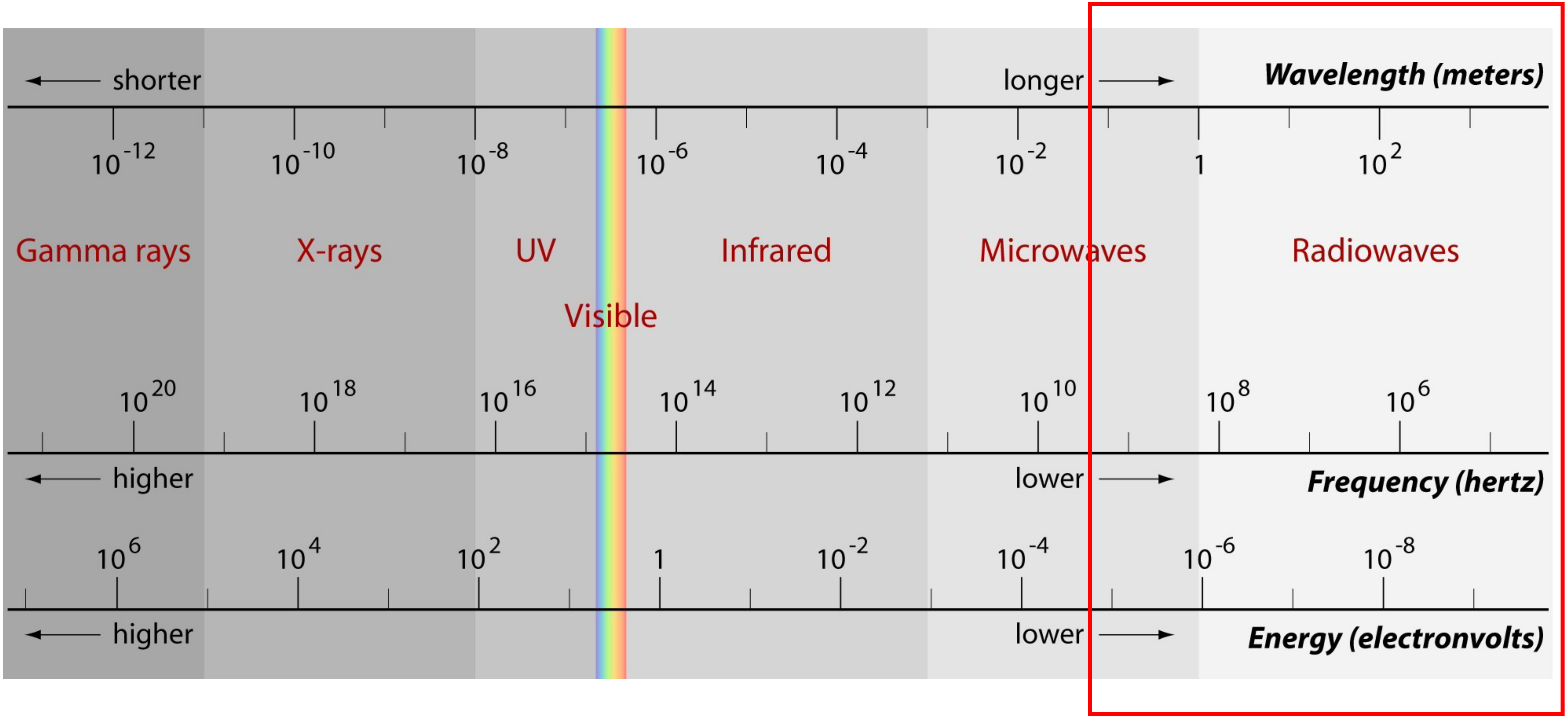


Properties of time-varying electromagnetic fields

Relevance for geophysical prospection



Ok, that's all very nice, but
what does it mean???

Depending on the frequency of the applied EM field, this field will behave differently in a specific medium.

Ok, that's all very nice, but
what does it mean???

Depending on the frequency of the applied EM field, this field will behave differently in a specific medium.

Properties of the applied EM field determines the response we get from the soil.

Electromagnetic methods in archaeological prospection

Ground penetrating radar (GPR)

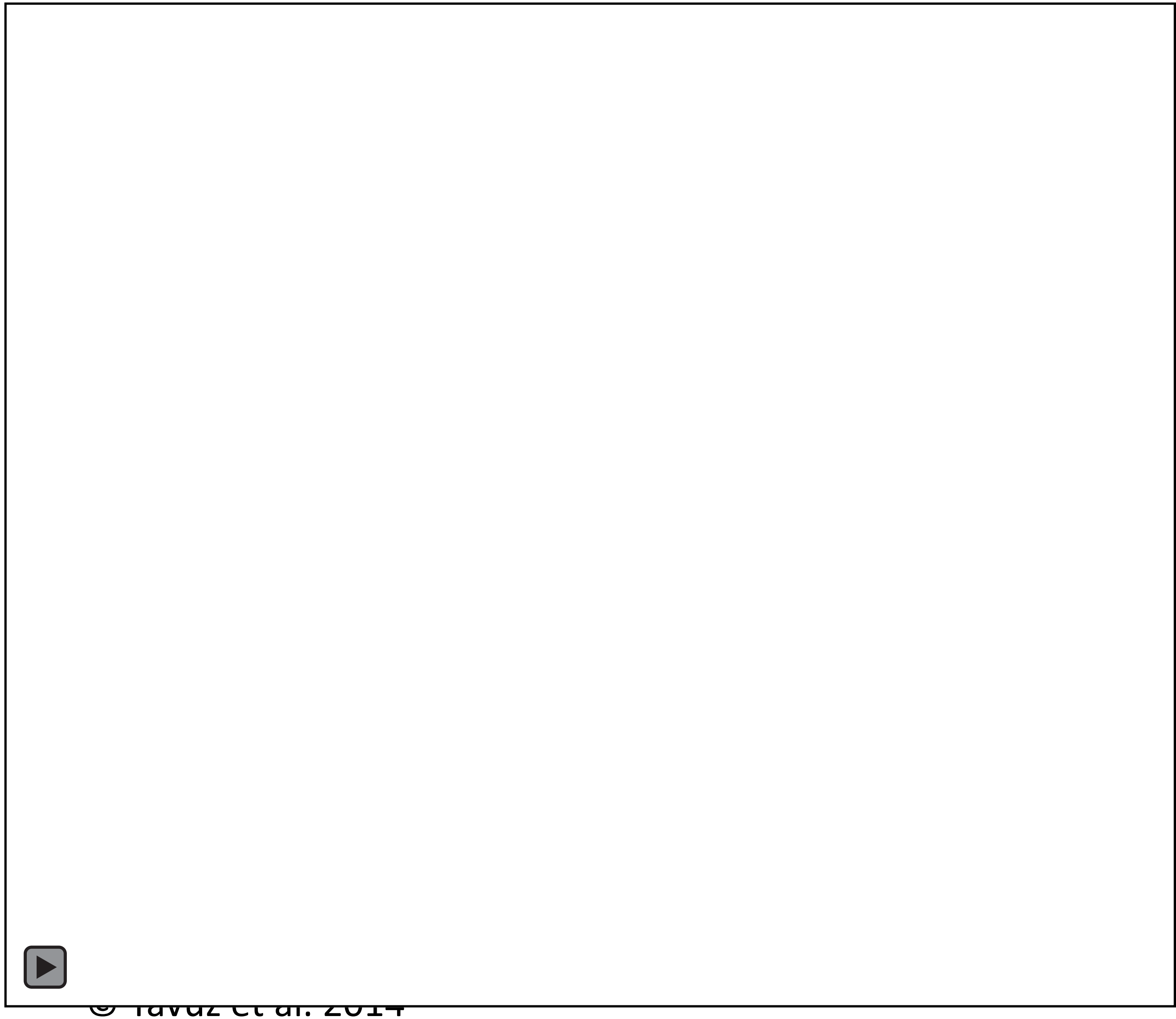
Electromagnetic induction (EMI)

Main difference between these two: frequency of the applied electromagnetic field

Ground penetrating radar (GPR)

Field frequency between **10 MHz to 1 GHz**

→ Field acts like a ***wave*** in a medium



Ground penetrating radar (GPR)

Field frequency between **10 MHz to 1 GHz**

→ Field acts like a **<u>wave</u>** in a medium

$$\vec{\nabla} \times \vec{\boldsymbol{H}} = \sigma \vec{\boldsymbol{E}} + \varepsilon \frac{\partial \vec{\boldsymbol{E}}}{\partial t}$$

Dielectric permittivity

Electromagnetic induction (EMI)

Field frequency between **1 kHz to 100 kH**

→ Field travels **diffusely** through a mediu

Electromagnetic induction (EMI)

Field frequency between **1 kHz to 100 kHz**

→ Field travels **diffusely** through a medium

$$\vec{\nabla} \times \vec{H} = \boxed{\sigma \vec{E} +} \varepsilon \frac{\partial \vec{E}}{\partial t}$$

Electrical conductivity

Electromagnetic induction (EMI)

Field frequency between **1 kHz to 100 kHz**

→ Field **<u>induces a response</u>**, a second magnetic field ***H.***

$$\overrightarrow{H_s} \propto \boldsymbol{\sigma} \text{ and } \kappa$$

Proportionate to **electrical** and **magnetic** properties of the soil

Properties influencing the EMI response

σ **or EC: electrical conductivity**

$$\sigma = \frac{1}{\rho}$$

*Expressed in Siemens per meter (**S/m**)*

κ **or MS: magnetic susceptibility**

$$\kappa = \frac{\overrightarrow{\boldsymbol{M}}}{\overrightarrow{\boldsymbol{H}}}$$

Dimensionless

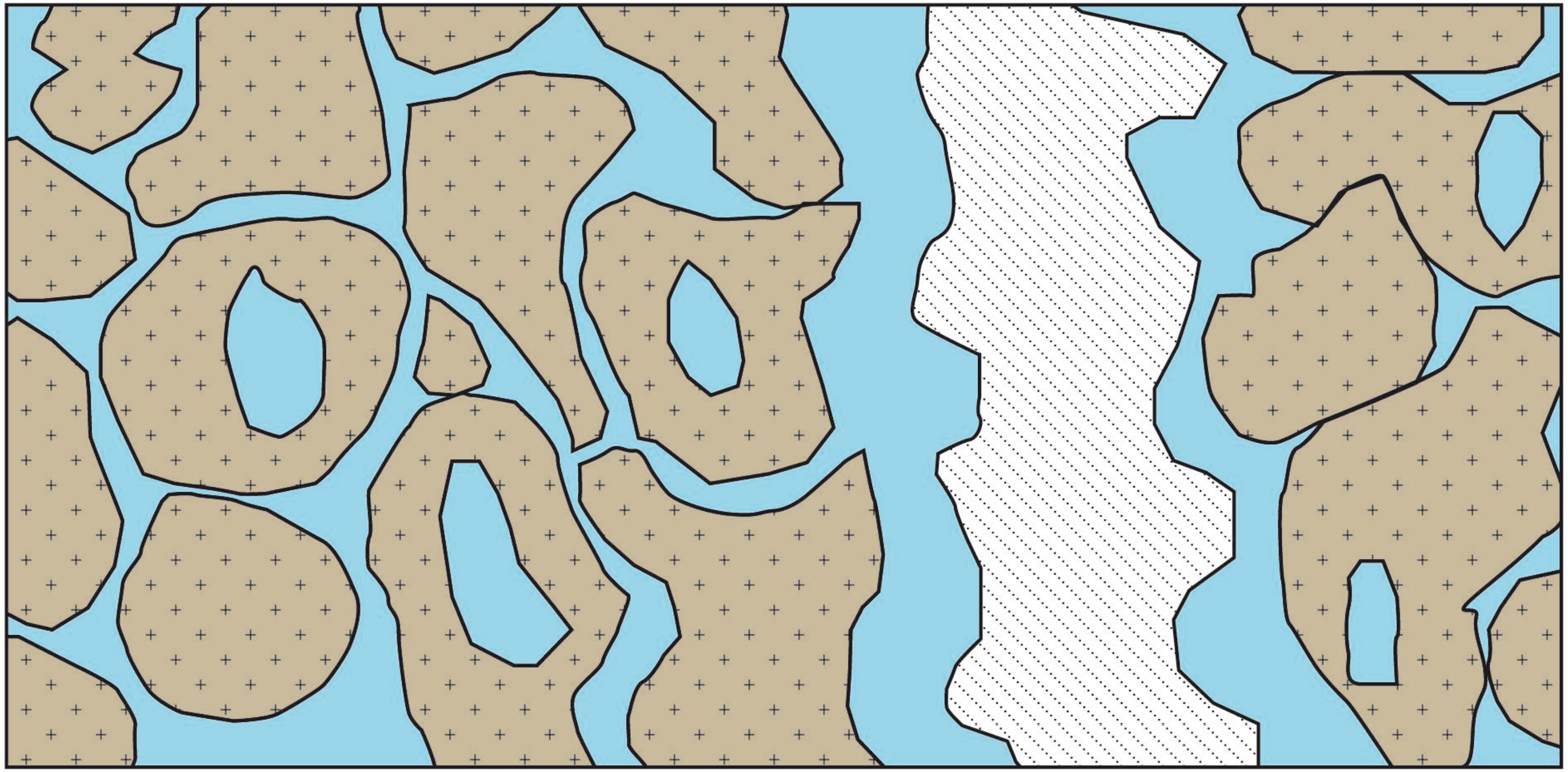
Electrical conductivity of soils

overall very poor conductivity

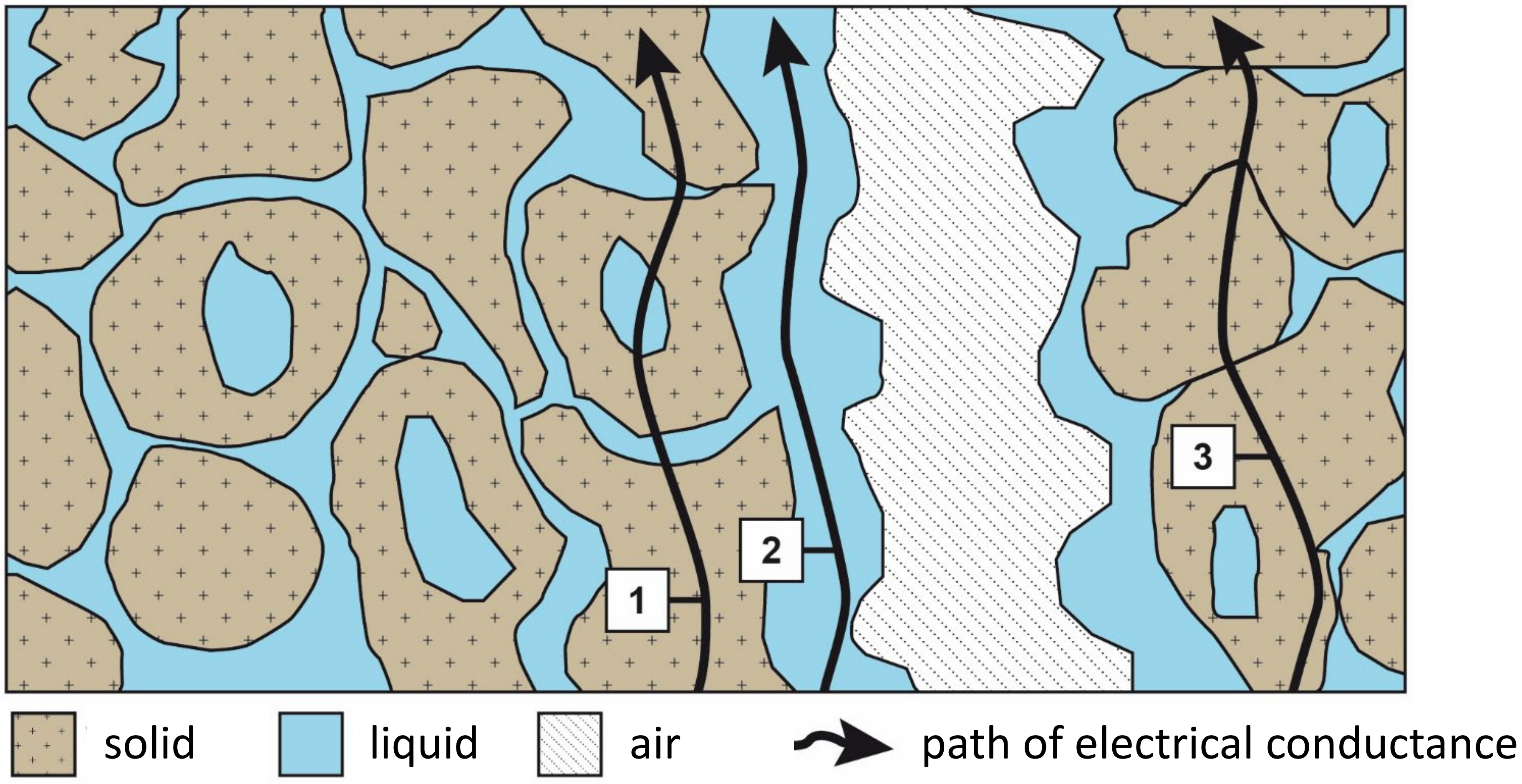
Material	ρ [Ωm]	σ [S/m]
Copper	1.72×10^{-8}	5.814×10^{7}
Aluminium	2.83×10^{-8}	3.534×10^{7}
Sand (wet)	20 – 200	0.005 – 0.05
Loess	20 – 40	0.025 – 0.05
Clay	5 – 25	0.04 – 0.2
Saline sand	1 – 10	0.1 – 1

Therefore soil EC is expressed in **milliSiemens per meter (mS/m)**

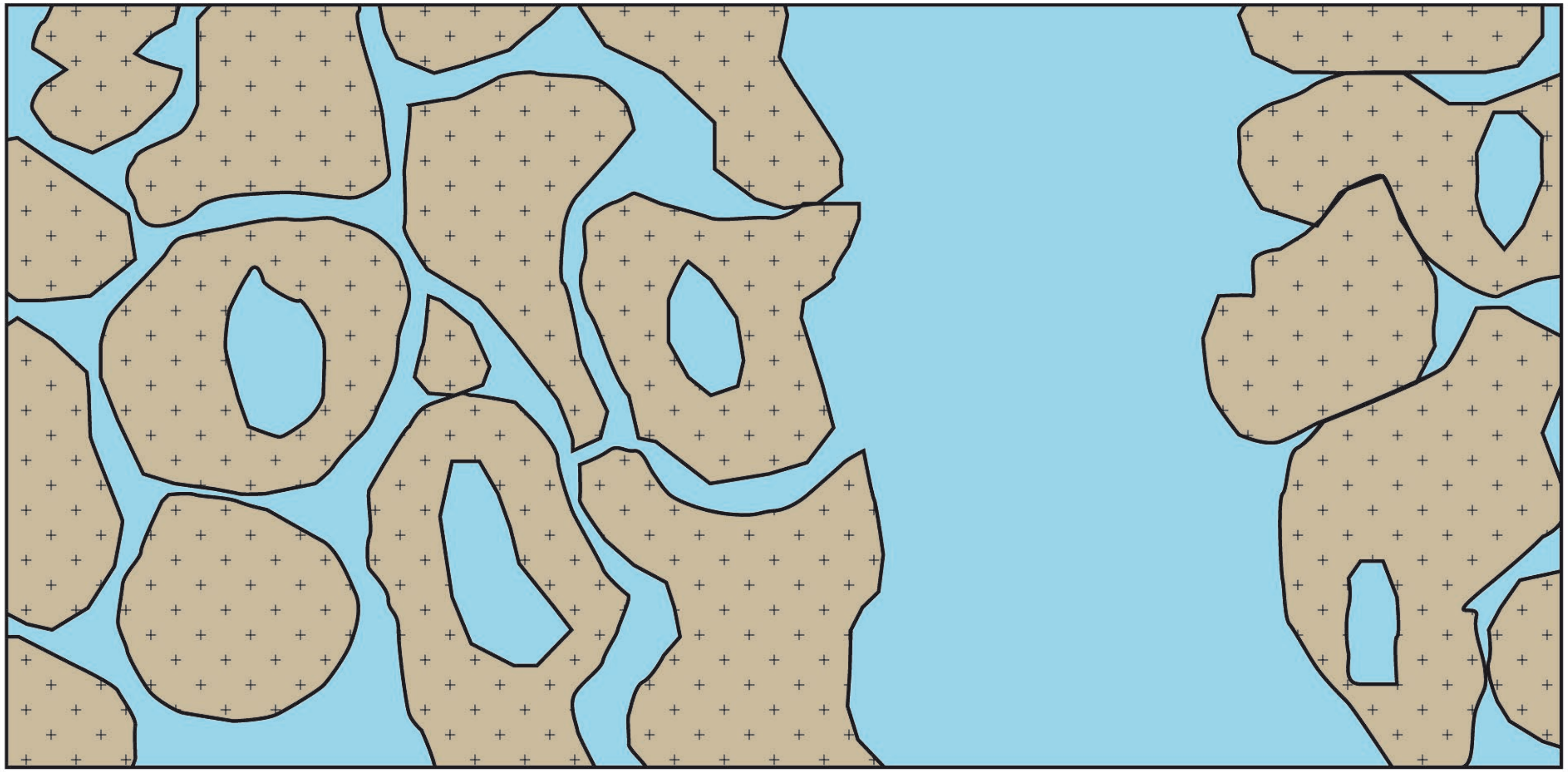
Electrical conductivity of soils

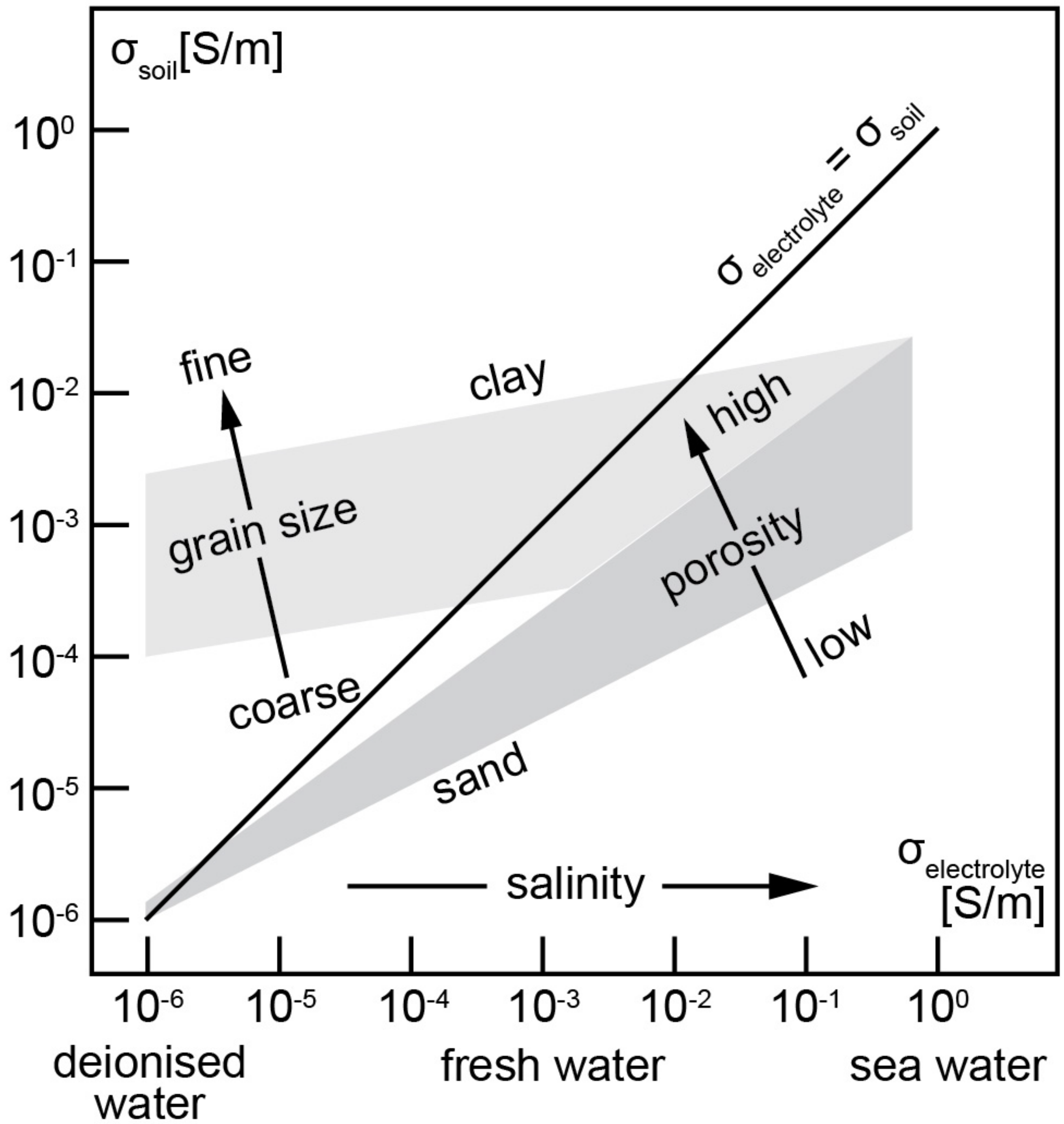


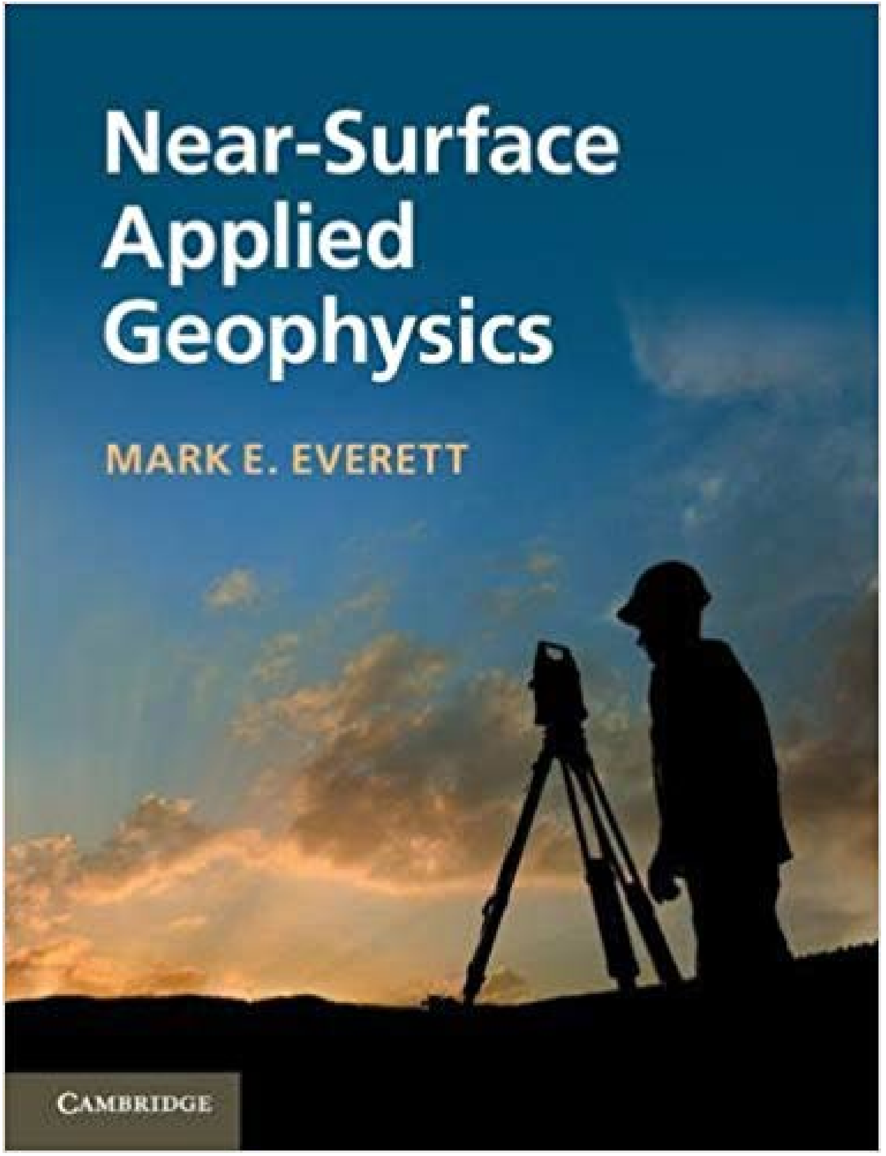
Electrical conductivity of soils



*Factors influencing EC of **water saturated soils***







Everett, 2013

Electrical conductivity of soils

SOLID FRACTION

- Predominantly electrically neutral (inert)
- Exception: components that can exchange charged particles (cations) in the soil matrix (cf. CEC / cation exchange capacity)
  → *clay, organic matter*

LIQUID PHASE

- Availability of free ions (e.g. salts) in the pore solution contribute to the soil conductivity

AIR

- Porosity contributes to the soil conductivity

Electrical conductivity of soils

NON-POROUS GEOLOGICAL MATERIAL

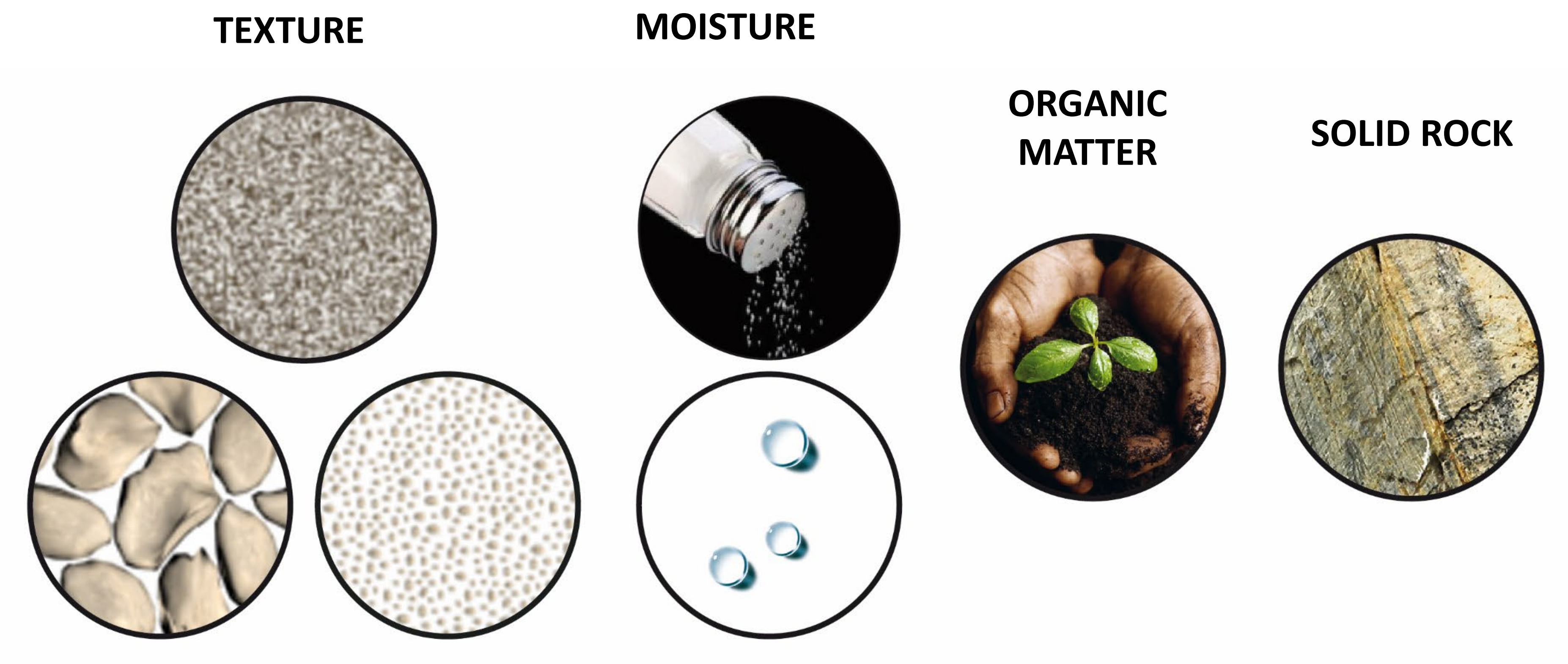
- Solid (bed)rock has a higher resistivity than unconsolidated sediment

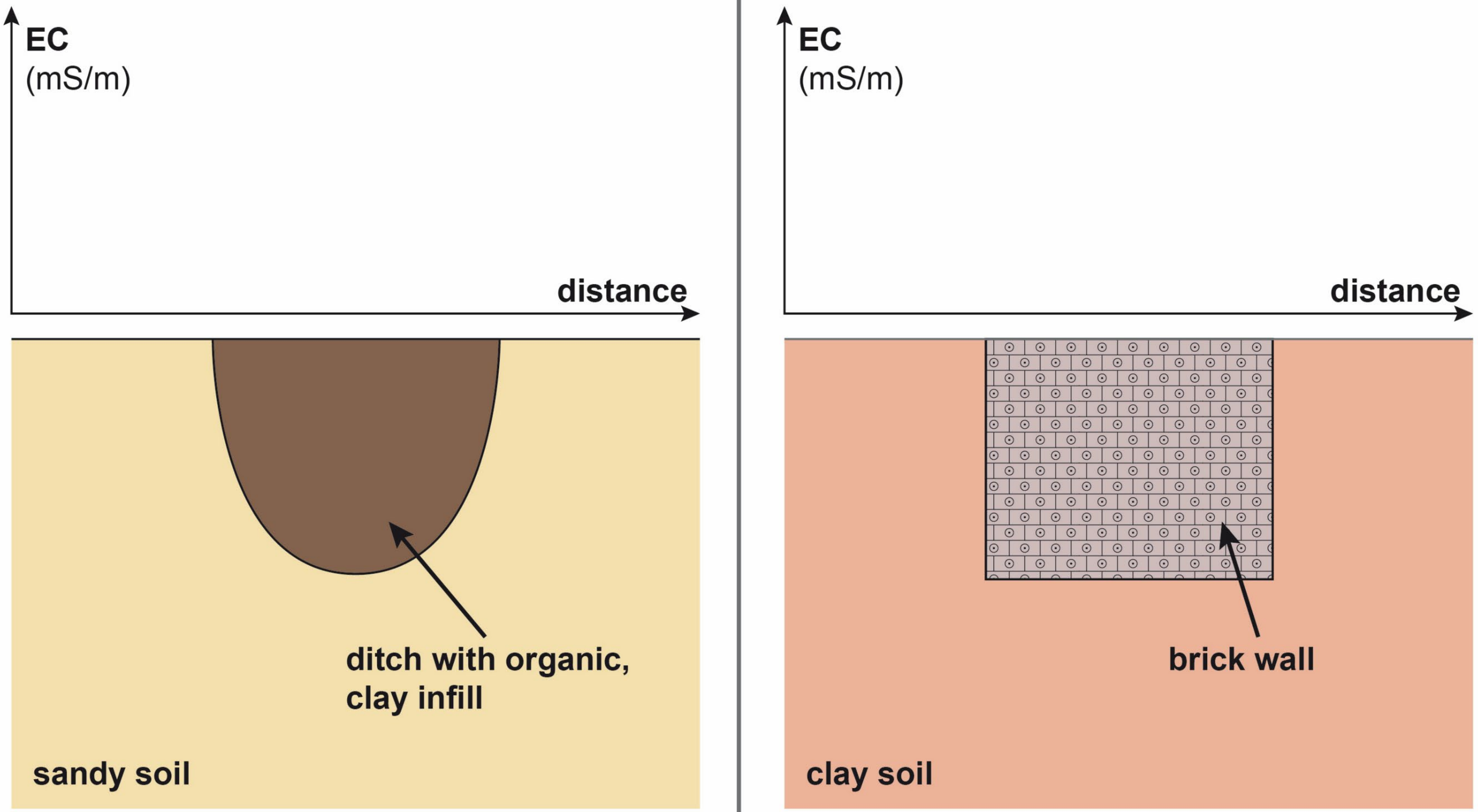
ANTROPOGENIC OBJECTS

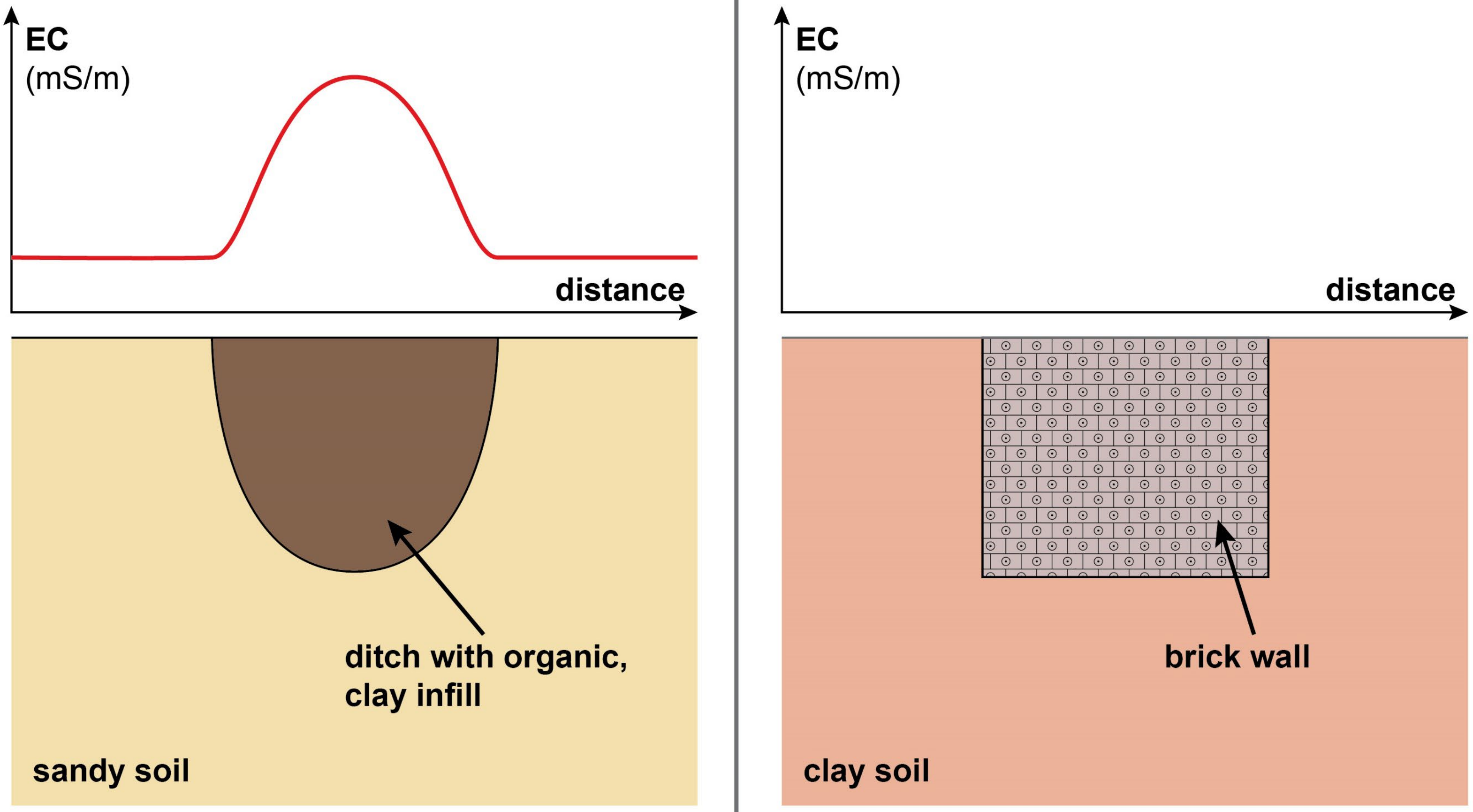
- Metal: very high conductivity (high inductive capacity)
- Non-porous materials (e.g. brick)

Electrical conductivity of soils

- Porosity
- Water content
- Organic matter content
- Clay content
- Salinity
- Geology




EC
(mS/m)
distance
ditch with organic,
clay infill
sandy soil
EC
(mS/m)
distance
brick wall
clay soil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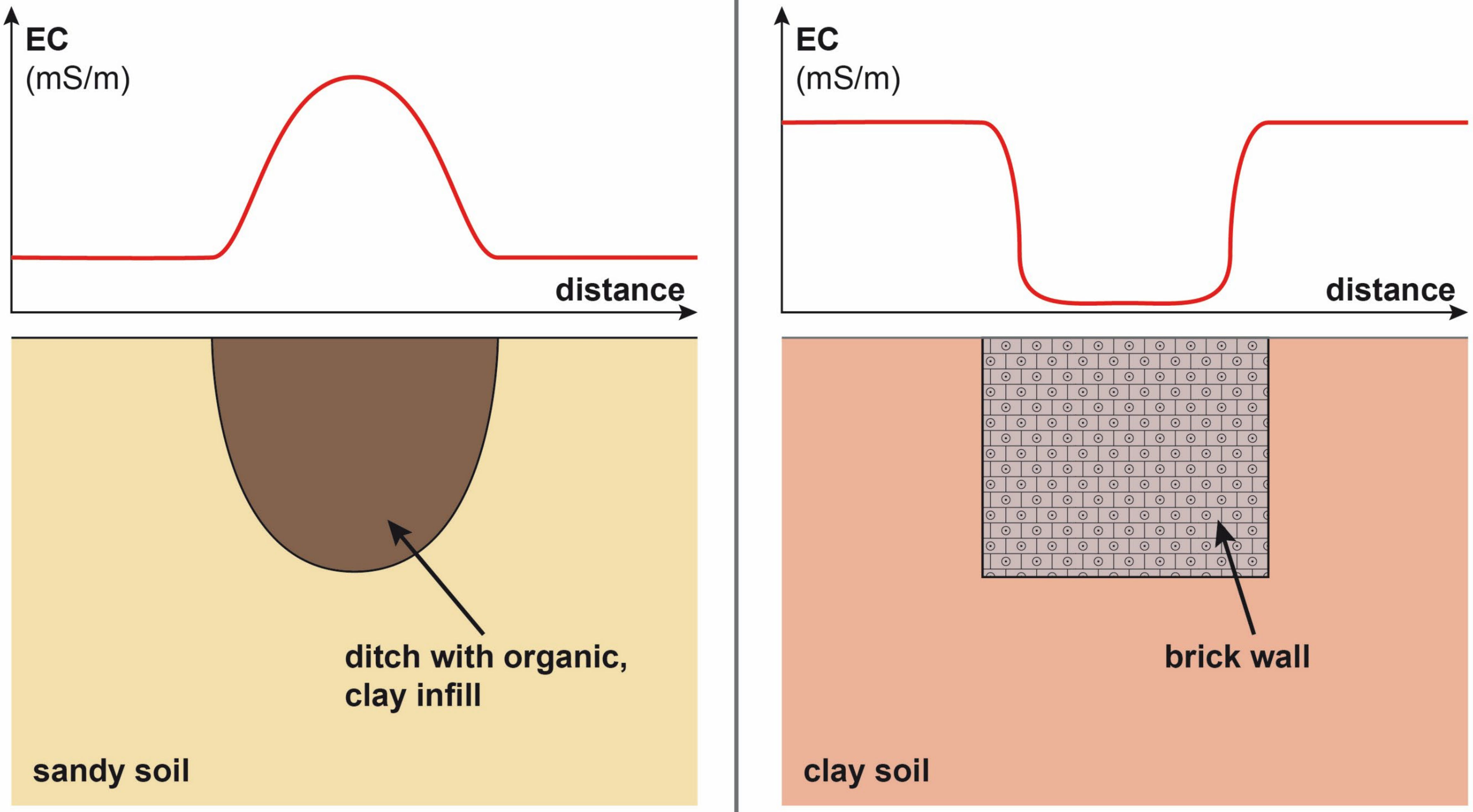

EC
(mS/m)
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ditch with organic,
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EC
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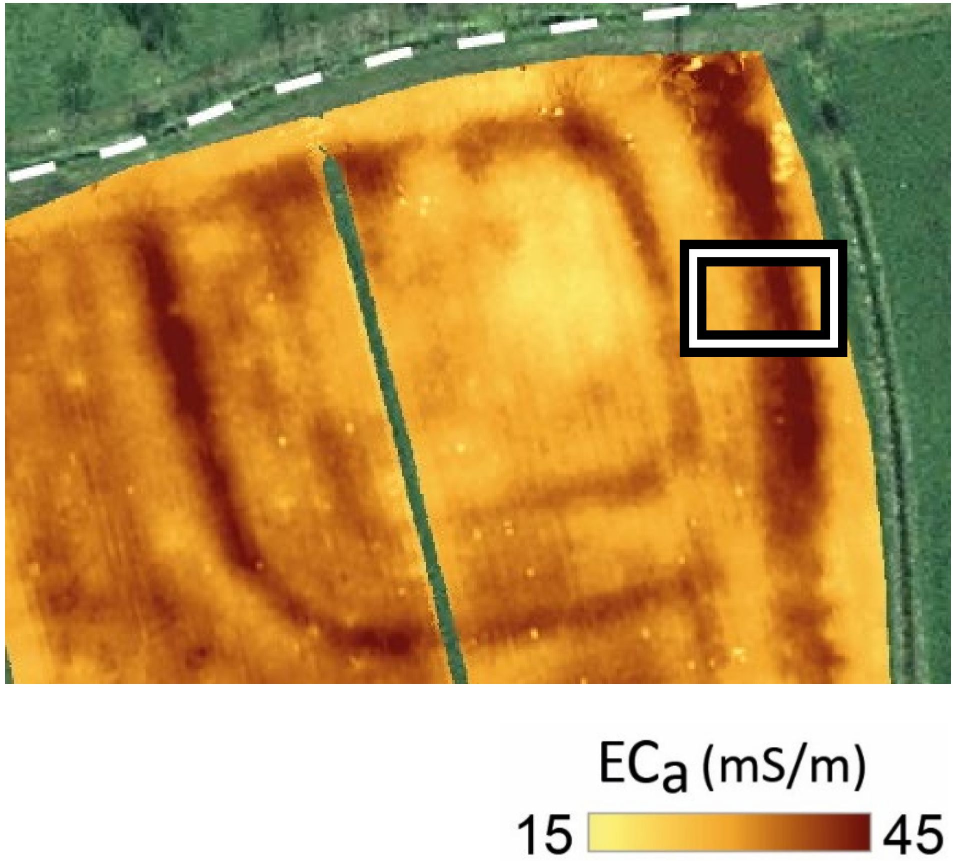
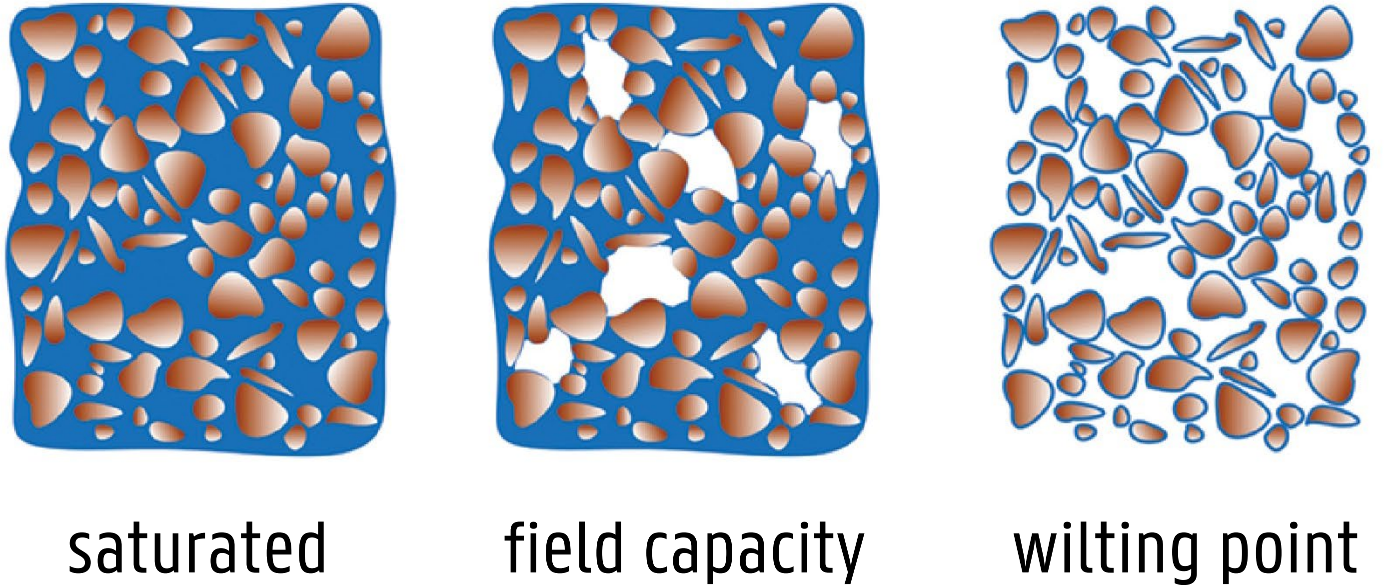
distance
brick wall
clay soil

Ditch with organic clay fill in sandy soil

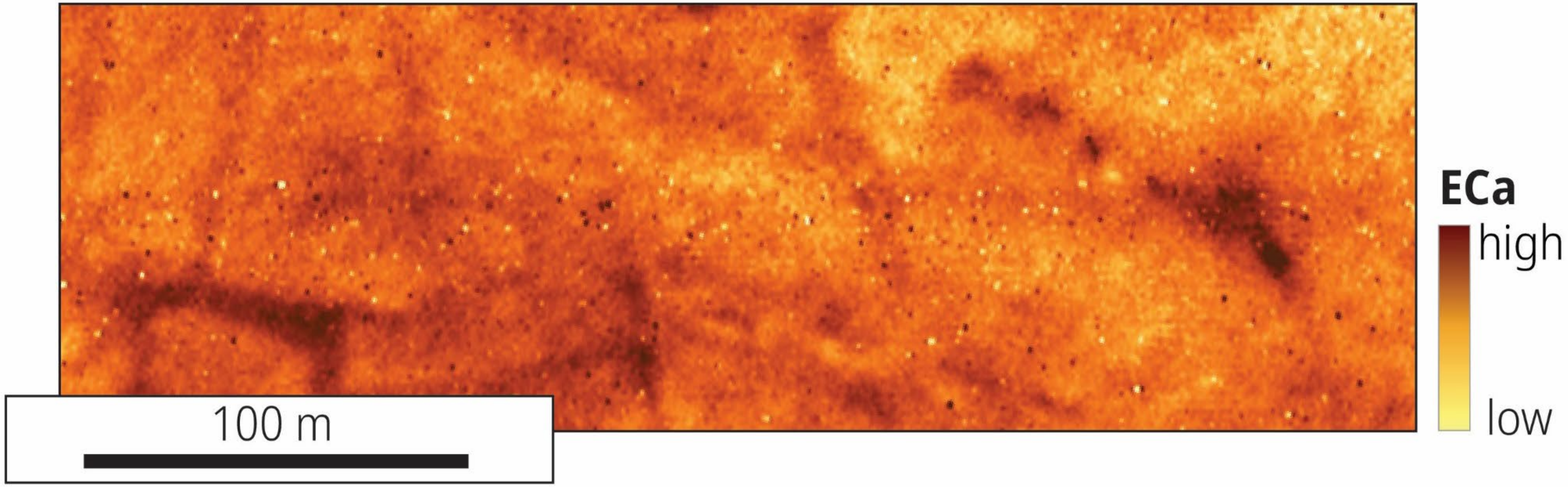
EC map obtained with EMI survey

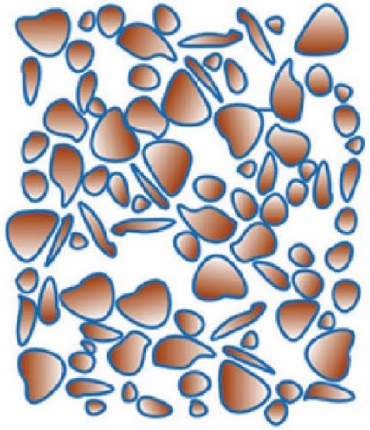


Electrical conductivity of soils: **the importance of moisture balance**

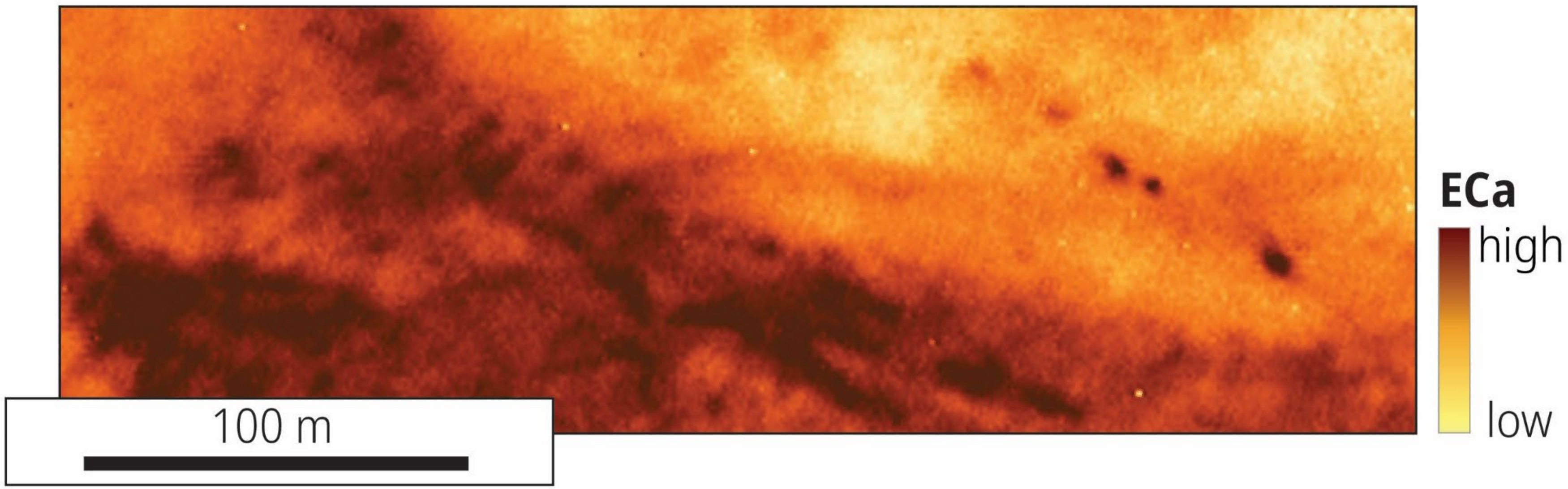


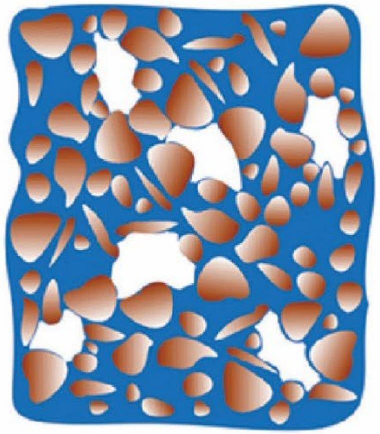
Example: **ECa variation observed under dry conditions**





Example: **ECa variation observed under wet conditions**





Properties influencing the EMI response

σ or EC: electrical conductivity

$$\sigma = \frac{1}{\rho}$$

Properties influencing the EMI response

***κ* or MS: magnetic susceptibility**

$$\kappa = \frac{\overrightarrow{\boldsymbol{M}}}{\overrightarrow{\boldsymbol{H}}}$$

Magnetic susceptibility of soils

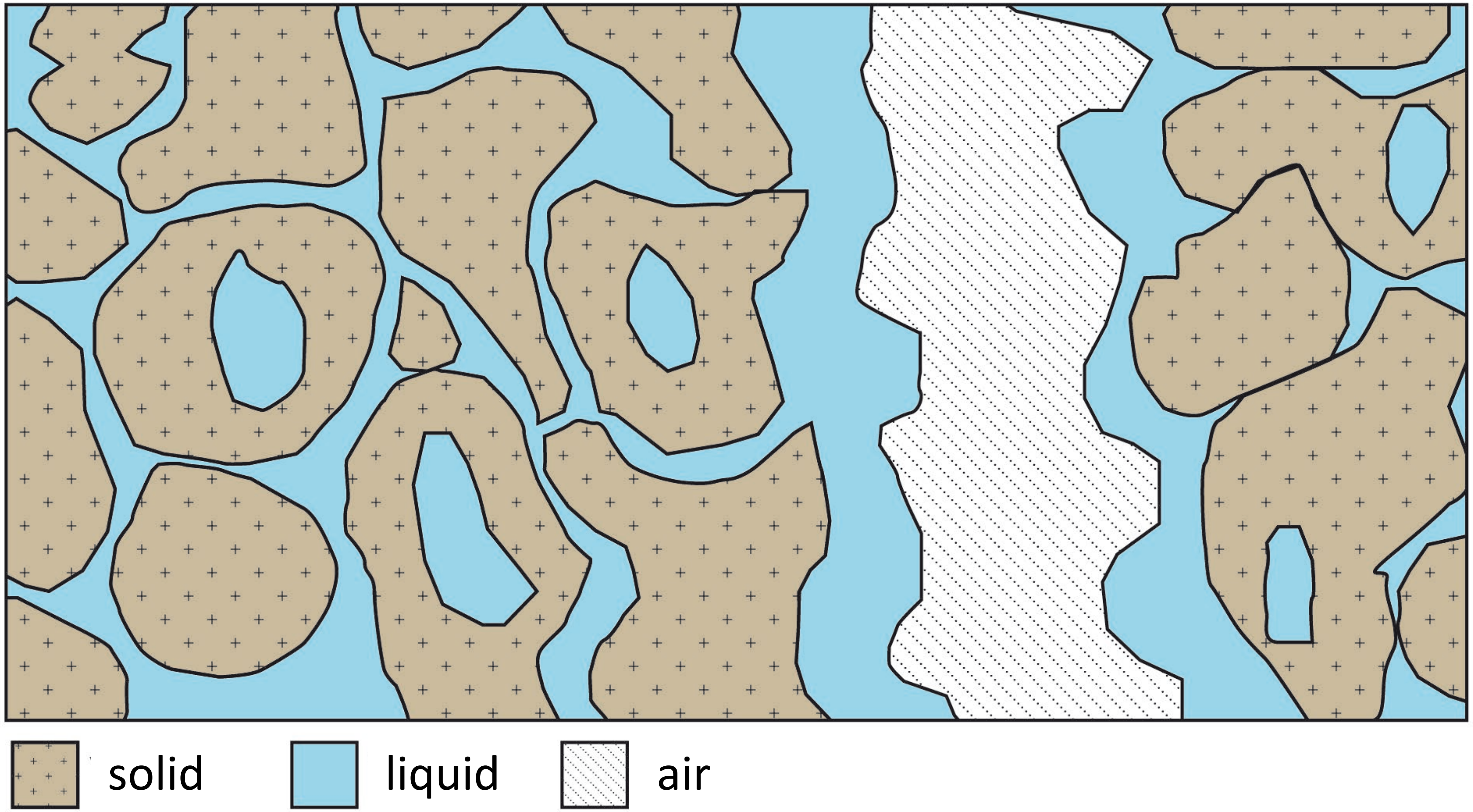
overall very low susceptibility

	κ (× 10^{-5})
Clay particles	15 – 25
quartzite	-17 – -13
calcite	-3.9 – -0.7
magnetite	100000 – 570000
maghemite	200000 – 250000
haematite	50 – 4000
goethite	110 – 1200

Primary influence from **iron oxides**

Magnetic susceptibility of soils

Which soil fraction contributes to the magnetic signal?



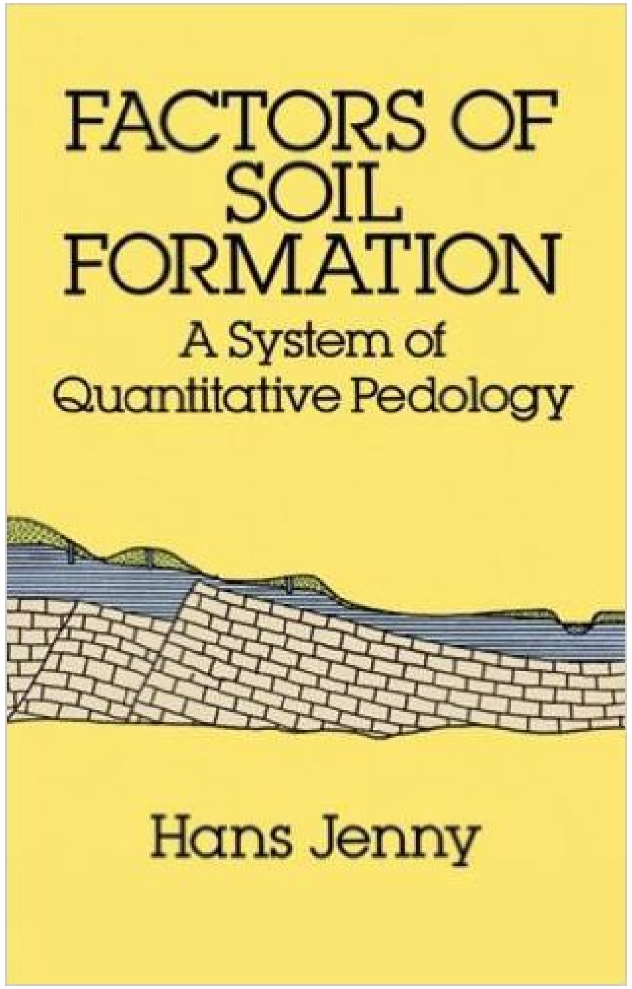
Magnetic susceptibility of soils

Form of iron oxides in soils depends on:

- Biochemical interaction between soil components, and the influence of living organisms
  => **Pedogenic** processes

- **External** factors:
  - Climate
  - Topography
  - Time
  - Human influence

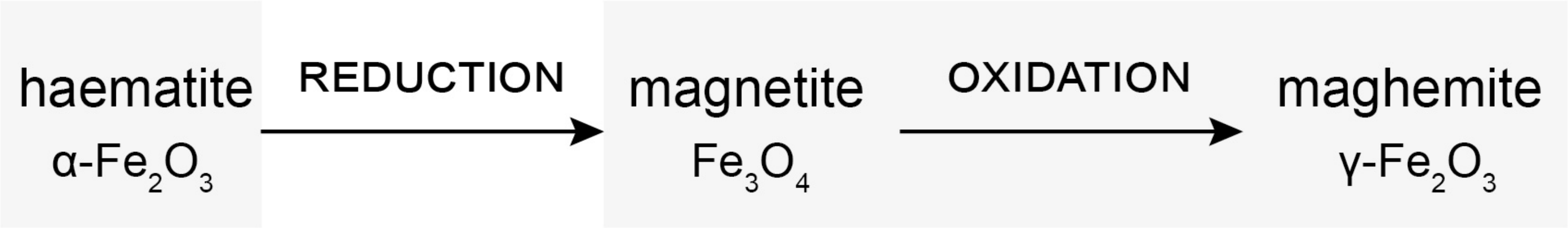
- **Geological** *(lithogenic magnetic particles)*



1. Reduction + oxidation

Process whereby poorly magnetic iron oxides are transformed to strongly magnetic variations

→ Often related to human occupation

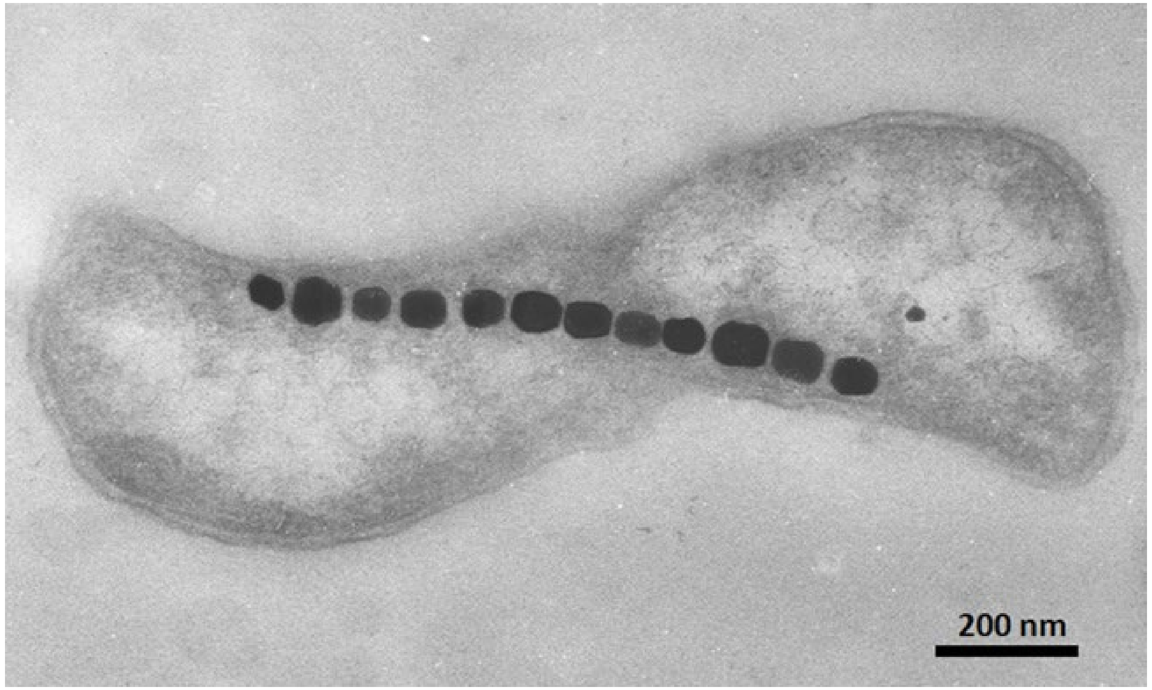


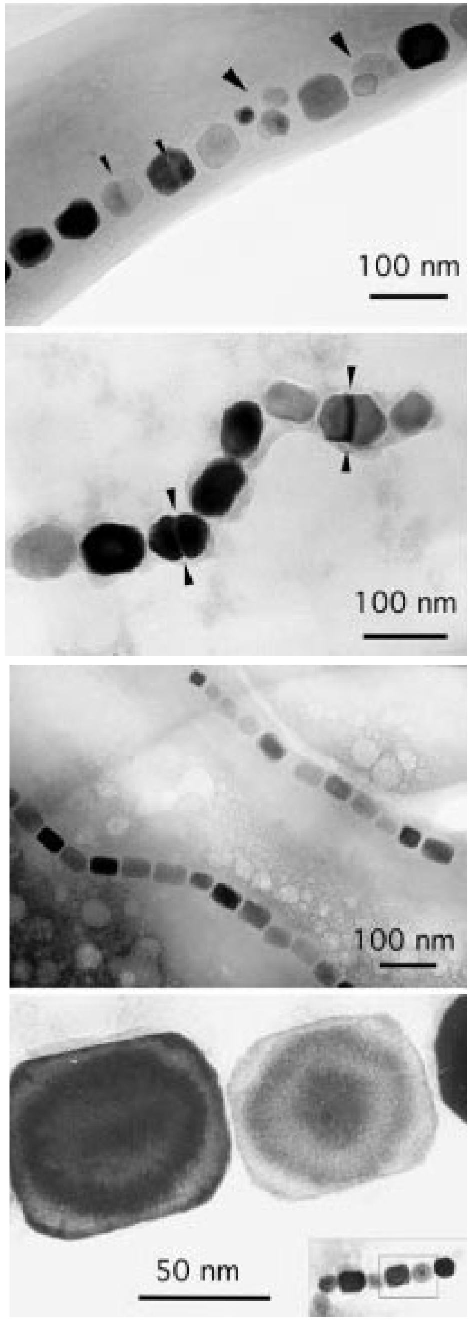
κ (× 10^{-5})	500-40,000	100,000 - 570,000	200,000-250,000

2. Bacterial magnetism – magnetotactic bacteria

Importance for archaeology: presence in organic soil layers
e.g. ditch or pit infillings, or postholes.

(*see Fassbinder & Stanjek, 1993*)

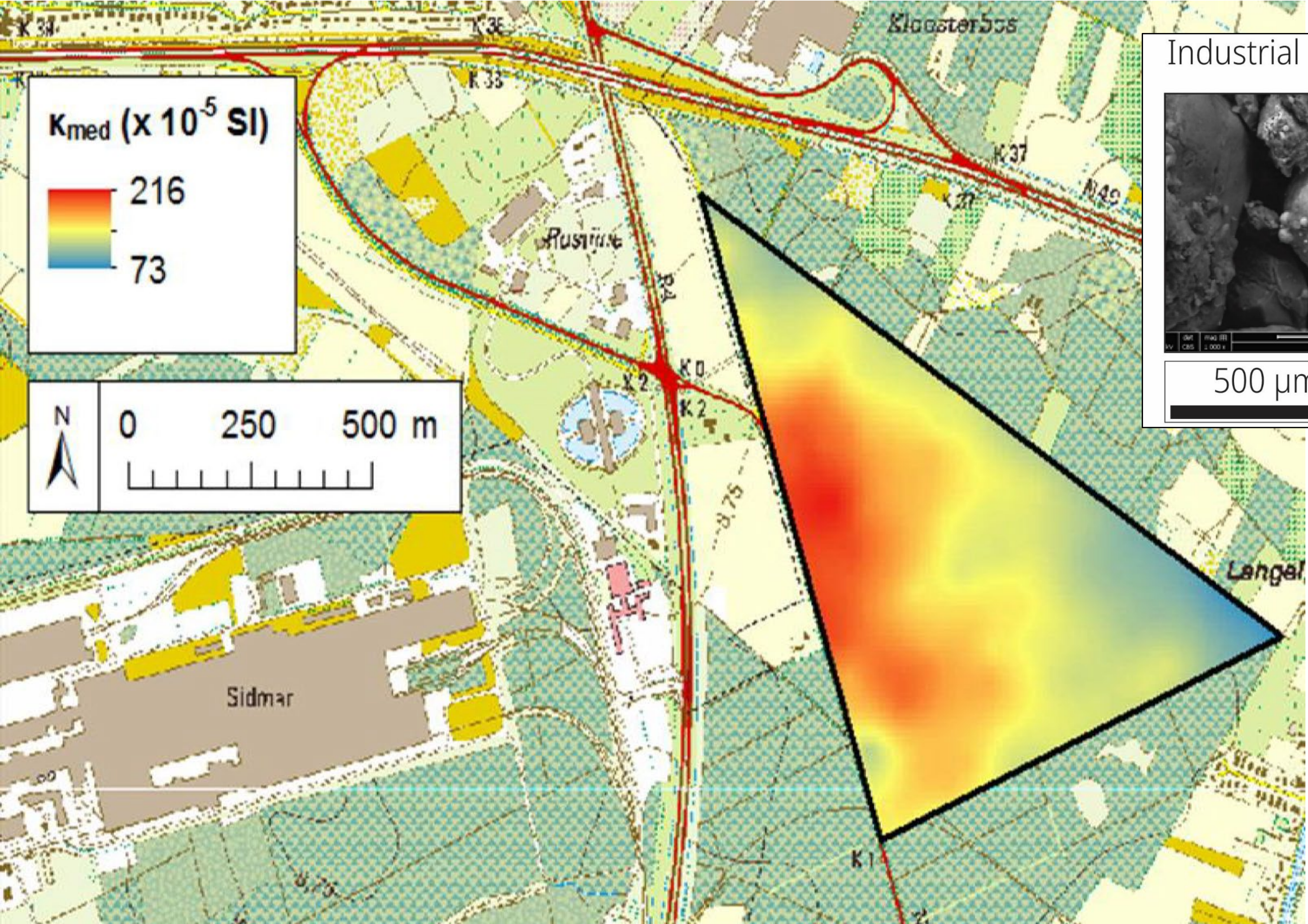




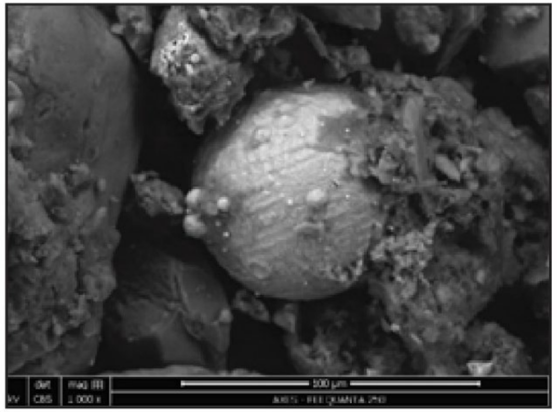
3. Detrital input

External input of magnetic particles: particulate matter (PM)

- **Naturally** (e.g. volcanic)
- **Anthropogenic** (related to specific production processes and activities)



Industrial pollutants



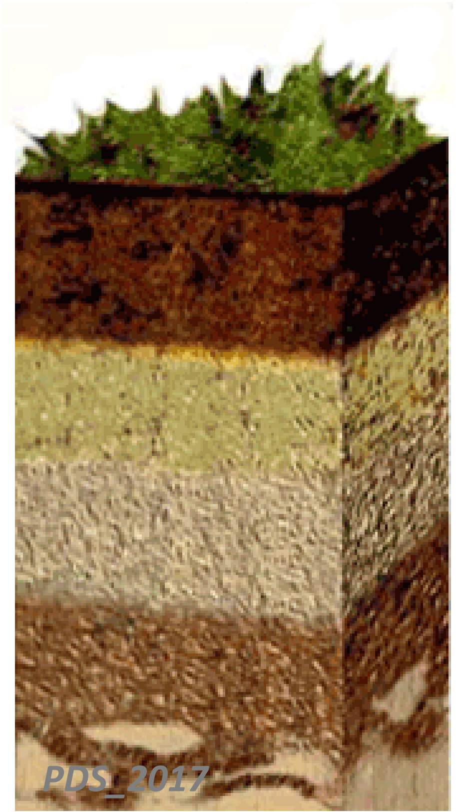
500 µm

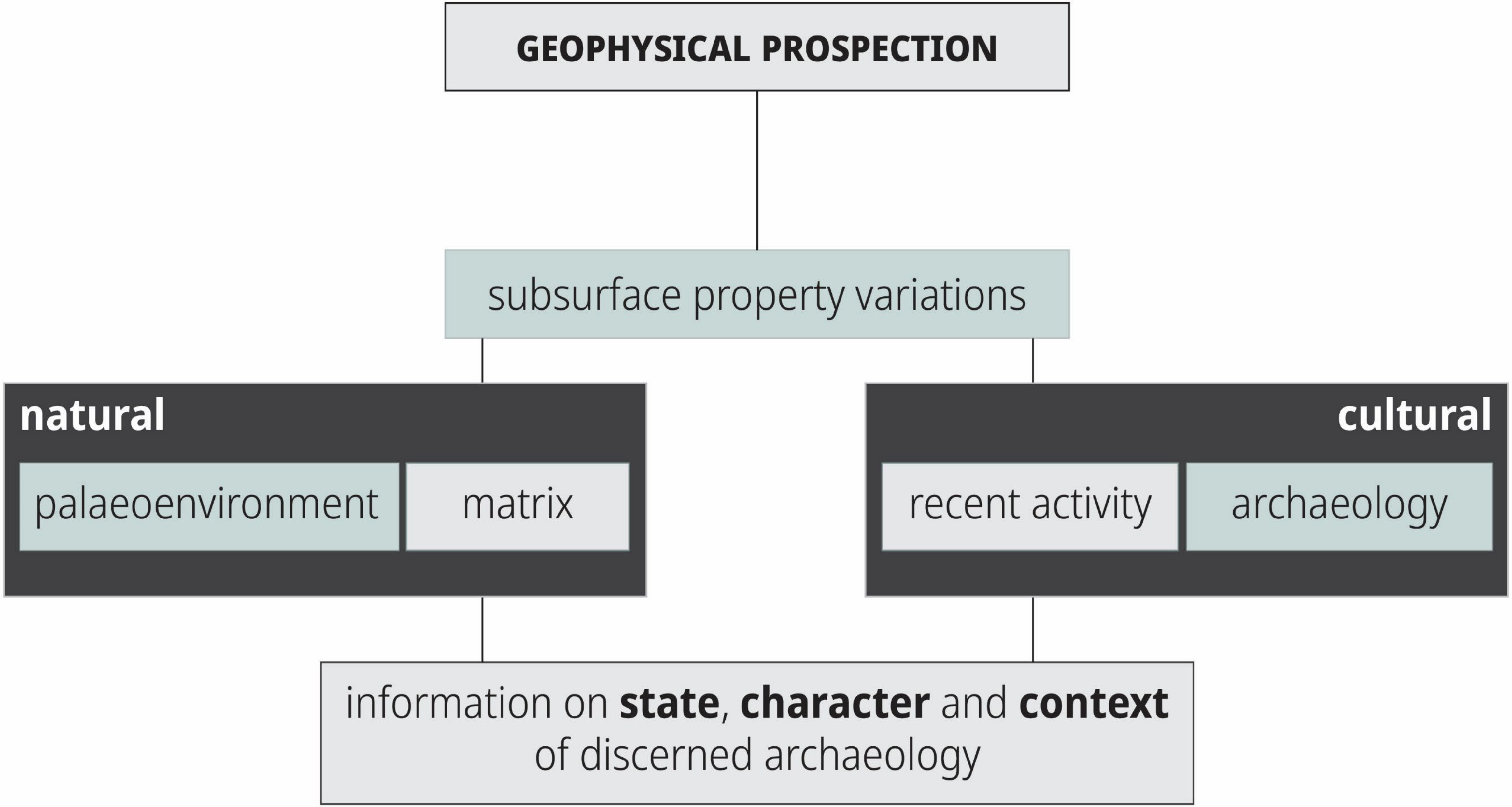
Magnetic enhancement of soils

- **Reduction + oxidation**
- **Bacterial**
- **Detrital**

+ anthropogenic objects + structures (metal, thermoremanence, …)

Primary influence on upper soil layers
(A horizons)



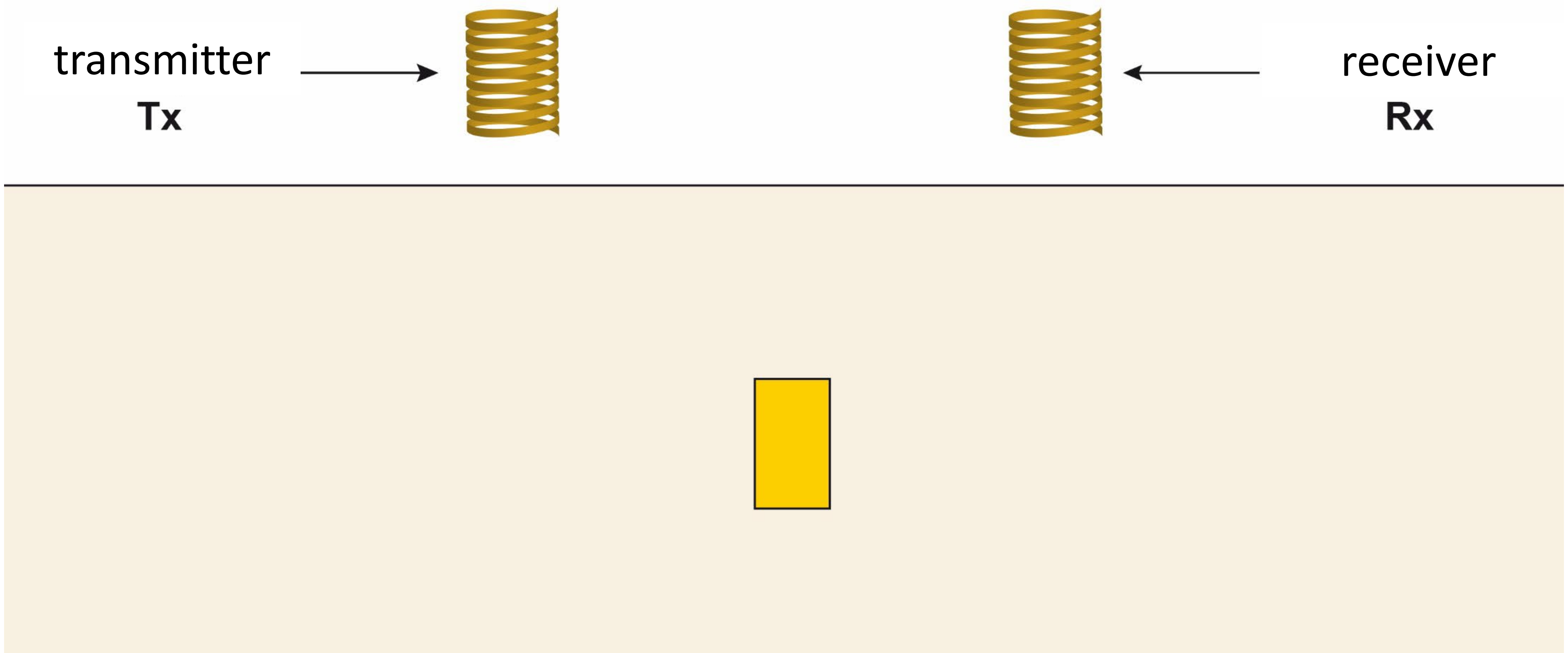

GEOPHYSICAL PROSPECTION
subsurface property variations
natural
palaeoenvironment
matrix
cultural
recent activity
archaeology
information on **state**, **character** and **context**
of discerned archaeology

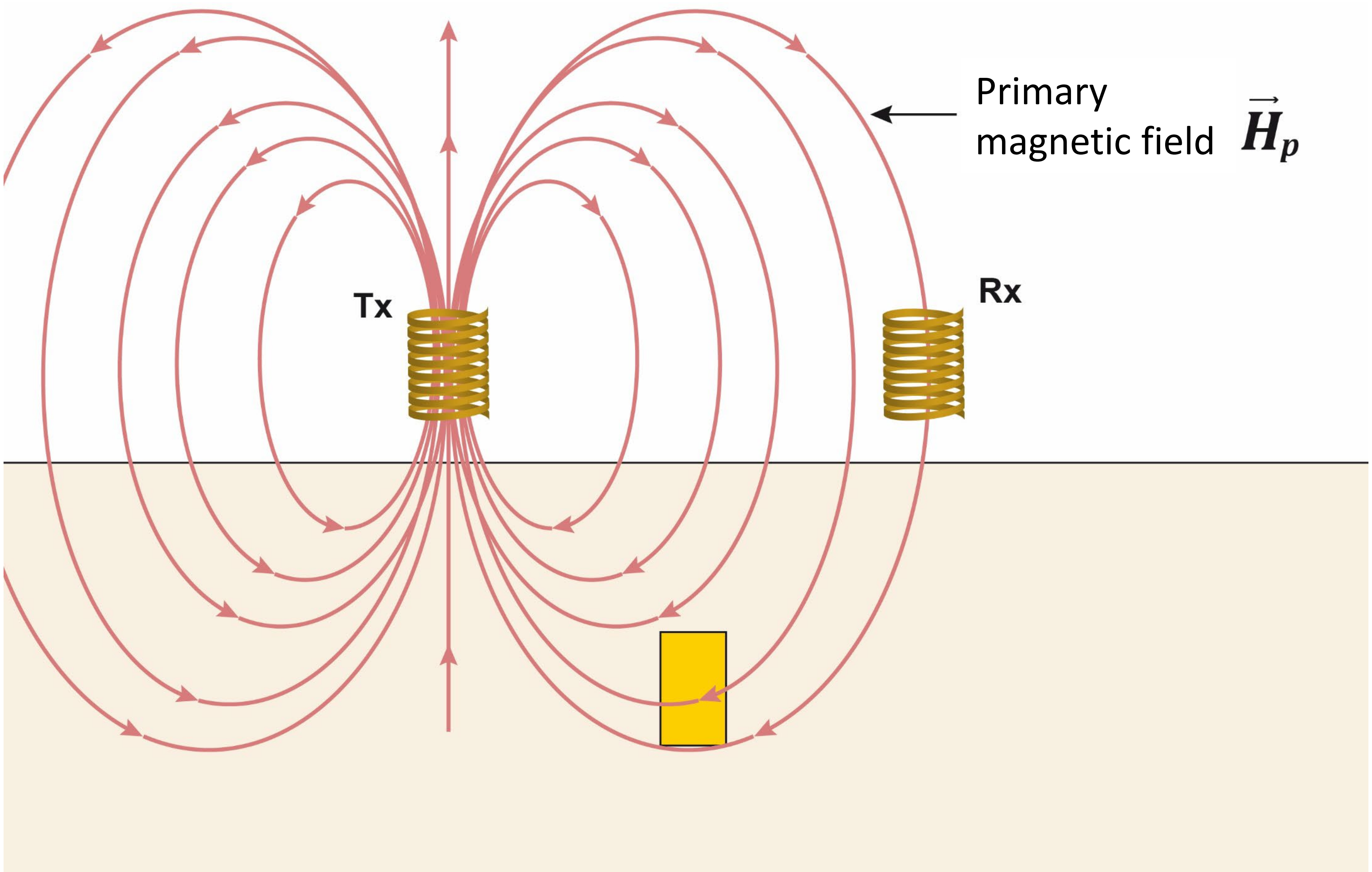
Prospection with EMI instruments

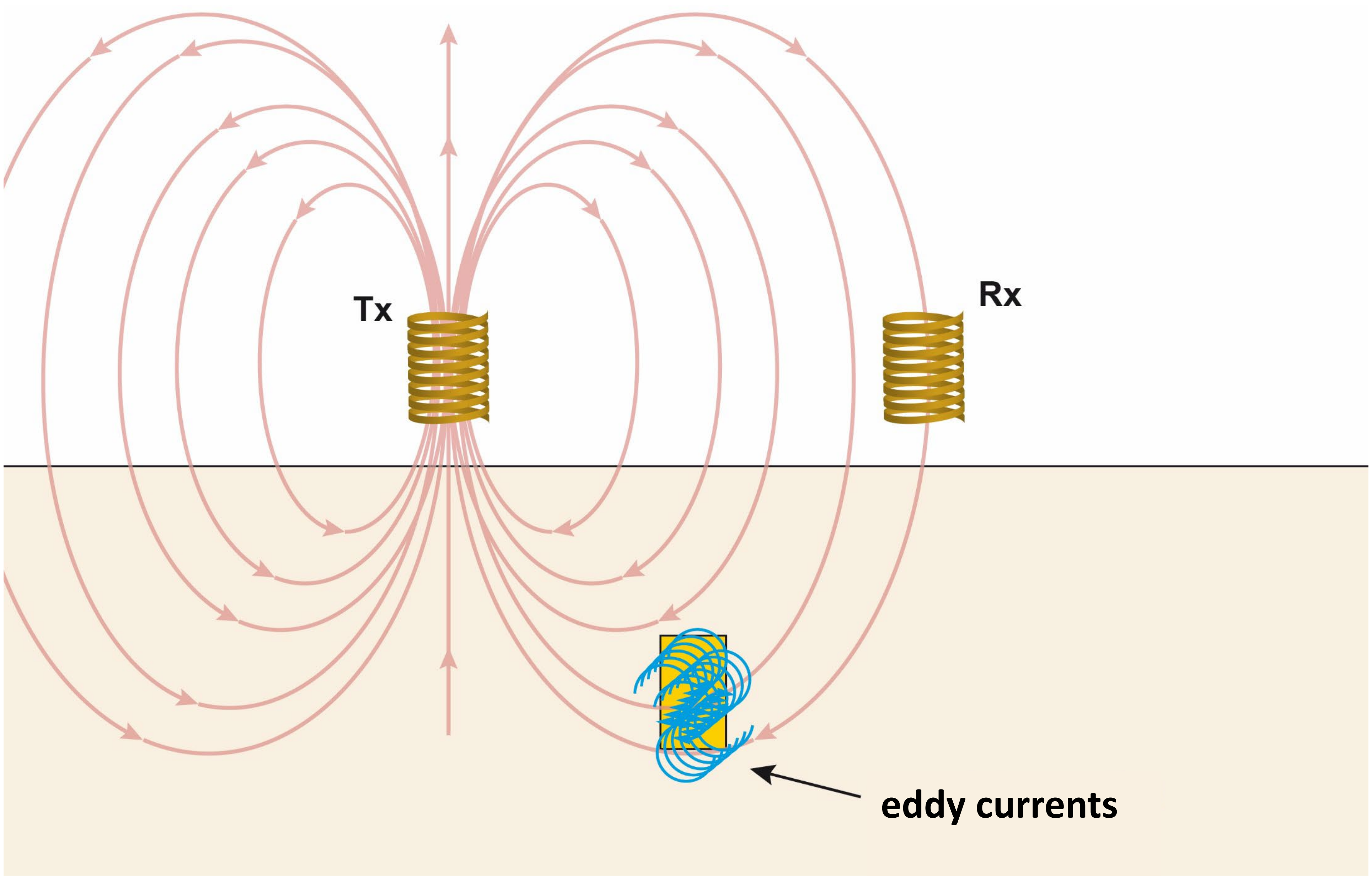


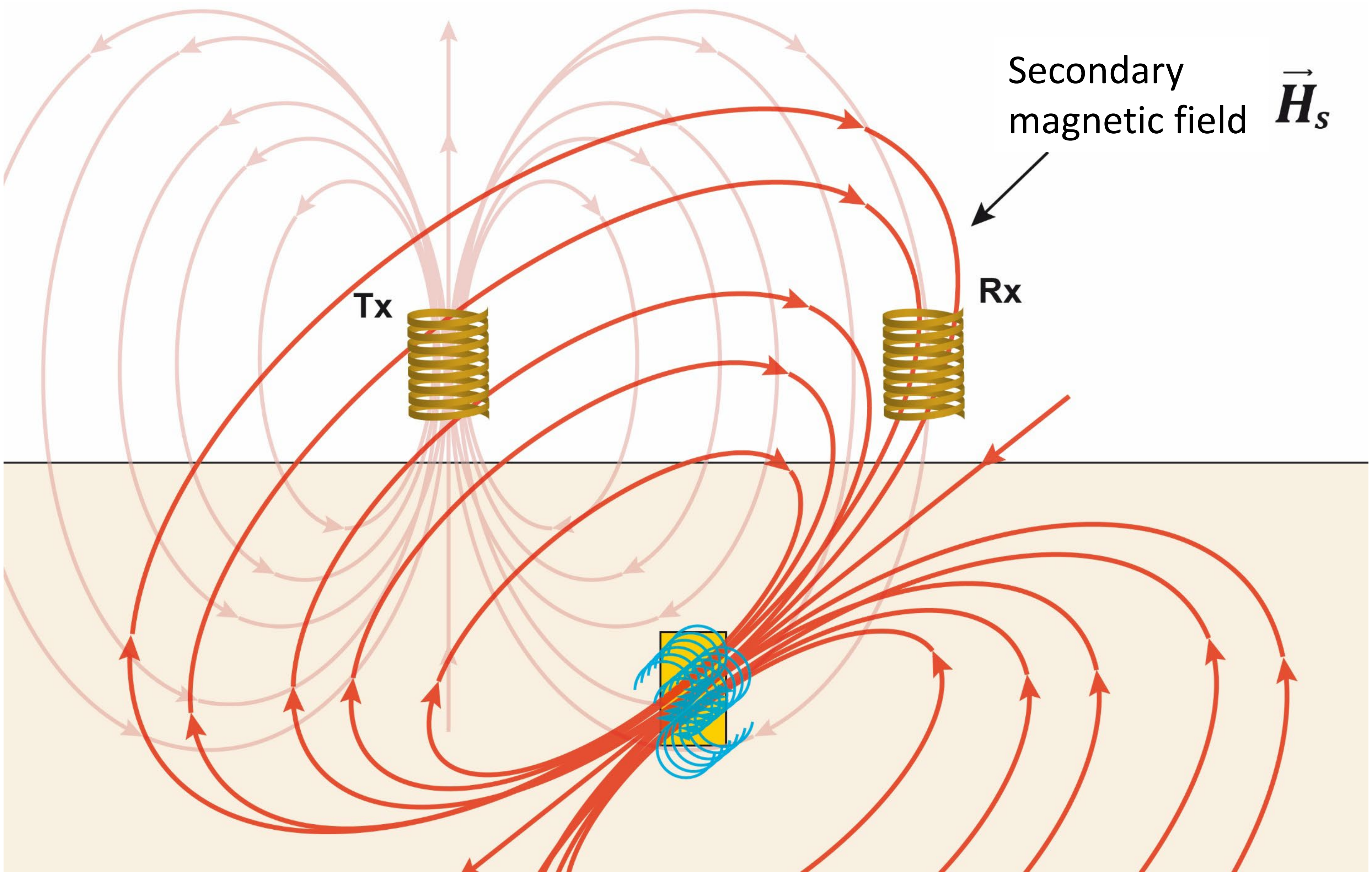

Working principle

Combining a **transmitter** coil that sends out a magnetic field
with a **receiver** coil that picks up the soil's response to the transmitted signal



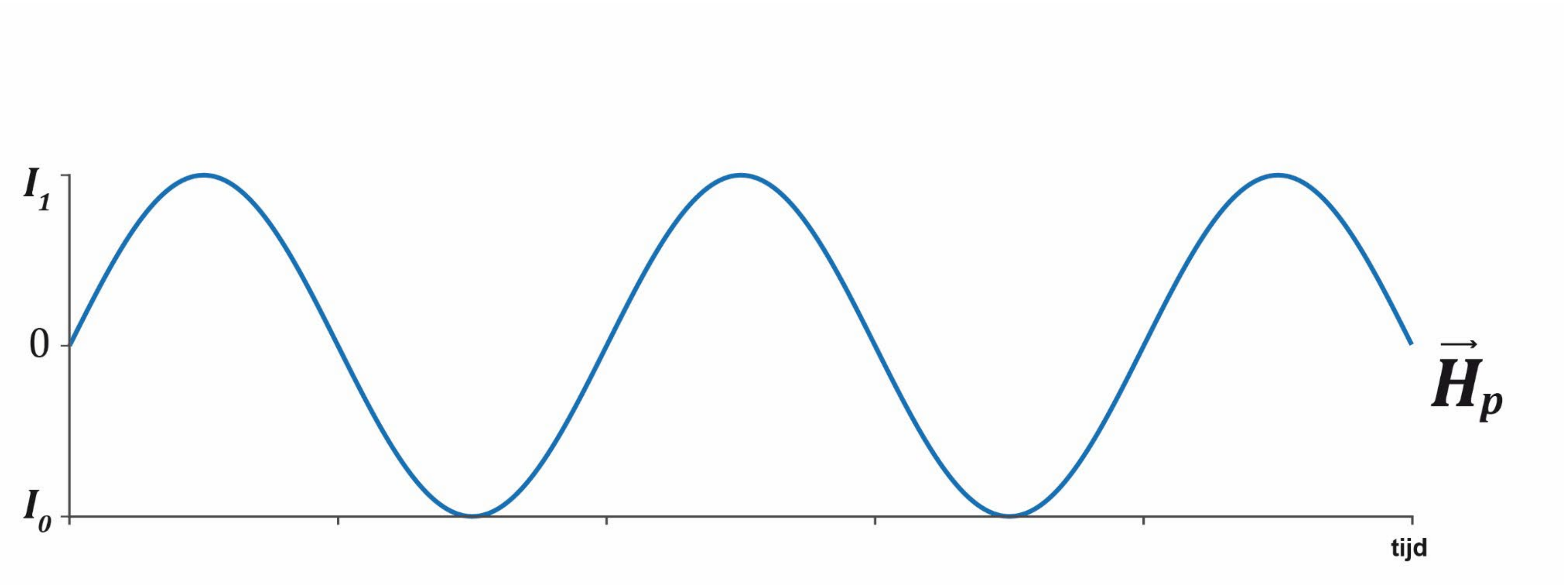

Primary
magnetic field $\vec{H}_p$
Tx
Rx


Tx
Rx
eddy currents


Secondary magnetic field $\vec{H}_s$
Tx
Rx

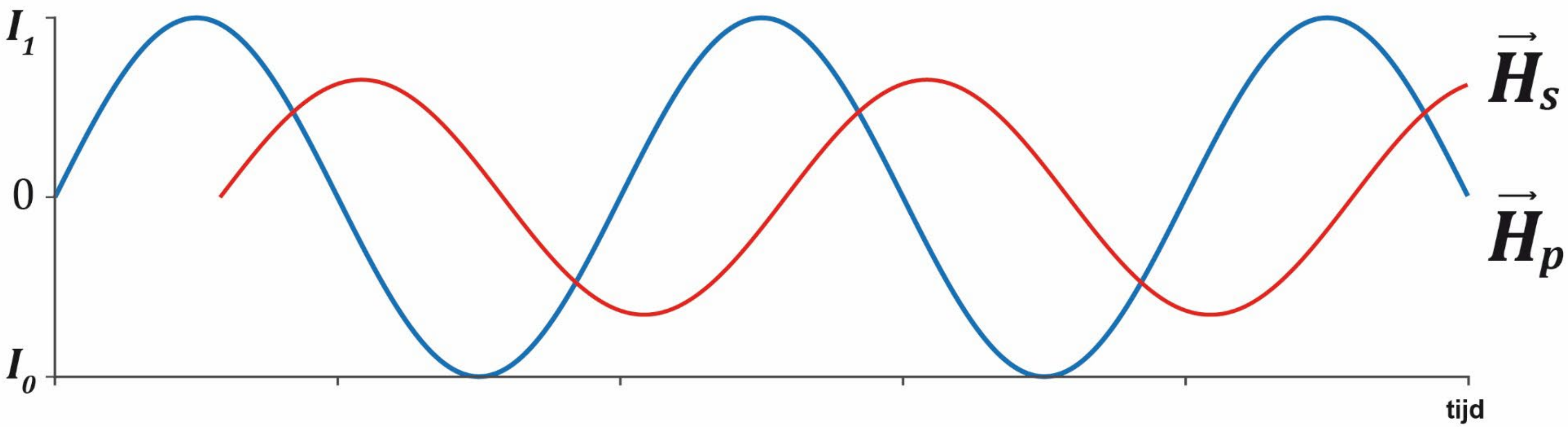
$\vec{H}_p$ vs $\vec{H}_s$ (primary versus secondary magnet field)

Primary veld $\vec{H}_p$ with a given frequency and amplitude



$\vec{H}_p$ vs $\vec{H}_s$ (primary versus secondary magnet field)

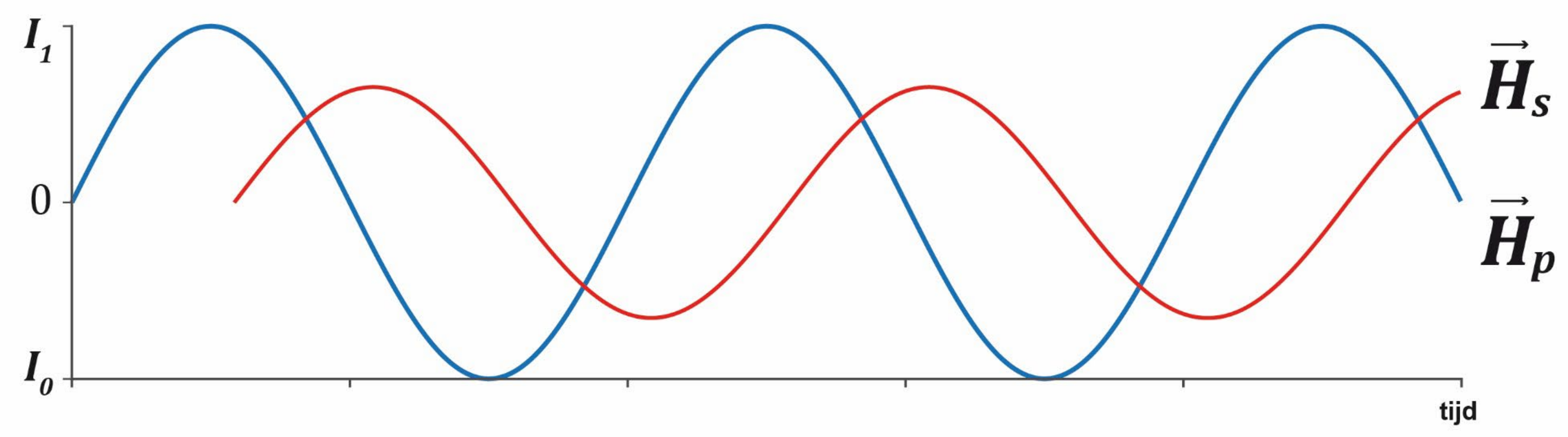
Secondary veld $\vec{H}_s$ that varies from $\vec{H}_p$ in function of electrical and magnetic soil properties



$\overrightarrow{H}_p$ vs $\overrightarrow{H}_s$ (primary versus secondary magnet field)

By comparing the properties of both fields we can derive information on EC and MS of the soil

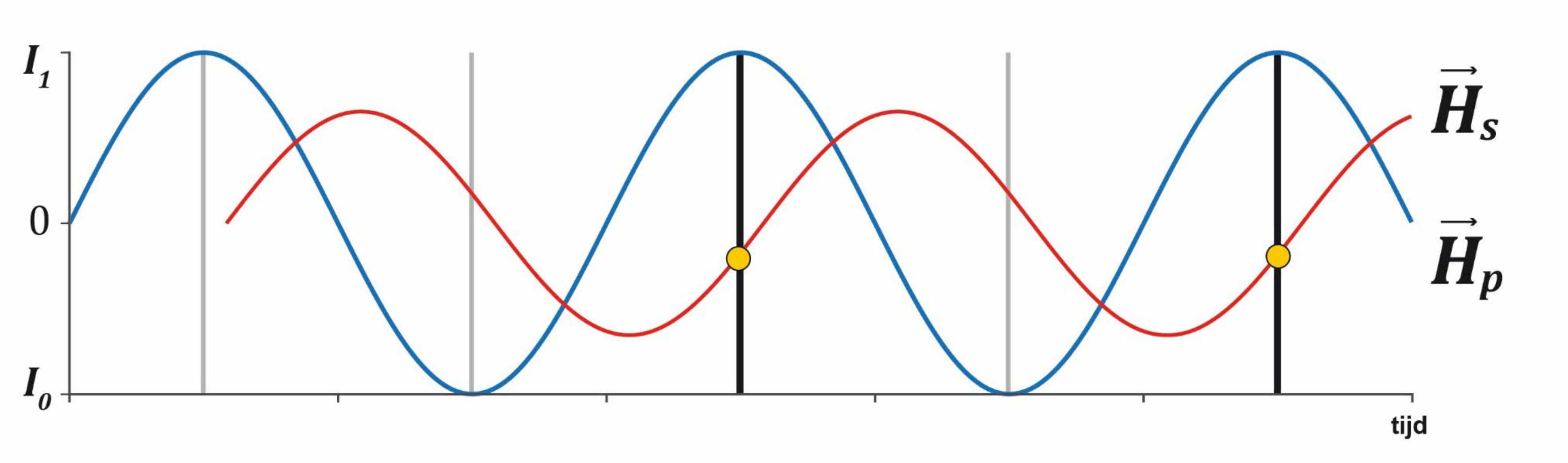
$$\frac{\overrightarrow{H}_s}{H_p}$$



$\vec{H}_p$ vs $\vec{H}_s$: deriving electrical and magnetic properties

In-phase component

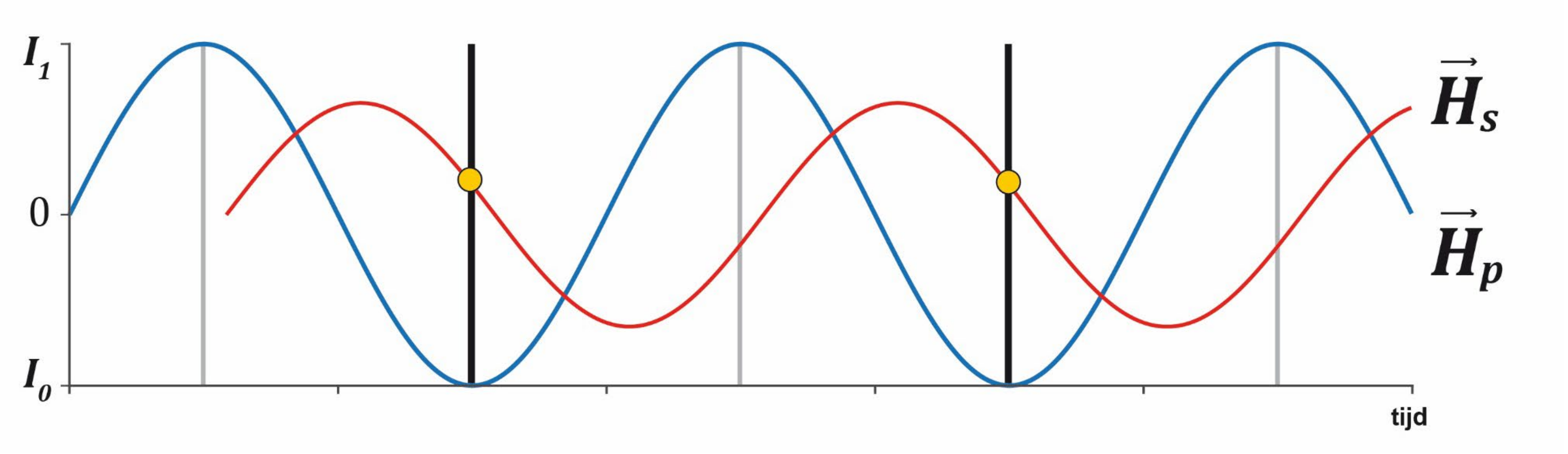
$$\frac{\vec{H}_s}{H_p} ip$$



$\overrightarrow{\boldsymbol{H}}_p$ vs $\overrightarrow{\boldsymbol{H}}_s$: deriving electrical and magnetic properties

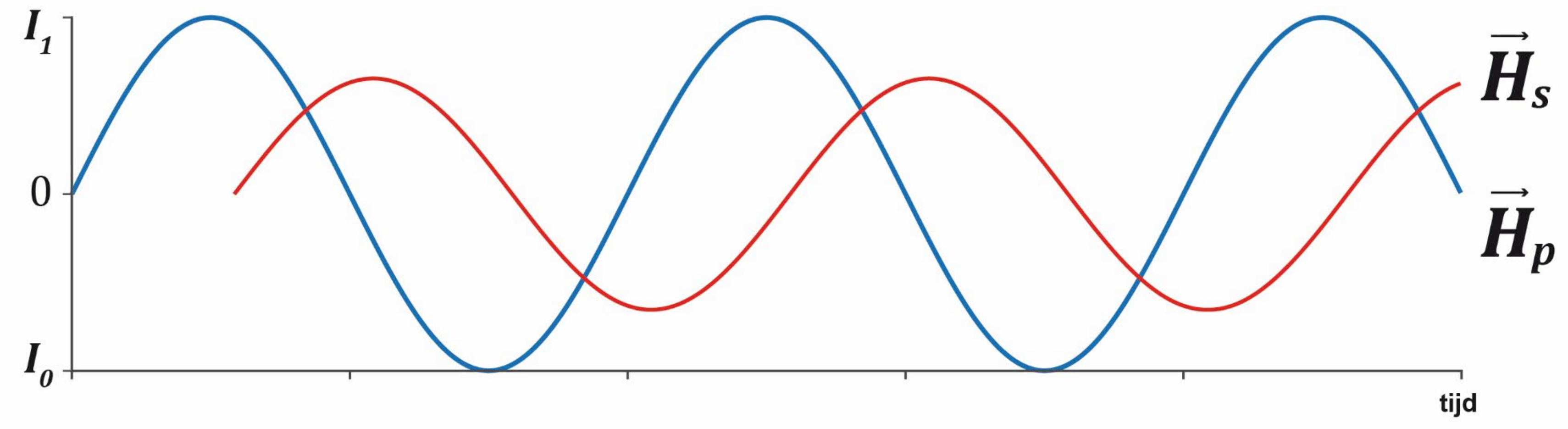
Quadrature (or out-of-phase) component

$$\frac{\overrightarrow{\boldsymbol{H}}_s}{\boldsymbol{H}_p} qp$$



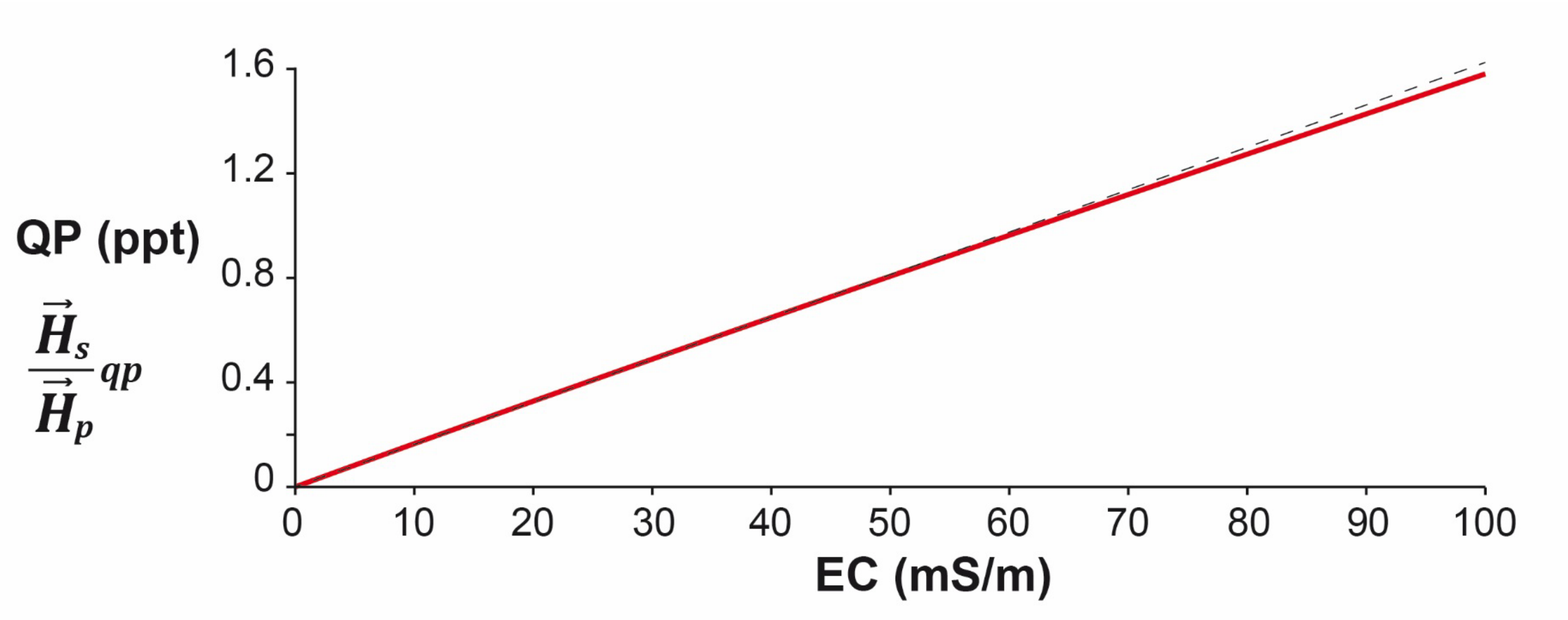
So: one signal, two components

$$\frac{\vec{H}_s}{H_p} = \text{potential investigation of two electromagnetic properties}$$



The quadrature phase: QP

- Most commonly used.
- Quasi-lineair relationship with soil **ELECTRICAL CONDUCTIVITY**.

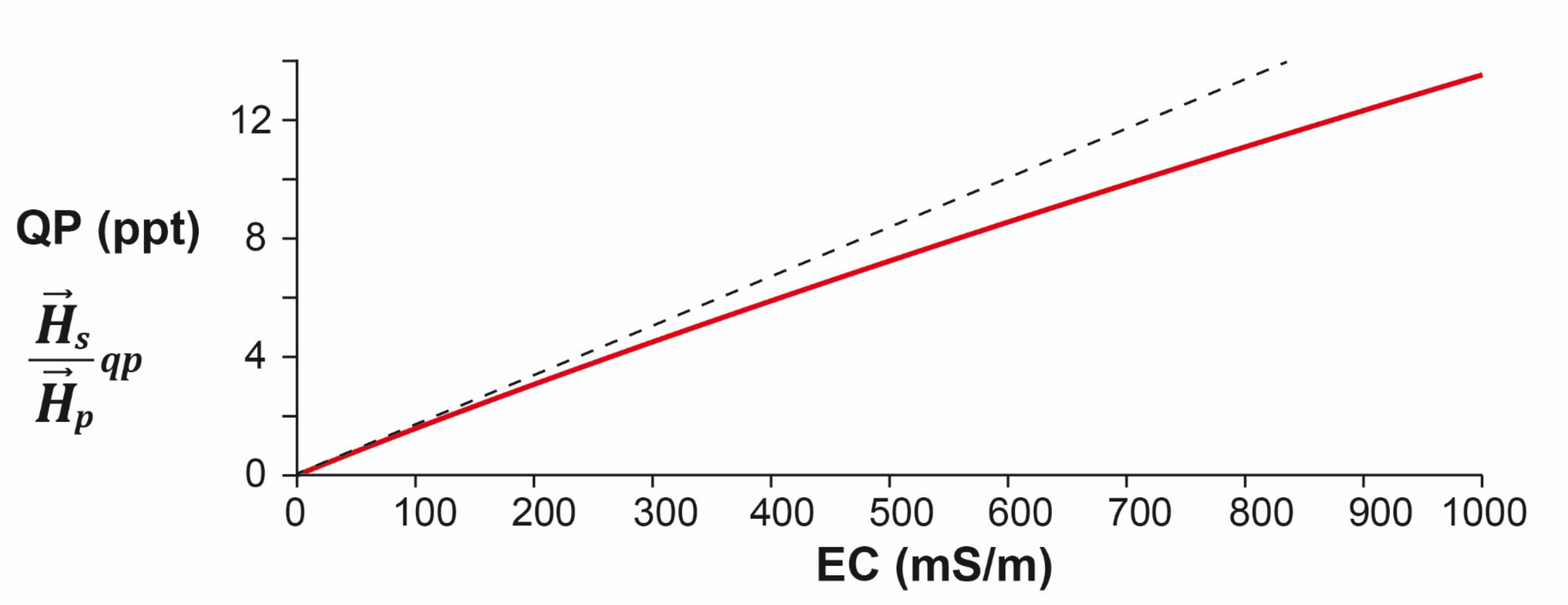


The quadrature phase: QP

- At increased conductivities (> 100mS/m) the linear relationship is no longer valid !!!

→ this is the case in saline conditions

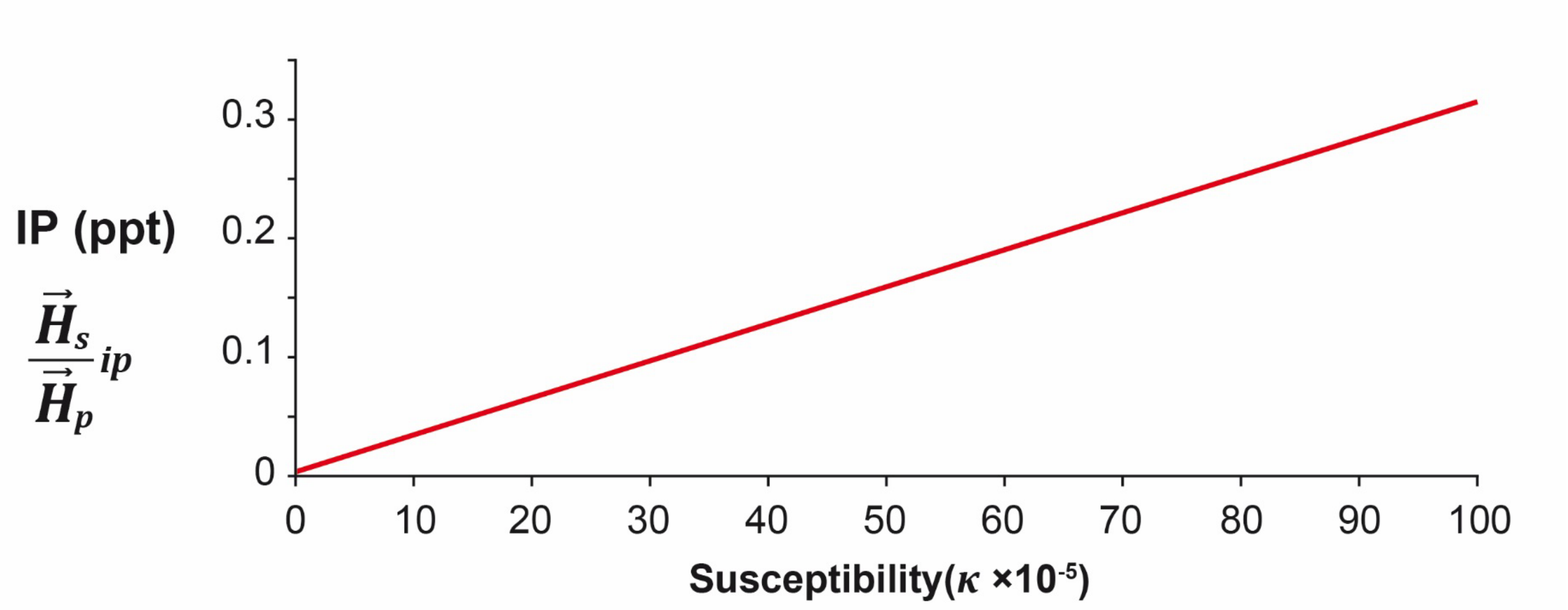
- Relative contrasts can still be observed, but can be dampened



The in-phase: IP

- Proportionate to the **<u>MAGNETIC SUSCEPTIBILITY</u>**.

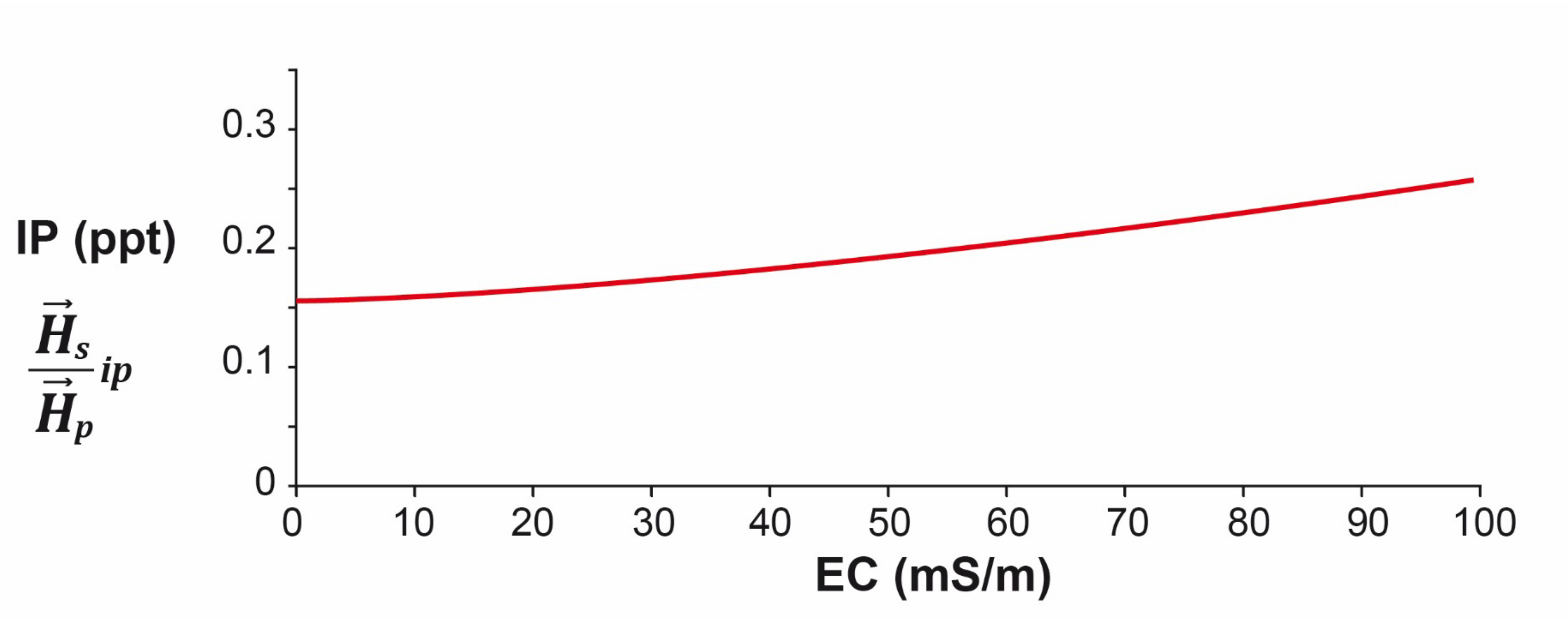
Example: sandy soil with conductivity of 10 mS/m, with varying $\boldsymbol{\kappa}$



The in-phase: IP

- **BUT:** also influenced by the soil electrical conductivity

Example: soil with **κ** *of 50×10^{-5} with varying EC up to 100 mS/m*

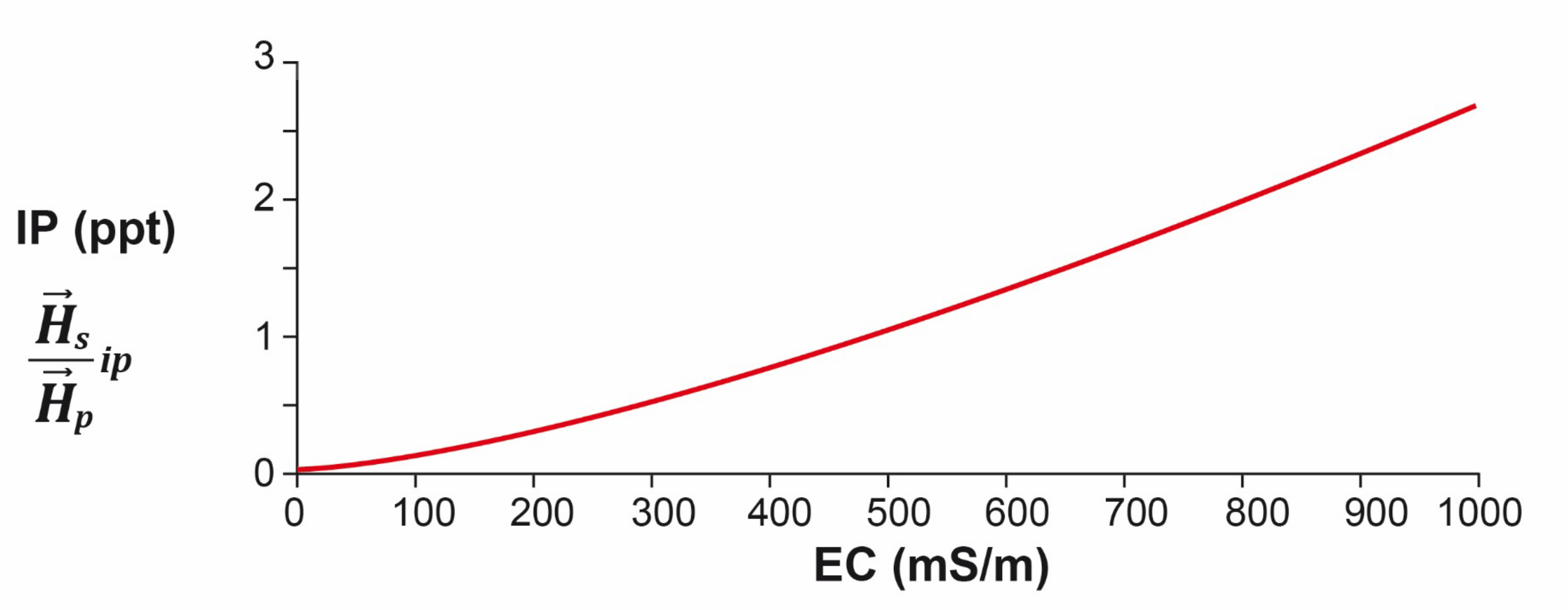


The in-phase: IP

- <u>Particularly relevant in saline conditions :</u>

  → conductivity starts dominating the response

Example: soil with **κ** *of 50×10^{-5} with varying EC up to 1000 mS/m*

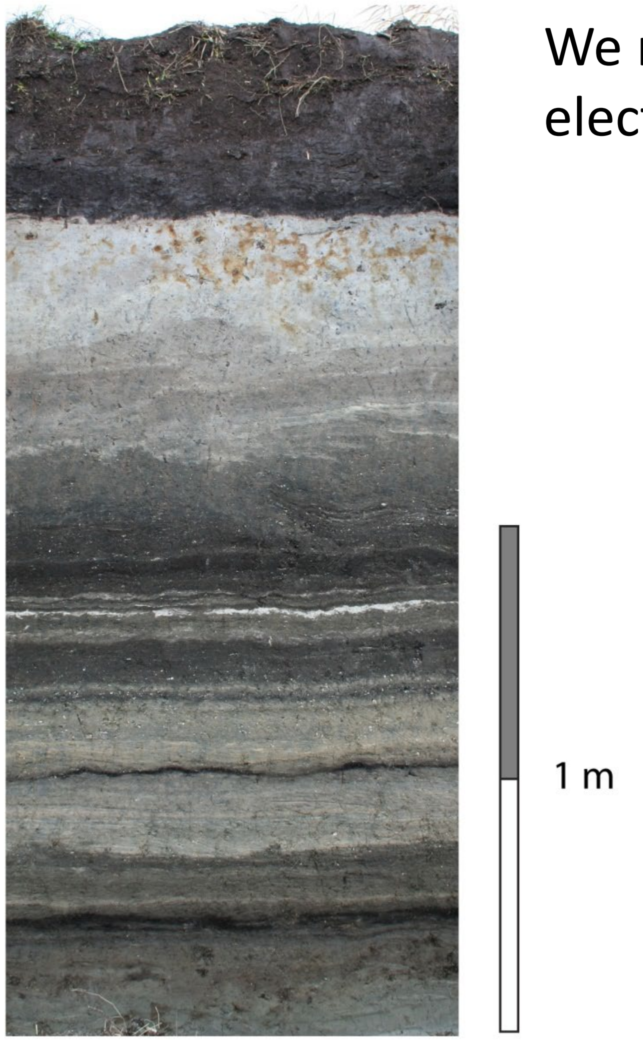


Electromagnetic responses: QP and IP

SUMMARY:

- **QP:**
  - Quasi-linear measure of the soil electrical conductivity in non-saline conditions.
  - Linear relationship becomes invalid at EC >>100 mS/m
- **IP:**
  - Proportionate to soil magnetic susceptibility in non-saline conditions.
  - Non-linear relationship, which becomes increasingly complex at higher conductivities.
  - In saline conditions EC dominates the IP response

Apparent measurements: ECa



We record the **influence of properties within a volume**, integrating the electrical and magnetic properties of all materials/layers within this volume.

Apparent measurements: **depth of investigation and recorded soil volume**

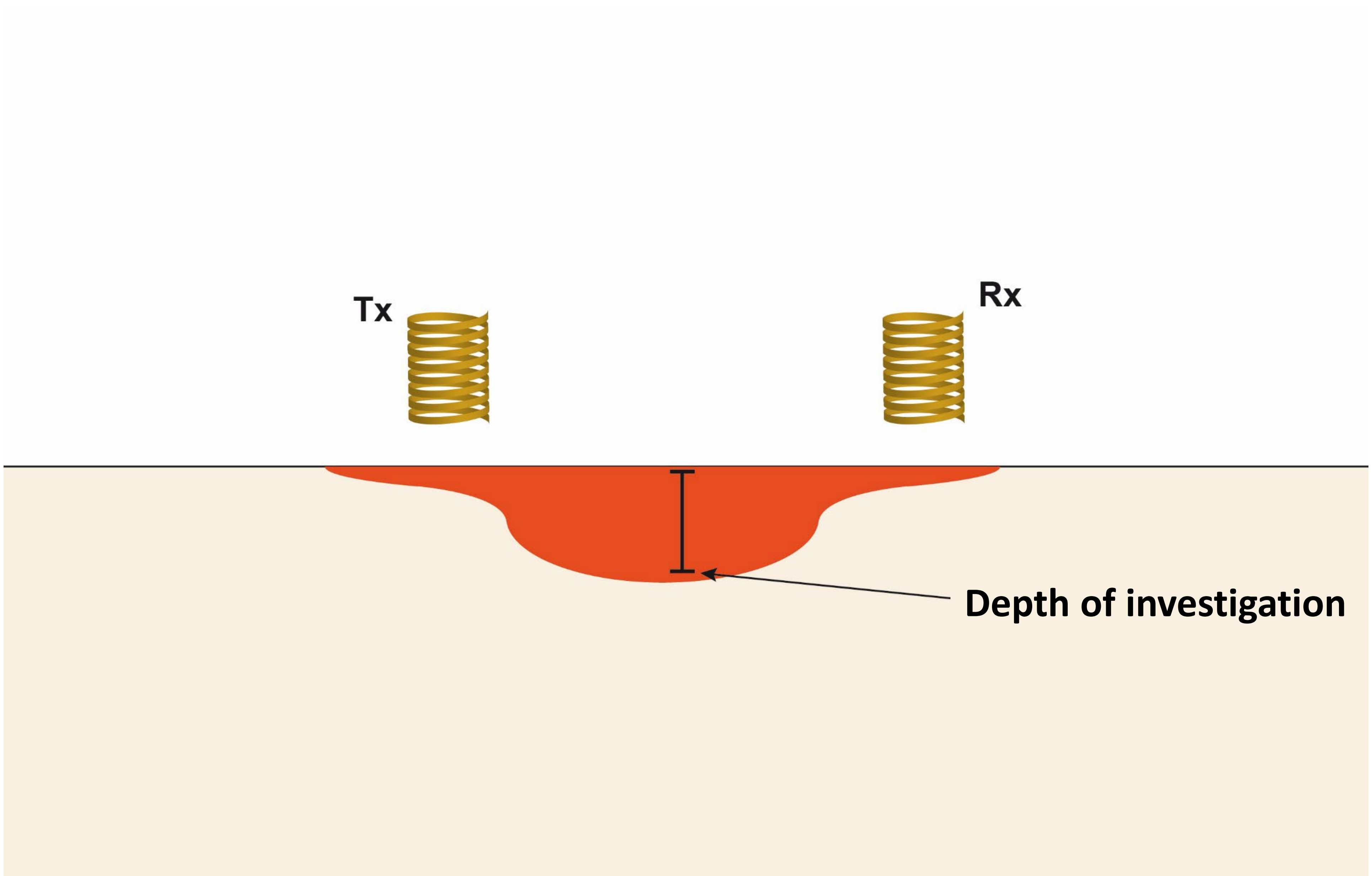
A **transmitter and receiver pair** of an EMI instrument **records a soil volume of a specific size and shape**

Apparent measurements: depth of investigation and recorded soil volume

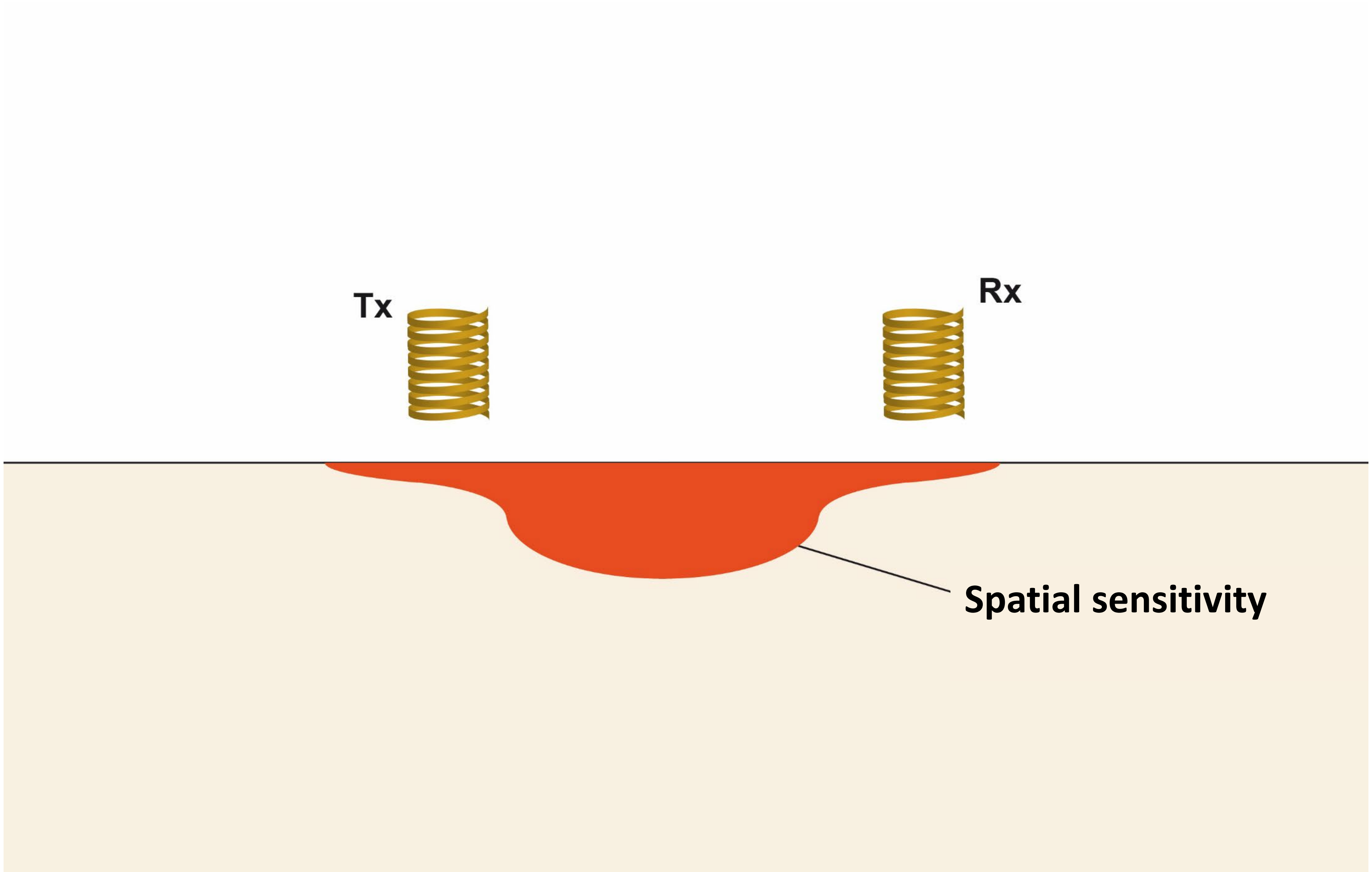
size and shape of the recorded soil volume

depends on the distance and relative orientation of Tx and Rx

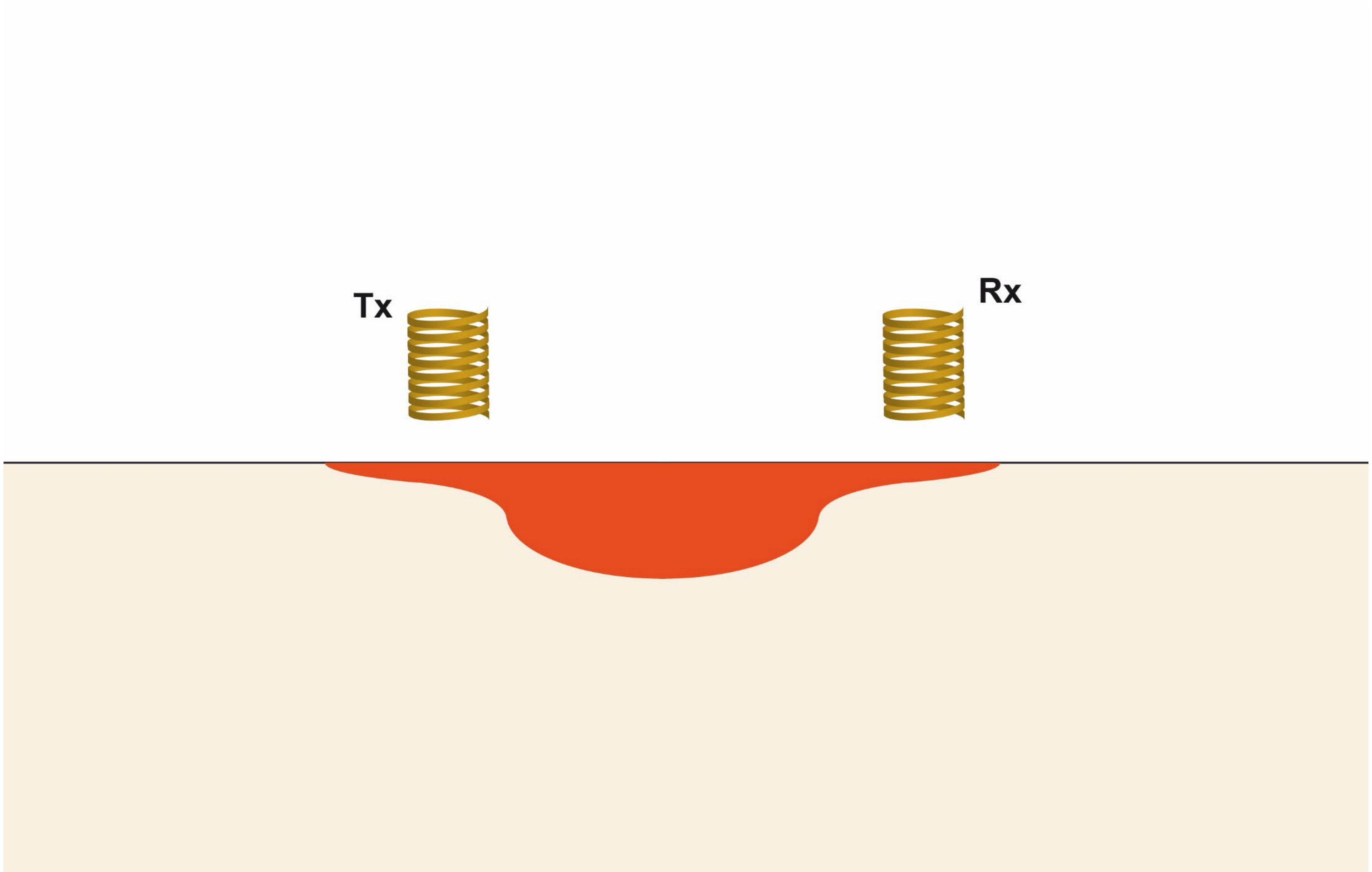
SEPARATION (distance between transmitter and receiver)



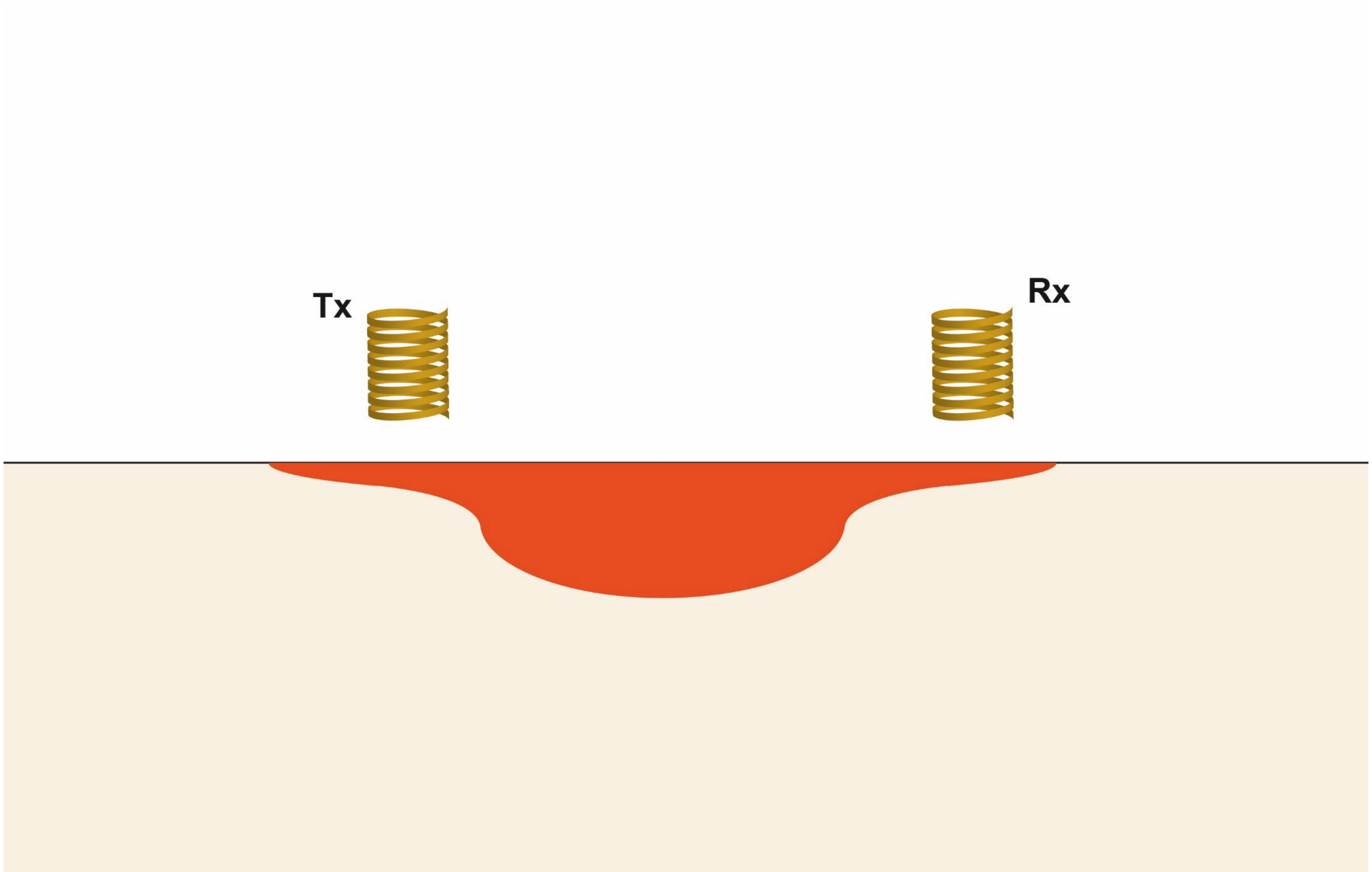
SEPARATION (distance between transmitter and receiver)



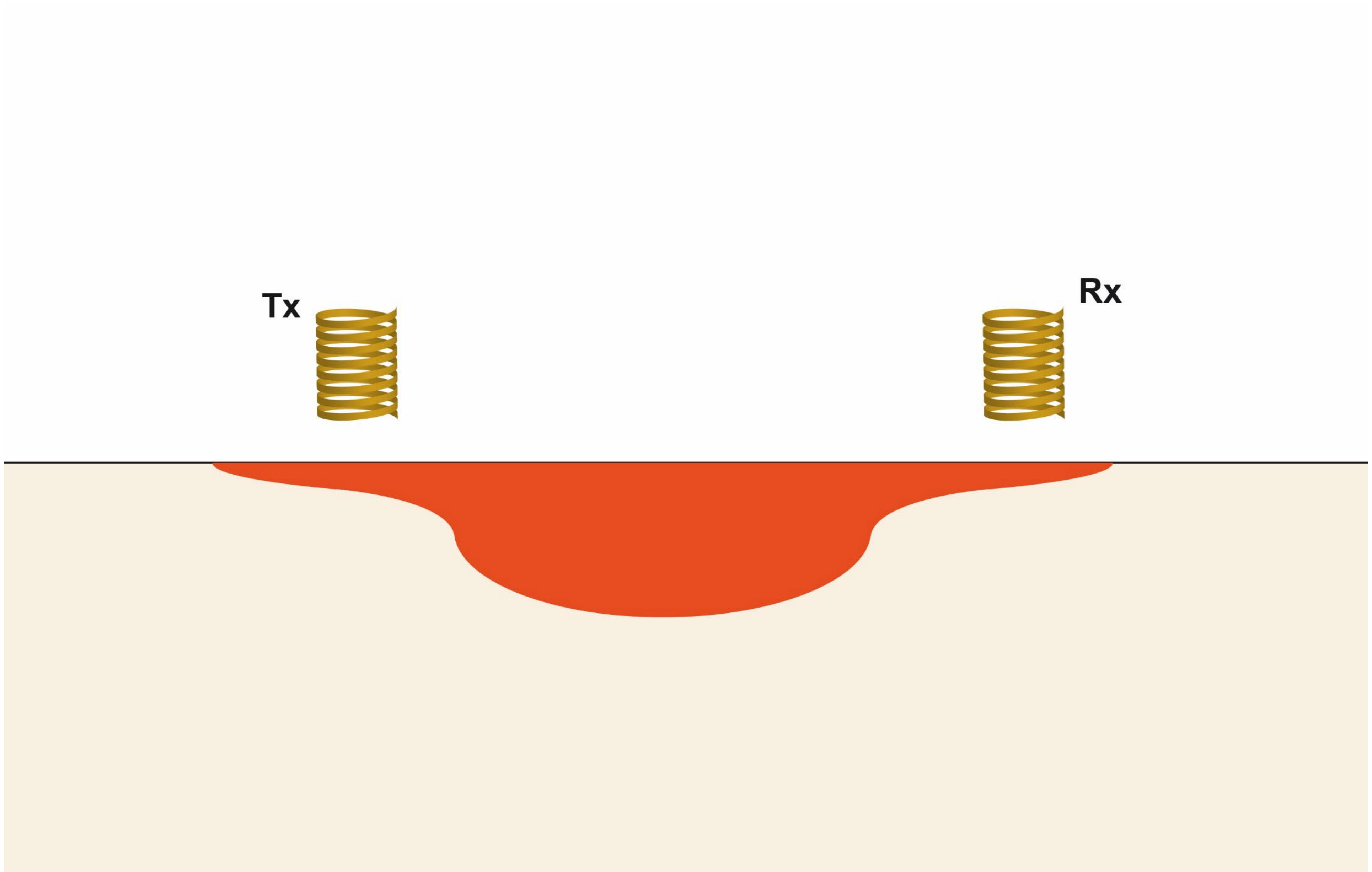
SEPARATION (distance between transmitter and receiver)



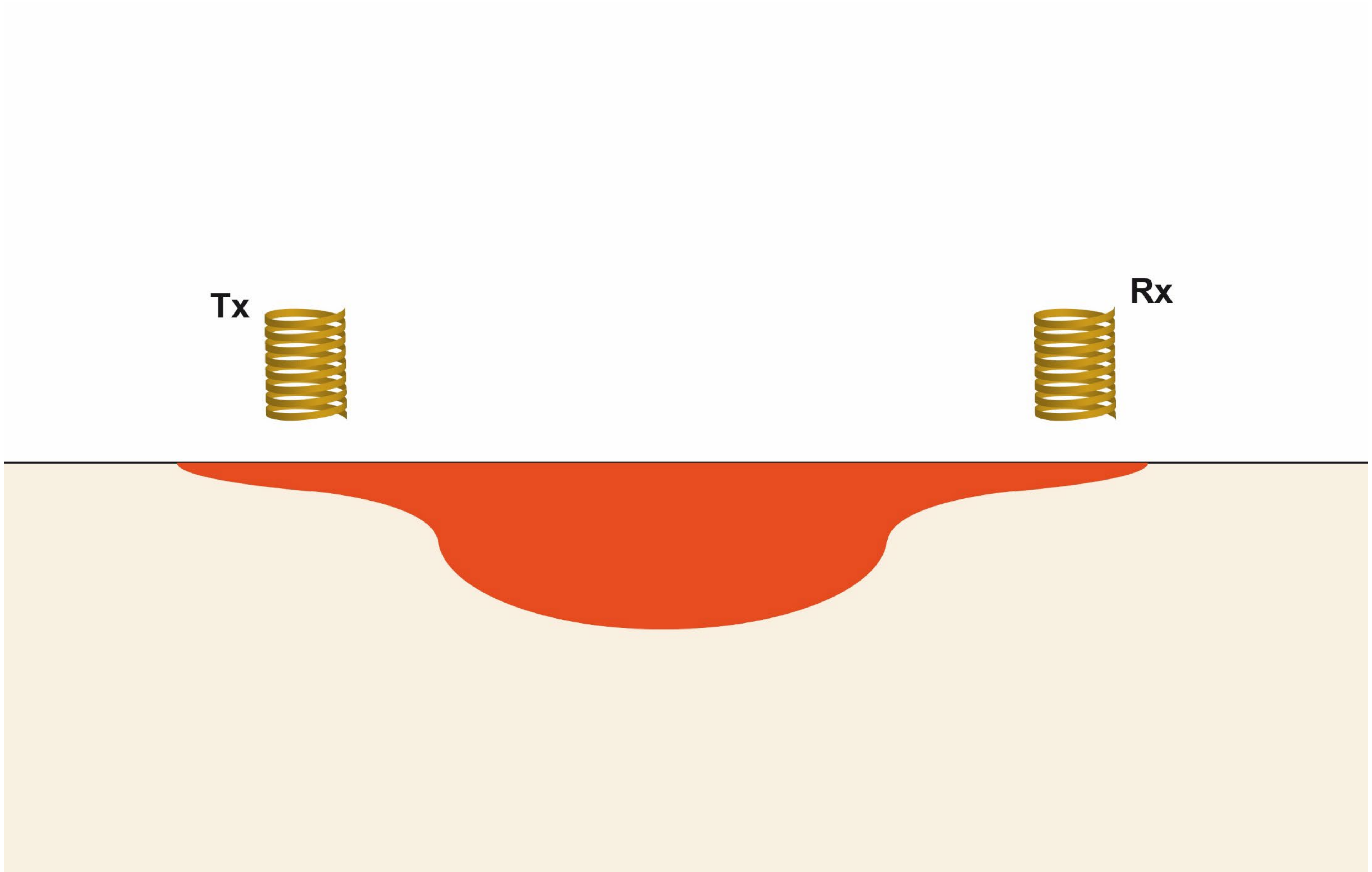
SEPARATION (distance between transmitter and receiver)



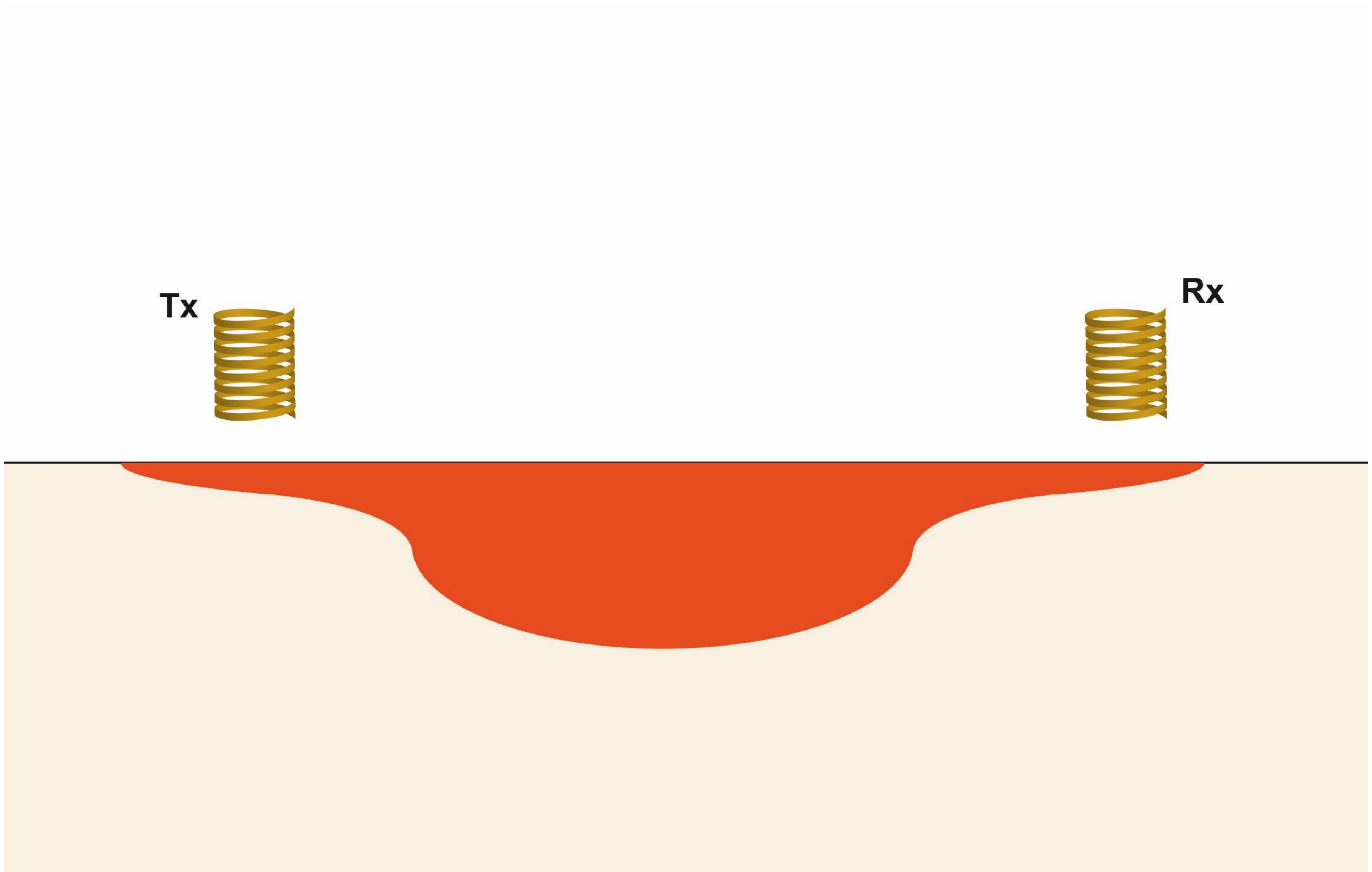
SEPARATION (distance between transmitter and receiver)



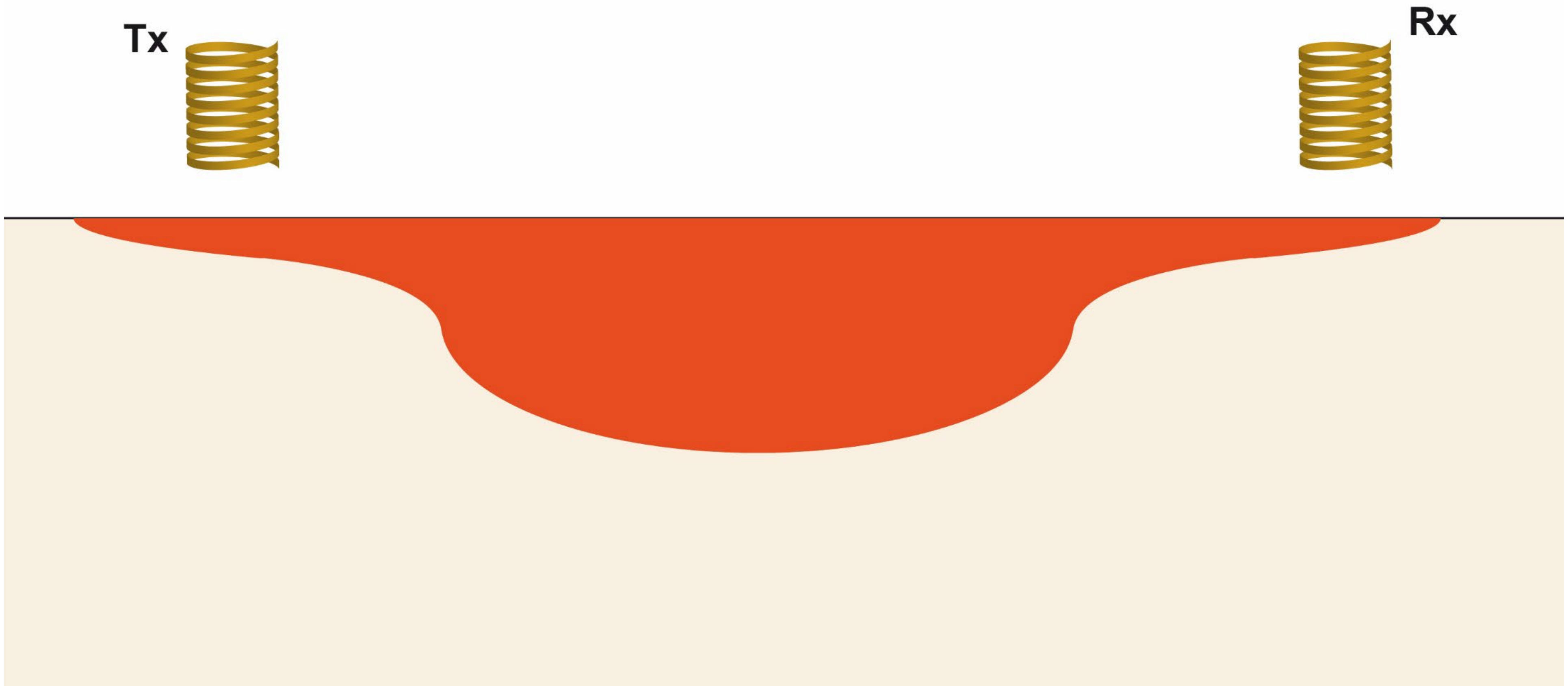
SEPARATION (distance between transmitter and receiver)



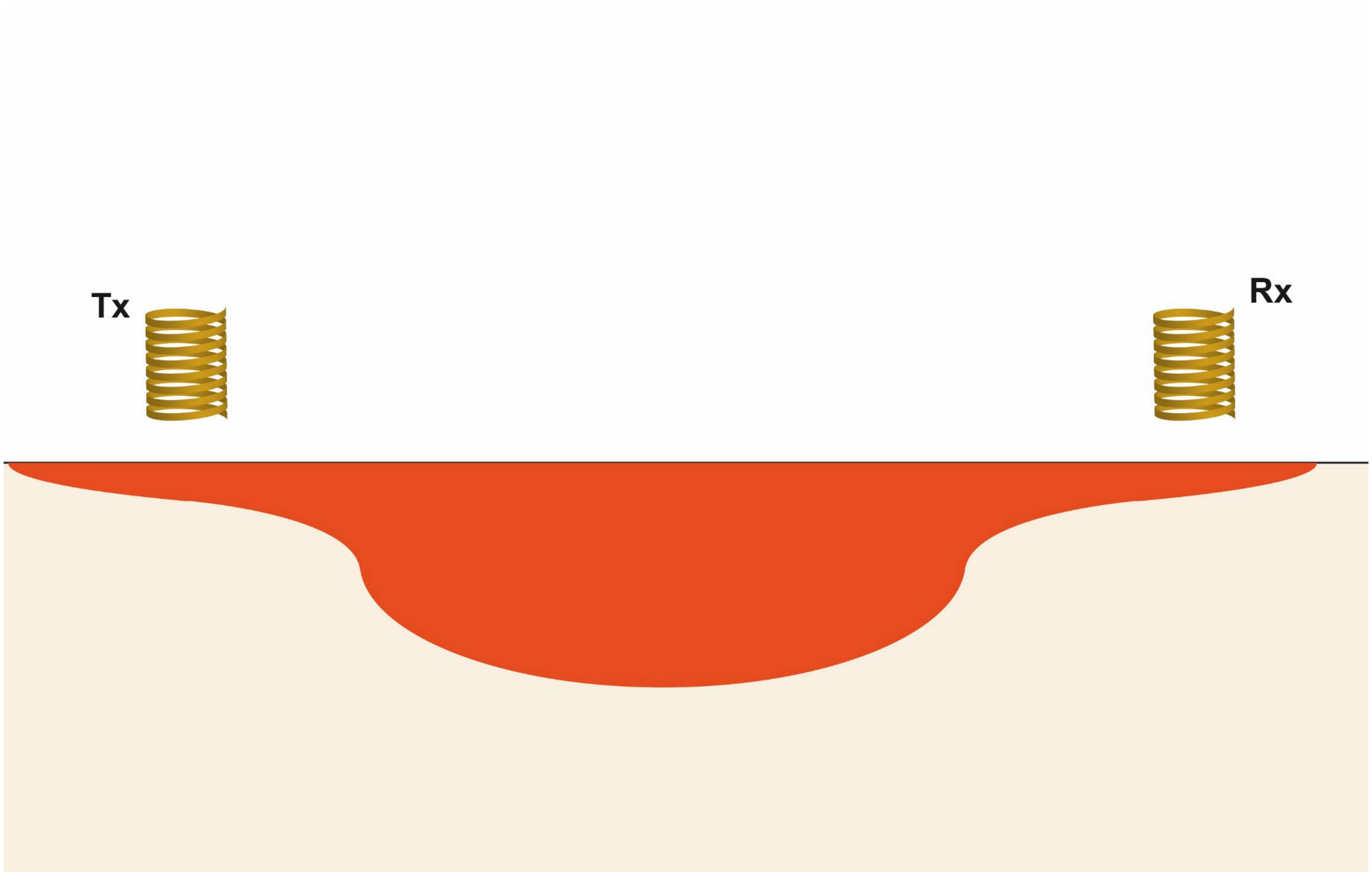
SEPARATION (distance between transmitter and receiver)



SEPARATION (distance between transmitter and receiver)

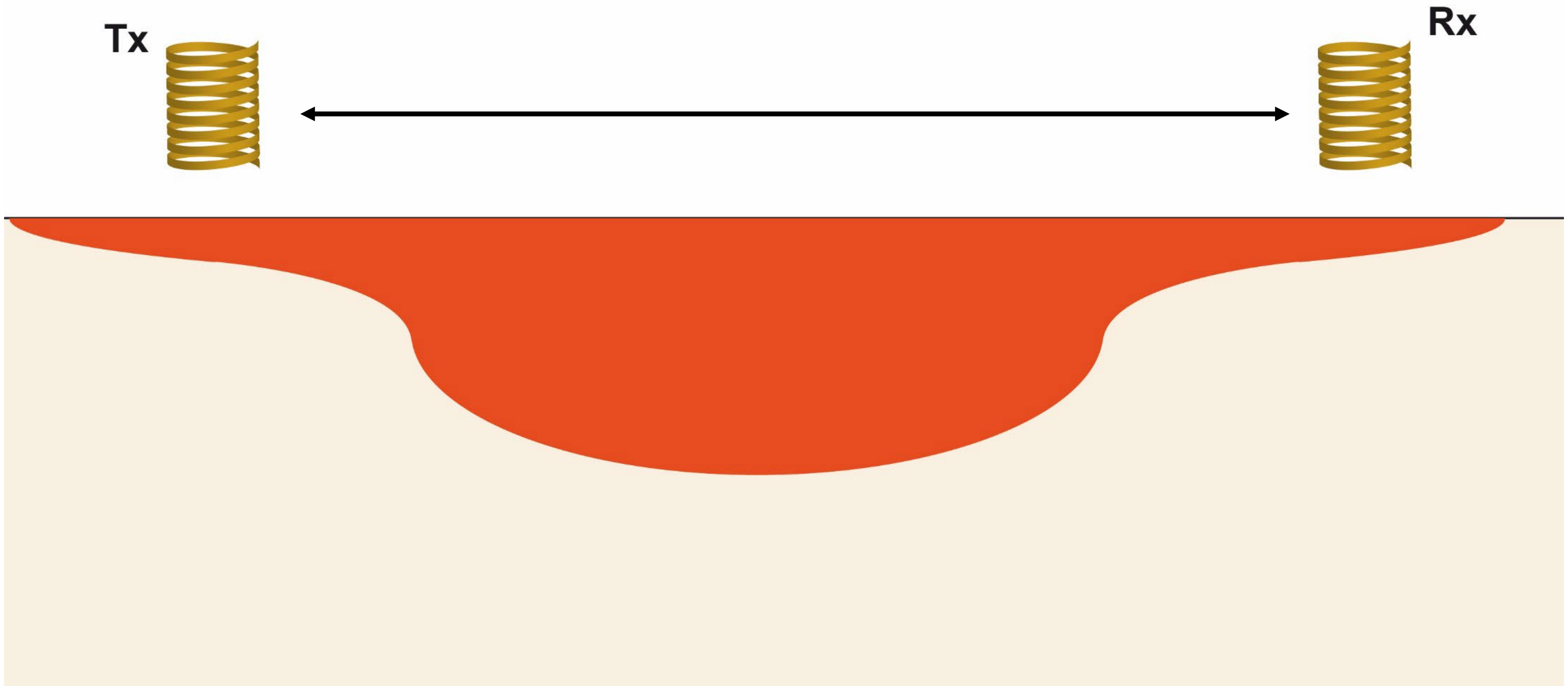


SEPARATION (distance between transmitter and receiver)



SEPARATION (distance between transmitter and receiver)

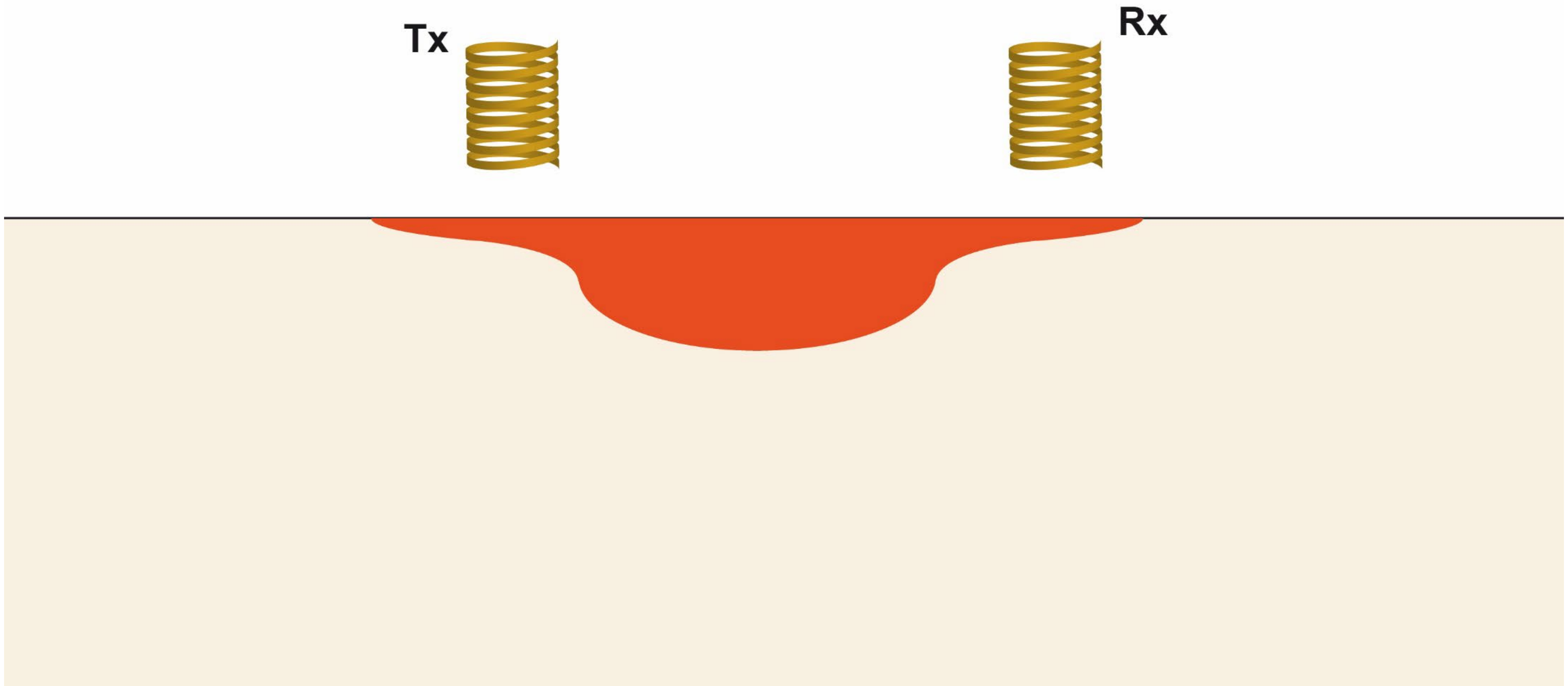
Separation of the receiver vs transmitter coil **determines** the **size** of the recorded soil volume



ORIENTATION (of receiver vs transmitter)

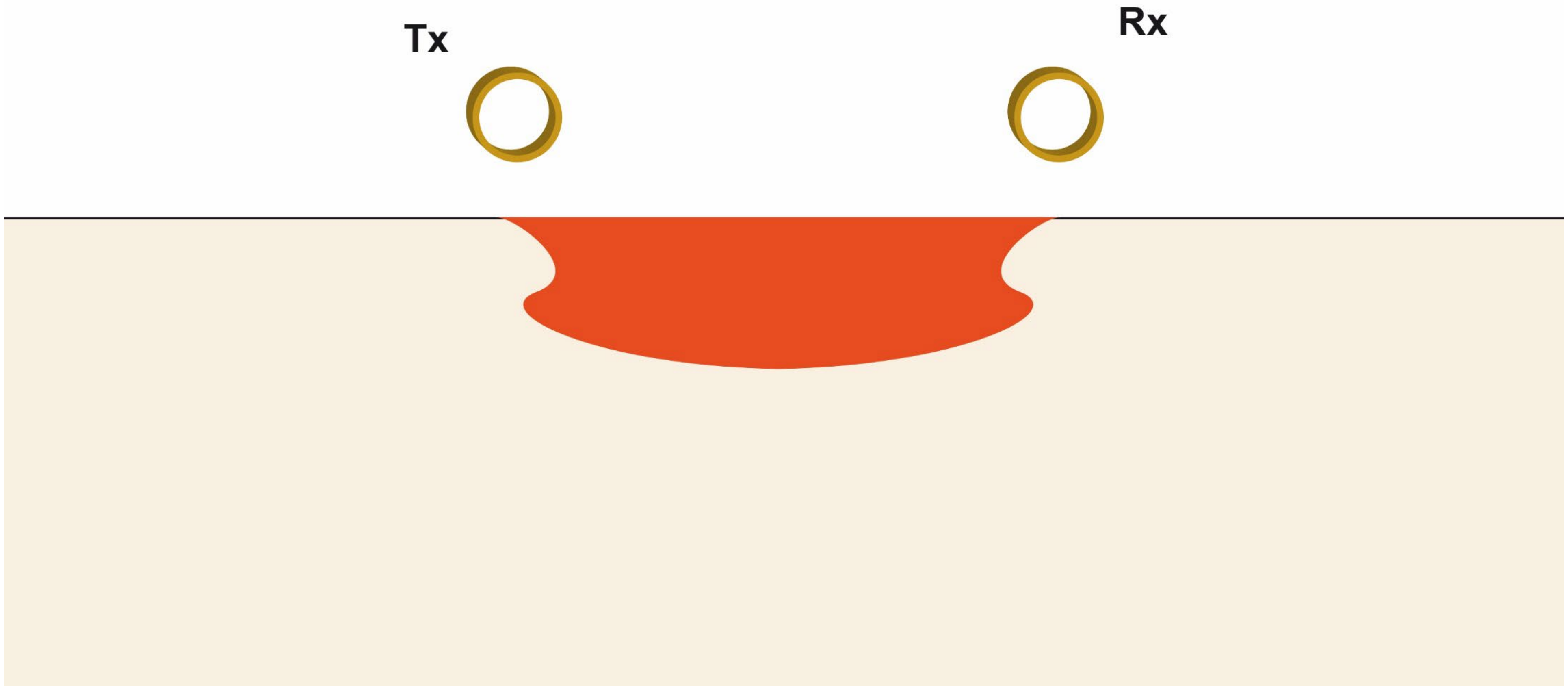
<u>Horizontal coplanair (**HCP**)</u>

Orientation of the receiver vs transmitter coil **determines** the **shape** of the recorded soil volume

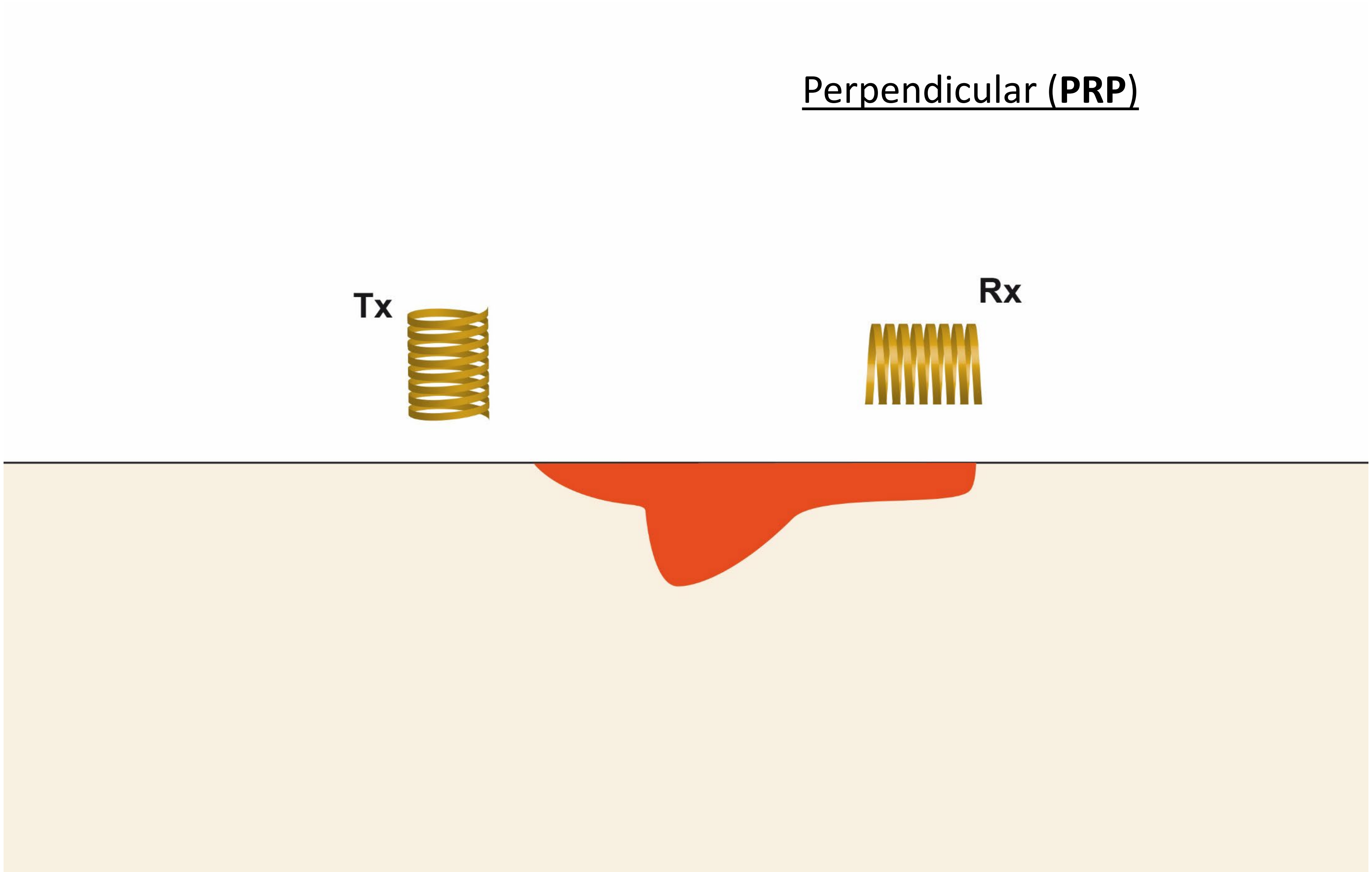


ORIENTATION (of receiver vs transmitter)

<u>Vertical coplanair (**VCP**)</u>

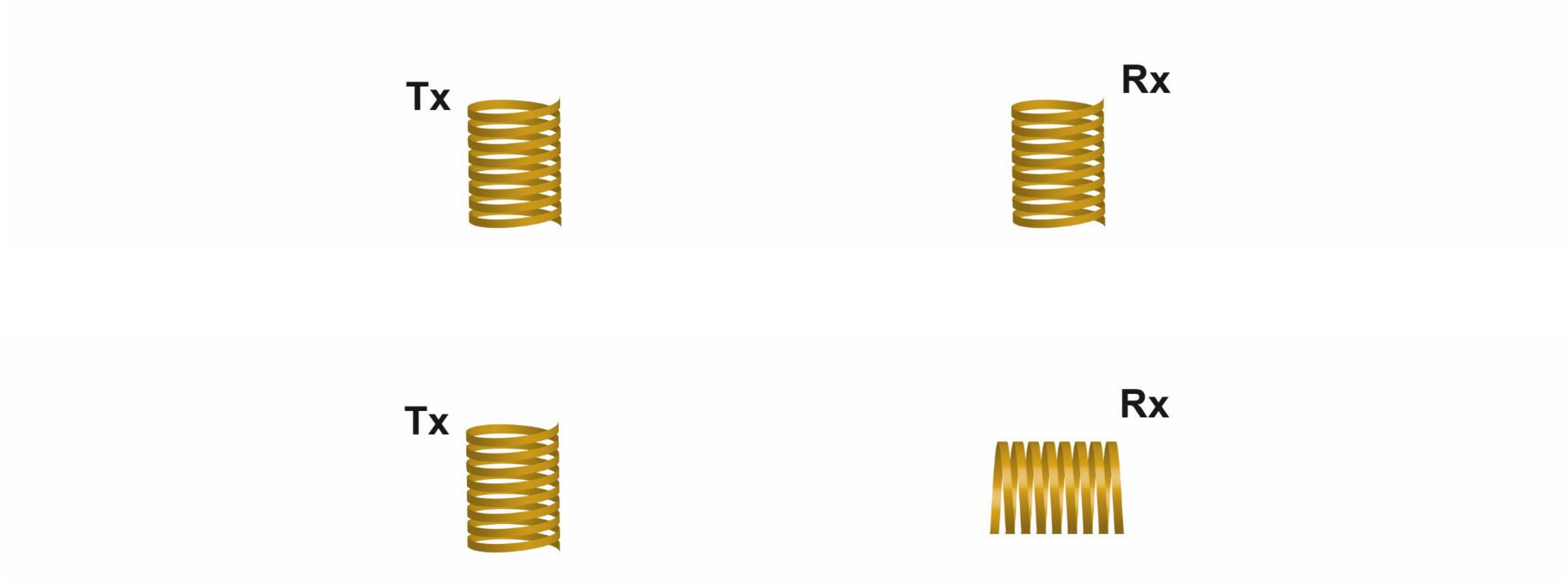


ORIENTATION (of receiver vs transmitter)



Size and shape of recorded soil volume

Depends on the **separation and orientation** of the transmitter and receiver coil



depth of investigation and size of recorded soil volume

Differs for IP and QP !!!

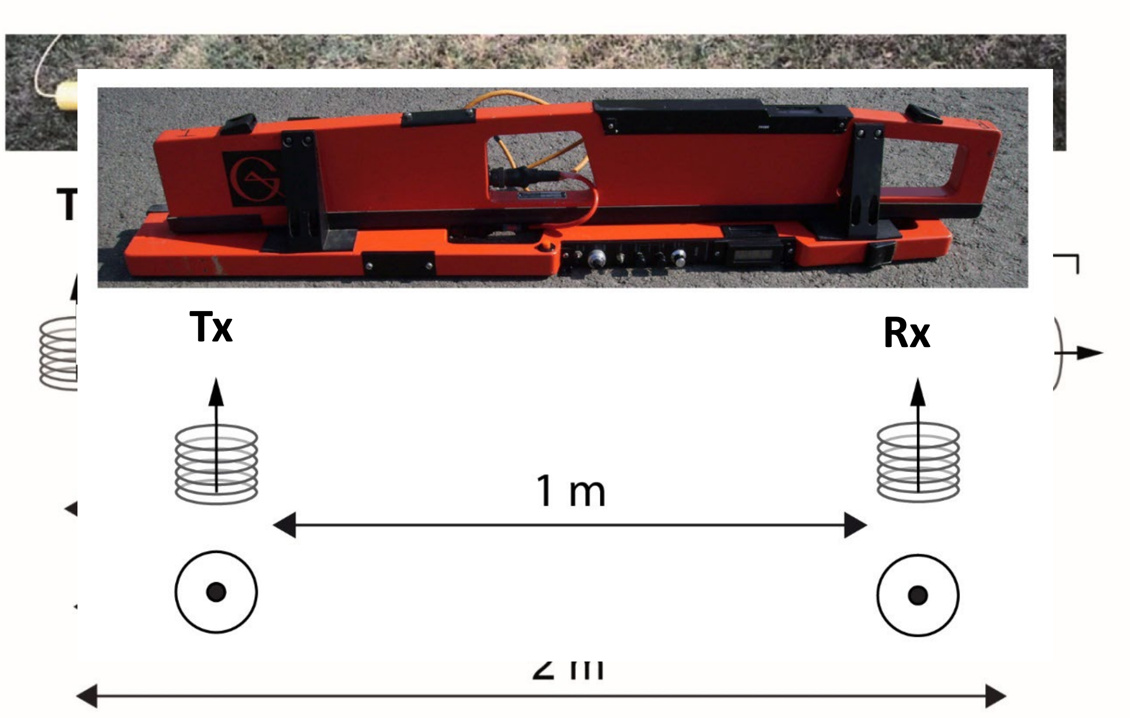
Multi-receiver/multi-configuration instruments

Combining different coil configurations in one instrument

- Different separations

- Different orientations

Voorbeeld:
Dualem 21HS
Geonics EM38 DD



EMI – working principle overview

- Potential to **simultaneously investigate electrical conductivity and magnetic susceptibility**
  - QP and IP response: ECa and in-phase susceptibility
  - Limiting conditions: saline environments (> 100 mS/m)

- Observations of a **soil volume**
  - Influence size and shape of investigated soil volume by different **Tx – Rx** configurations.
  - **Simultaneous investigation of multiple soil volumes** with multi-receiver/multi configuration instrumentation

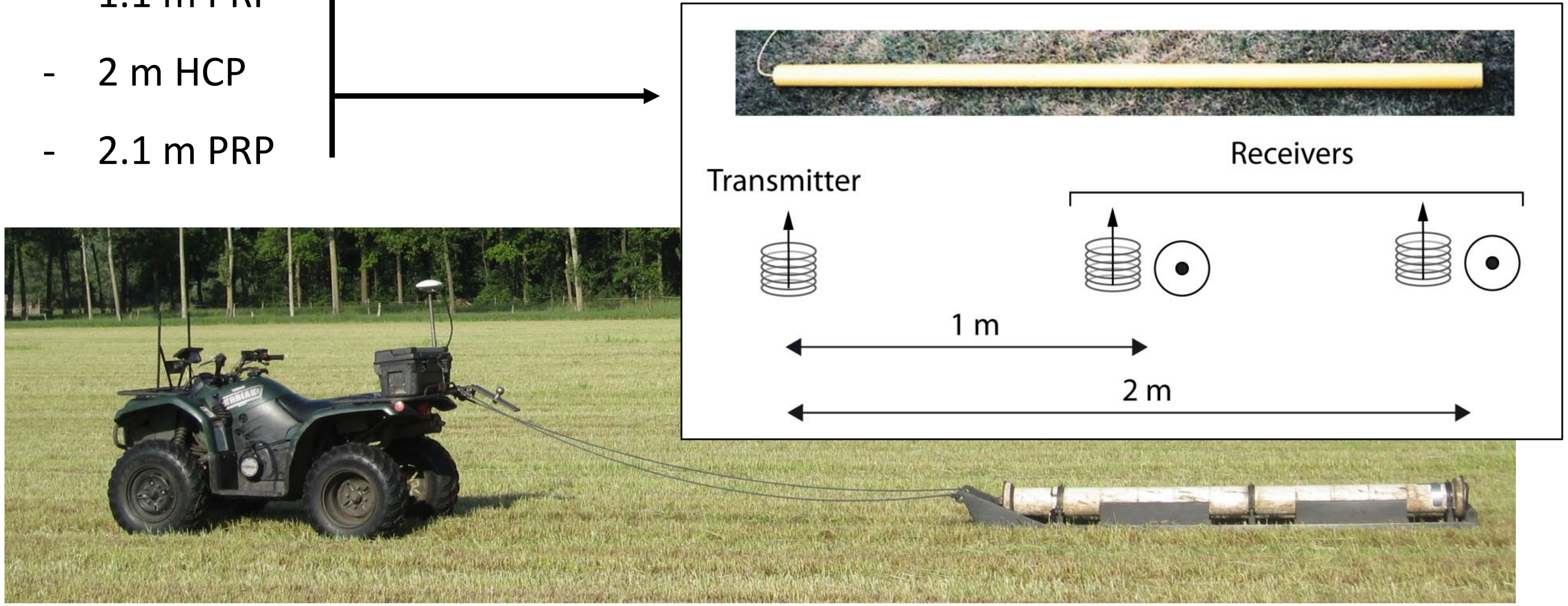
- Inductive method: **requires no contact with the soil**

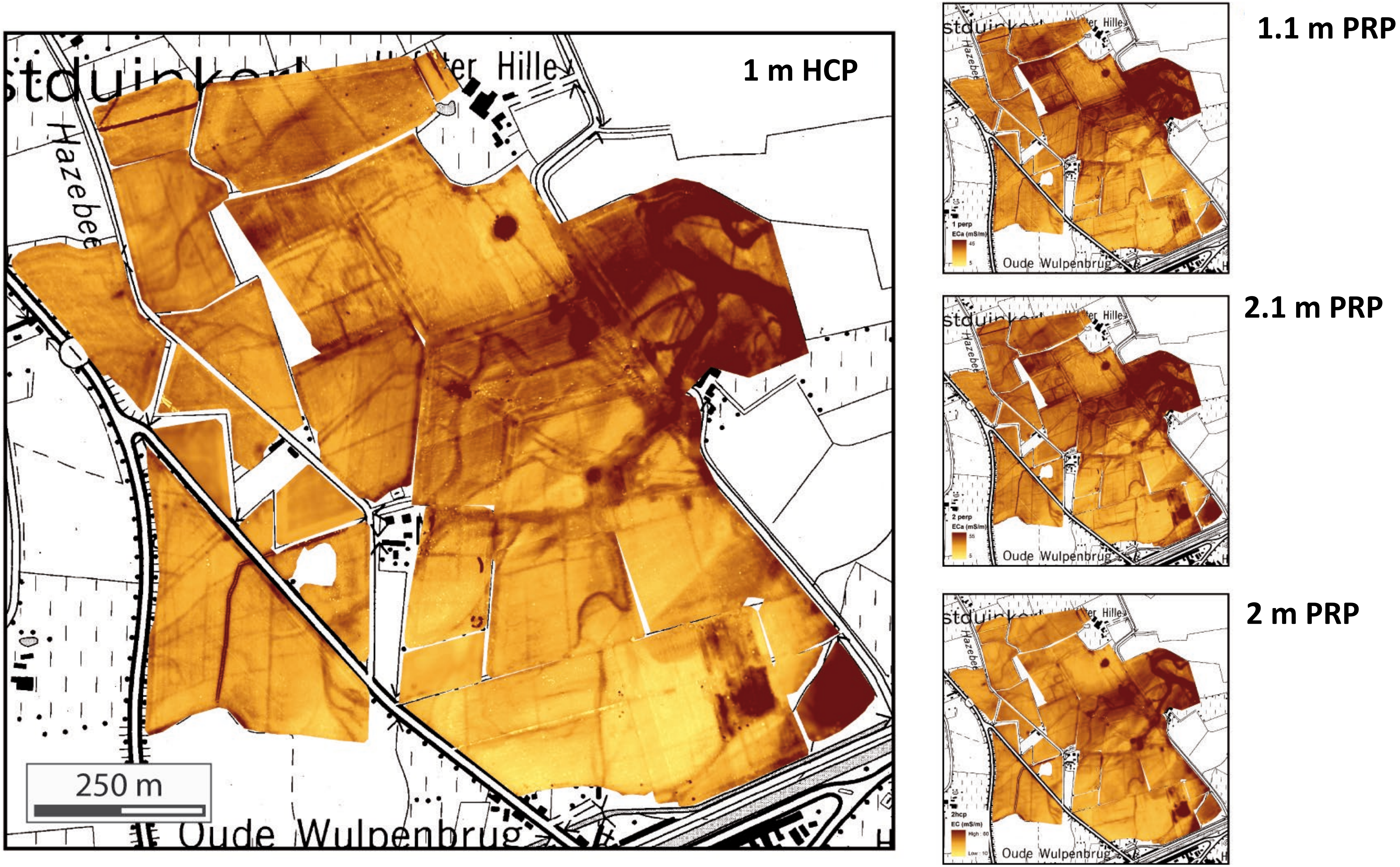
EMI – example 1: ECa mapping

Mobile survey with multi-receiver instrument

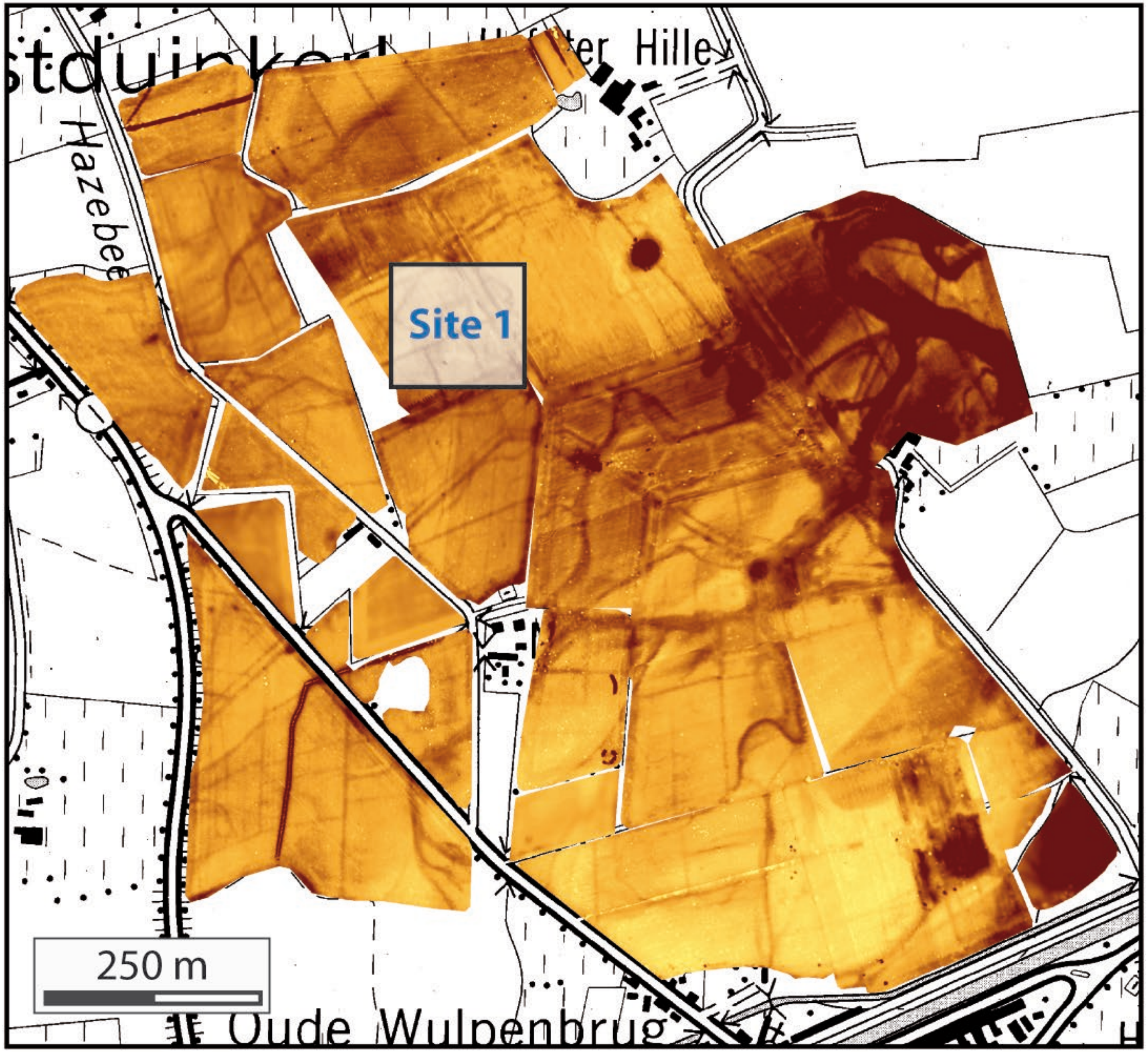
<u>**4 coil pairs**</u>

- 1 m HCP
- 1.1 m PRP
- 2 m HCP
- 2.1 m PRP

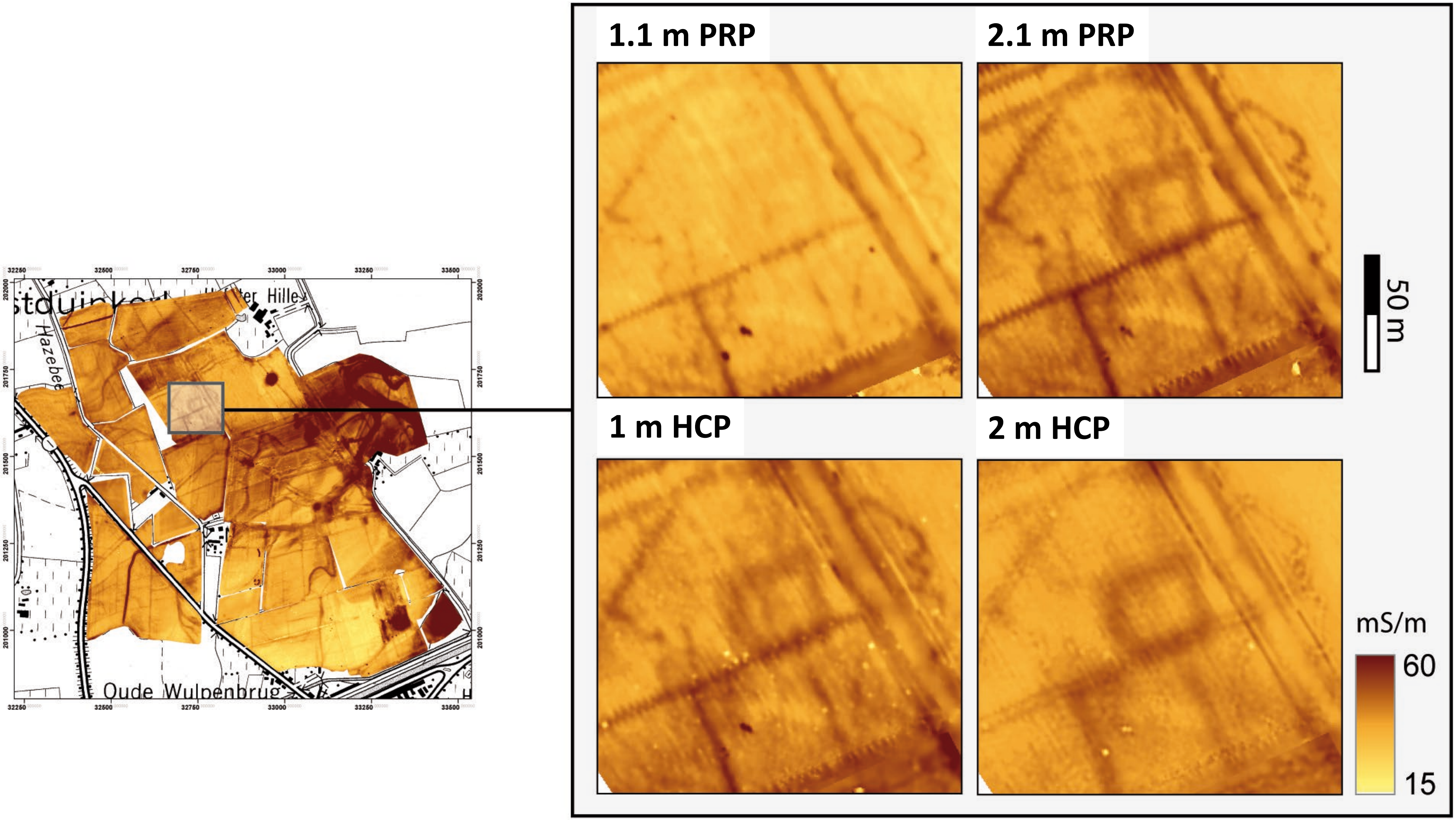


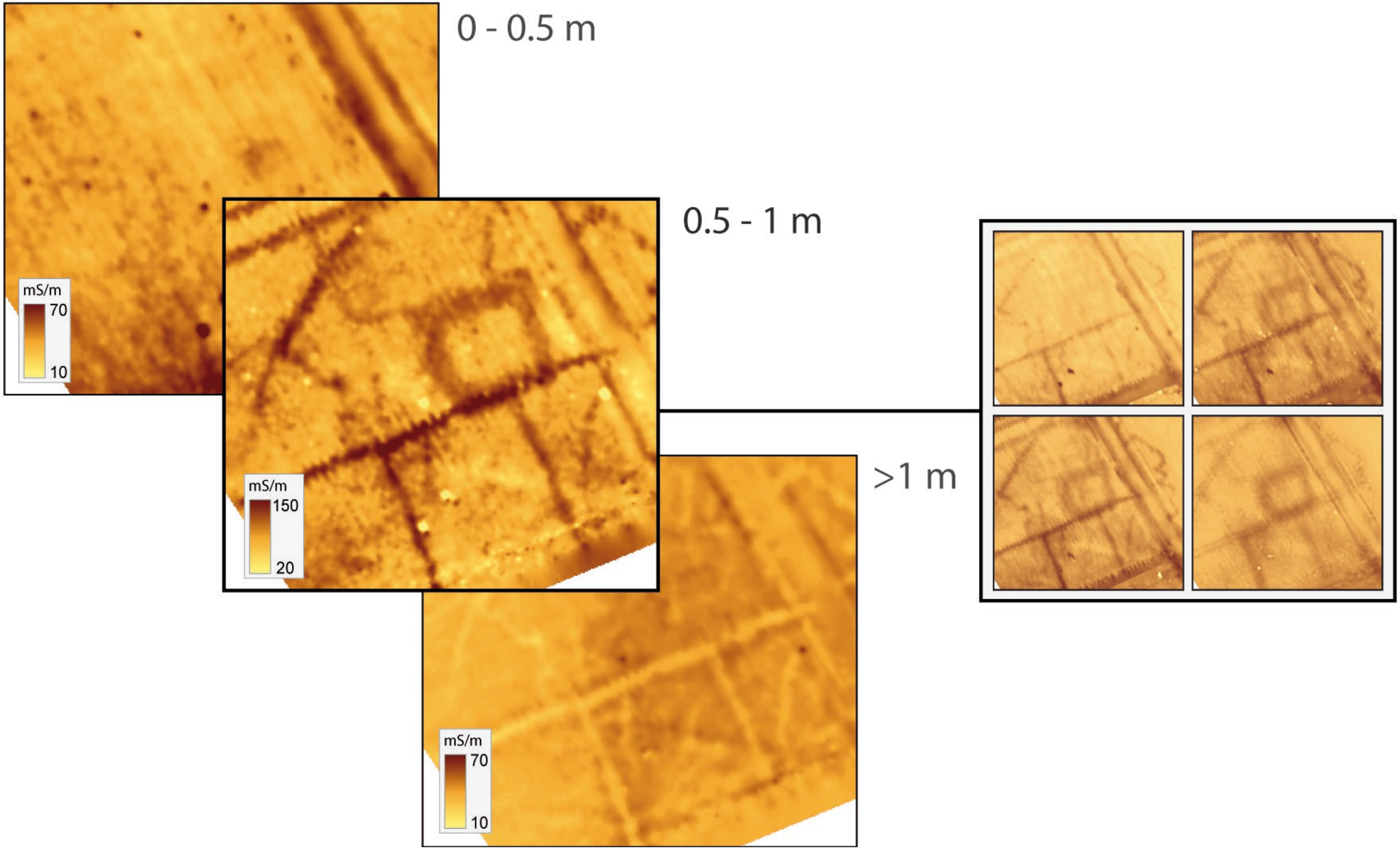


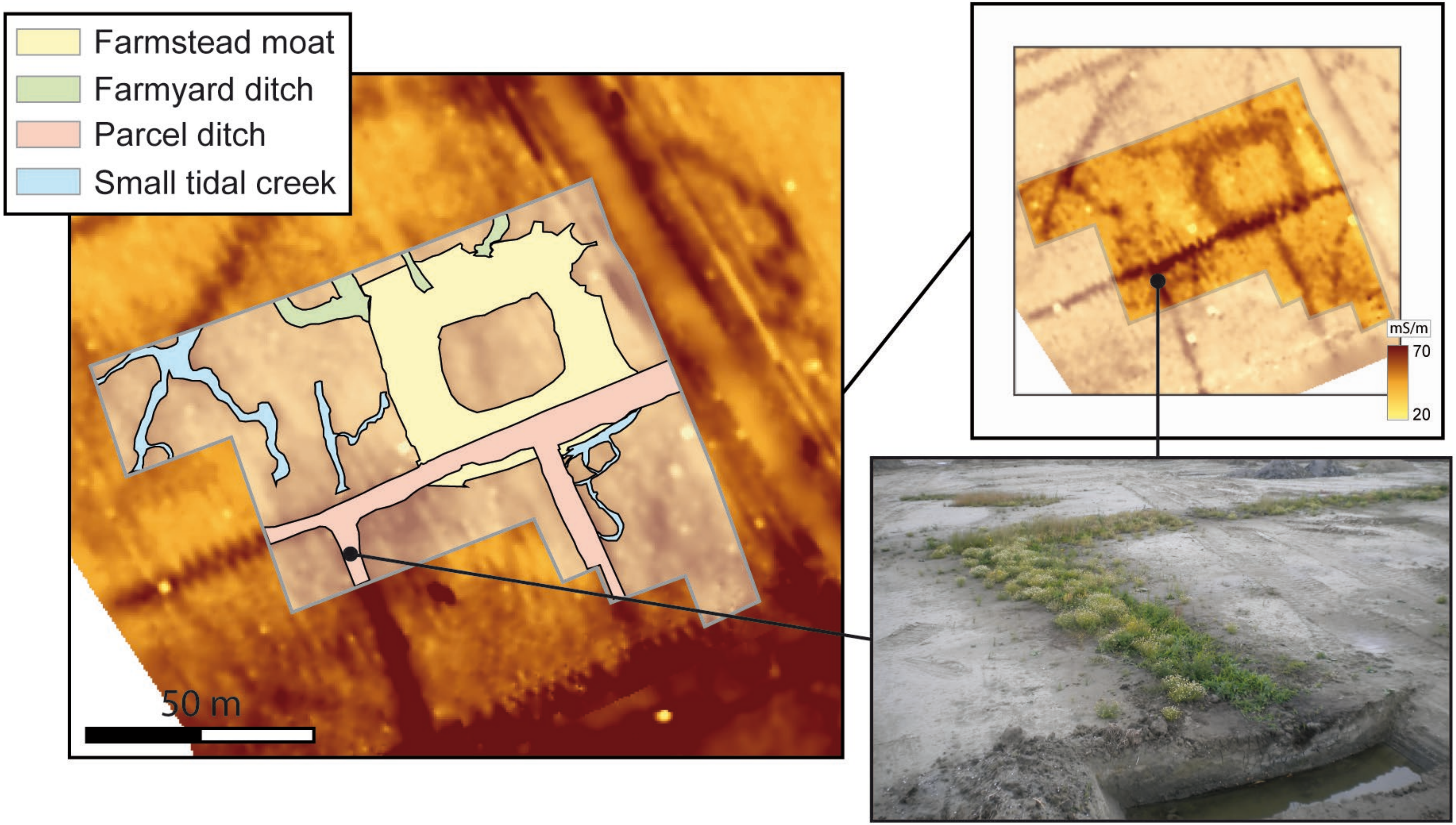
1 m HCP
1.1 m PRP
2.1 m PRP
2 m PRP
Hazebee
Hille
Oude Wulpenbrug
250 m

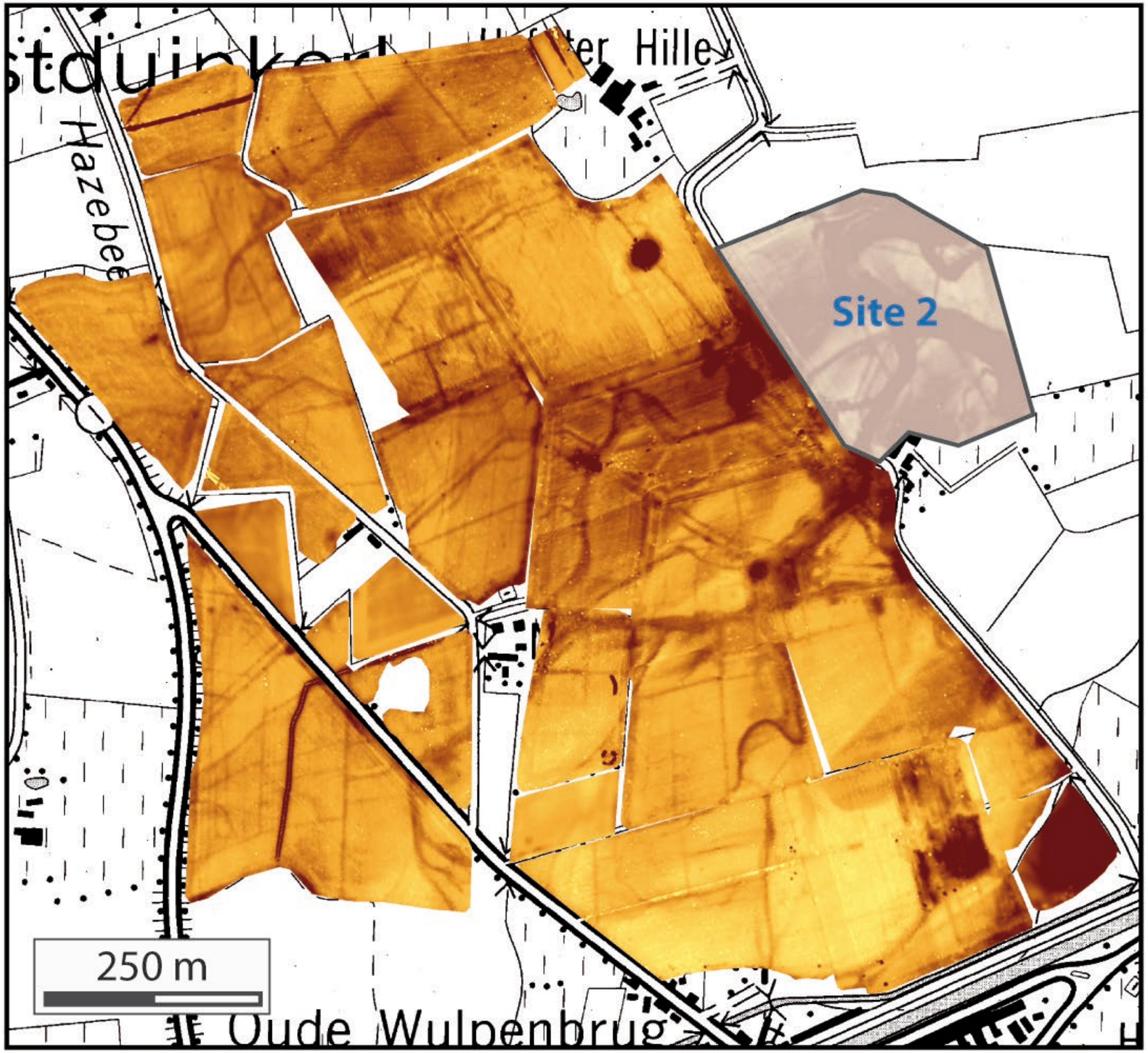


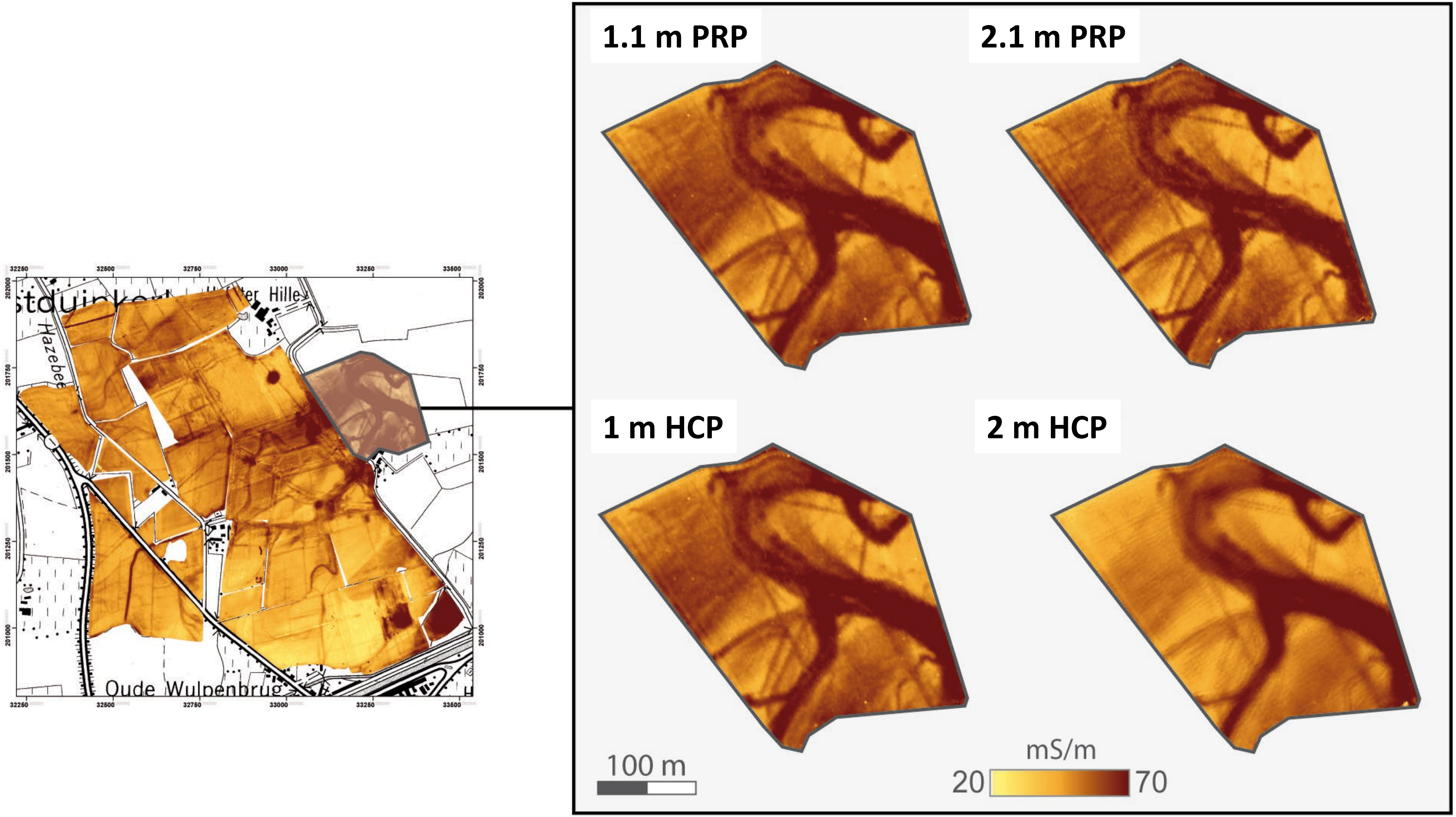
Hille
Site 1
250 m
Oude Wulpenbrug

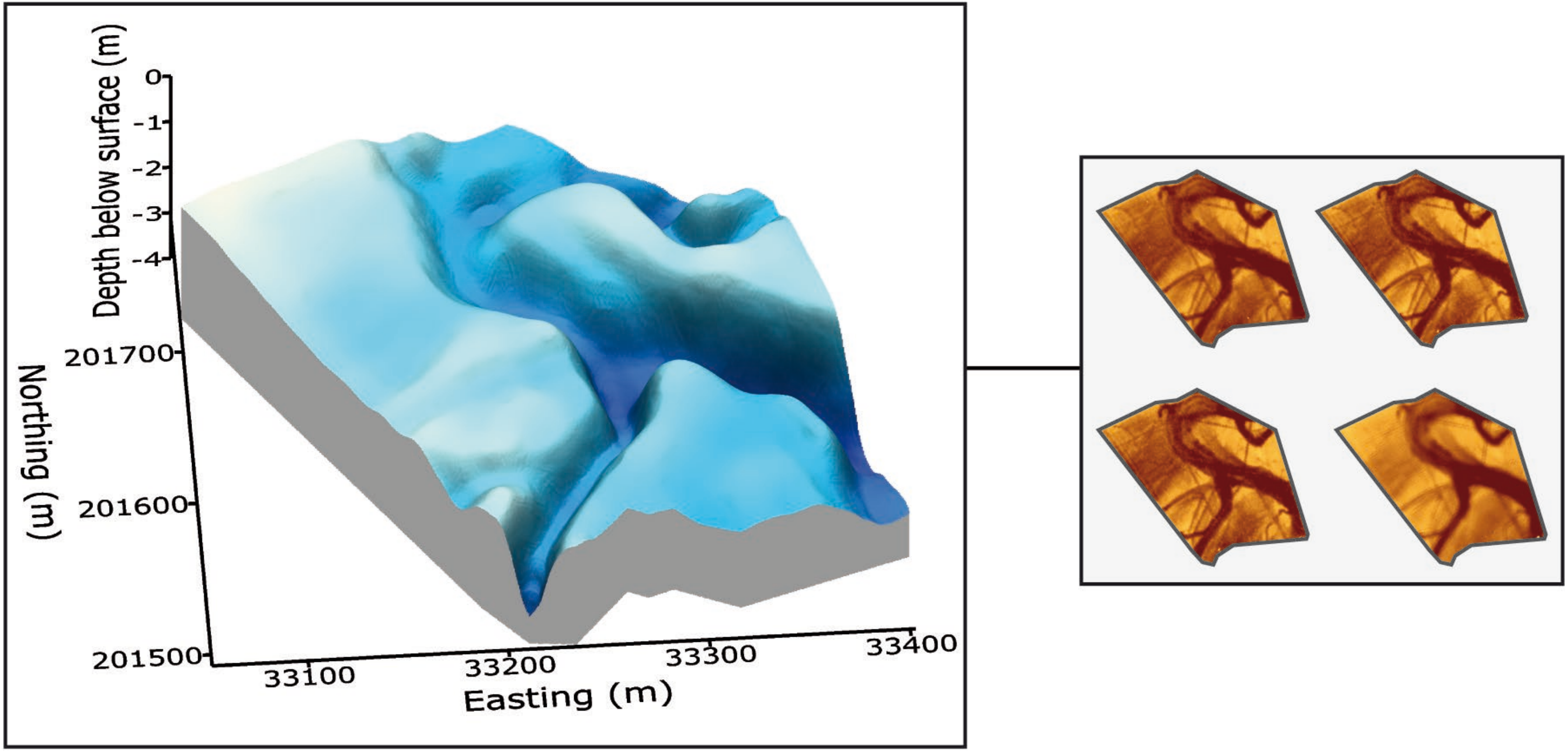

1.1 m PRP
2.1 m PRP
1 m HCP
2 m HCP
50 m
mS/m
60
15
Oude Wulpenbrug


0 - 0.5 m
mS/m
70
10
0.5 - 1 m
mS/m
150
20
>1 m
mS/m
70
10

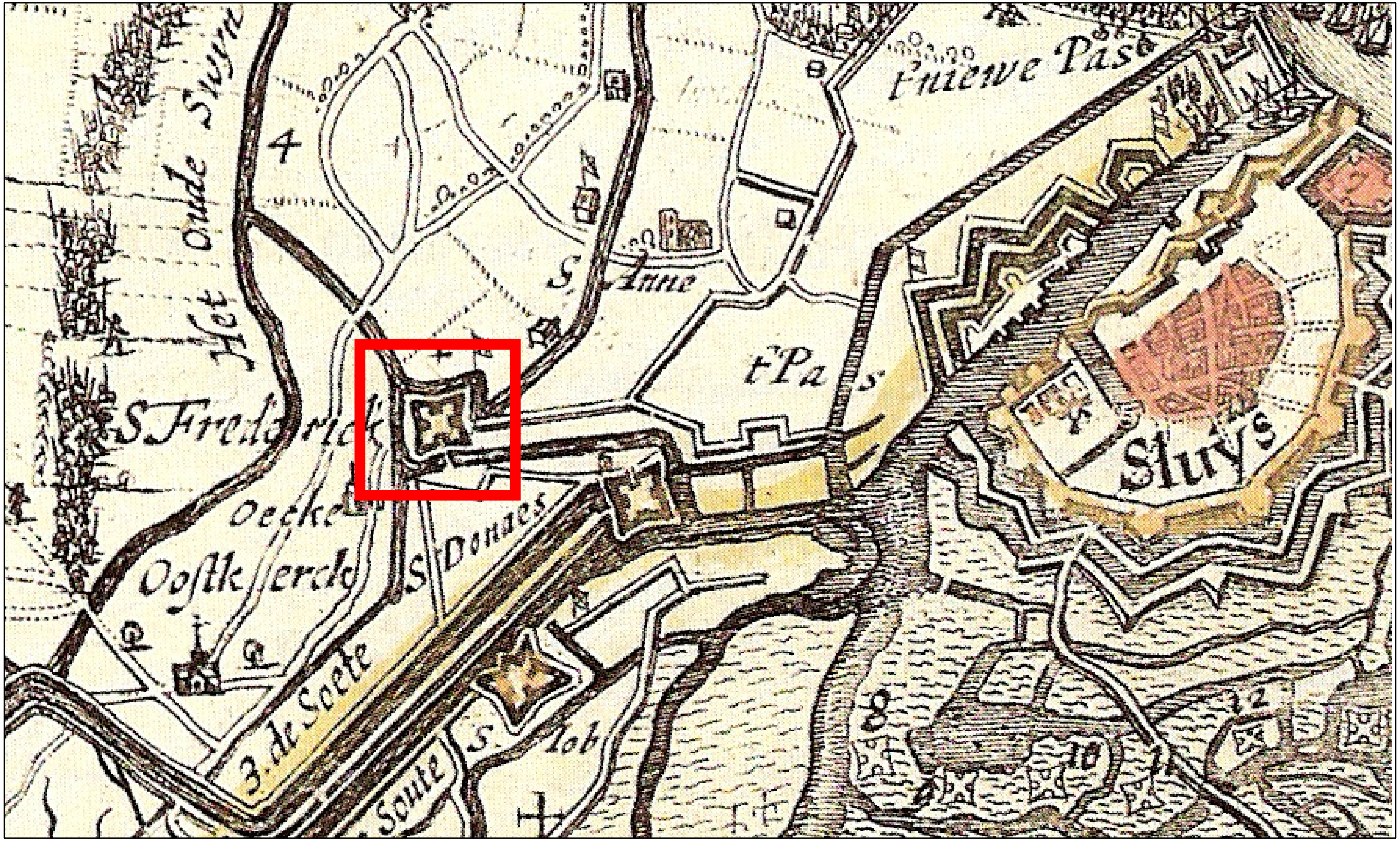

Farmstead moat
Farmyard ditch
Parcel ditch
Small tidal creek
50 m
mS/m
70
20


Site 2
250 m
Hille
Oude Wulpenbrug

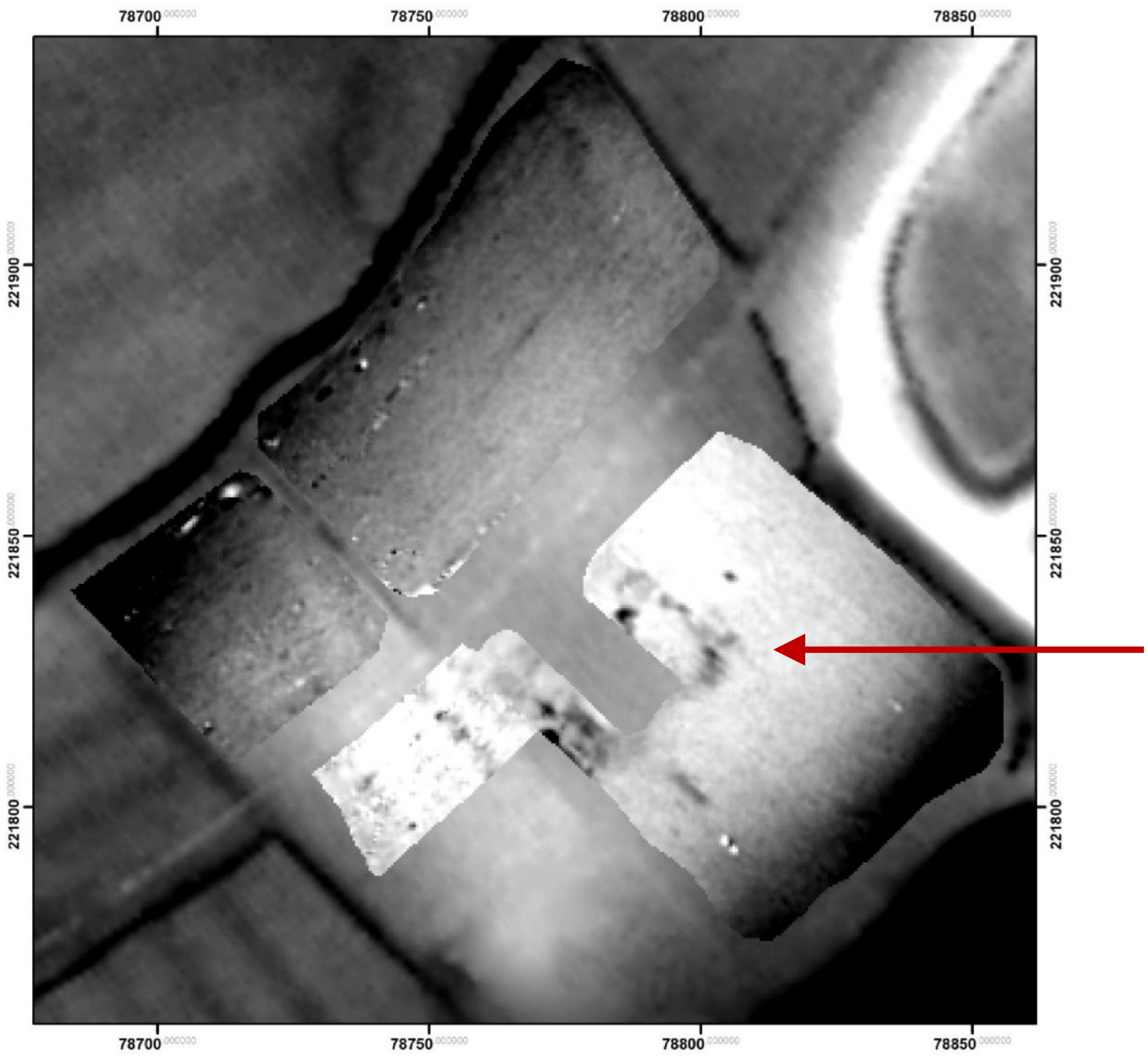

1.1 m PRP
2.1 m PRP
1 m HCP
2 m HCP
100 m
mS/m
20
70
Hazebee
Hille
Oude Wulpenbrug
32250
32500
32750
33000
33250
33500
202000
201750
201500
201250
201000


Depth below surface (m)
0
-1
-2
-3
-4
Northing (m)
201700
201600
201500
33100
33200
33300
33400
Easting (m)

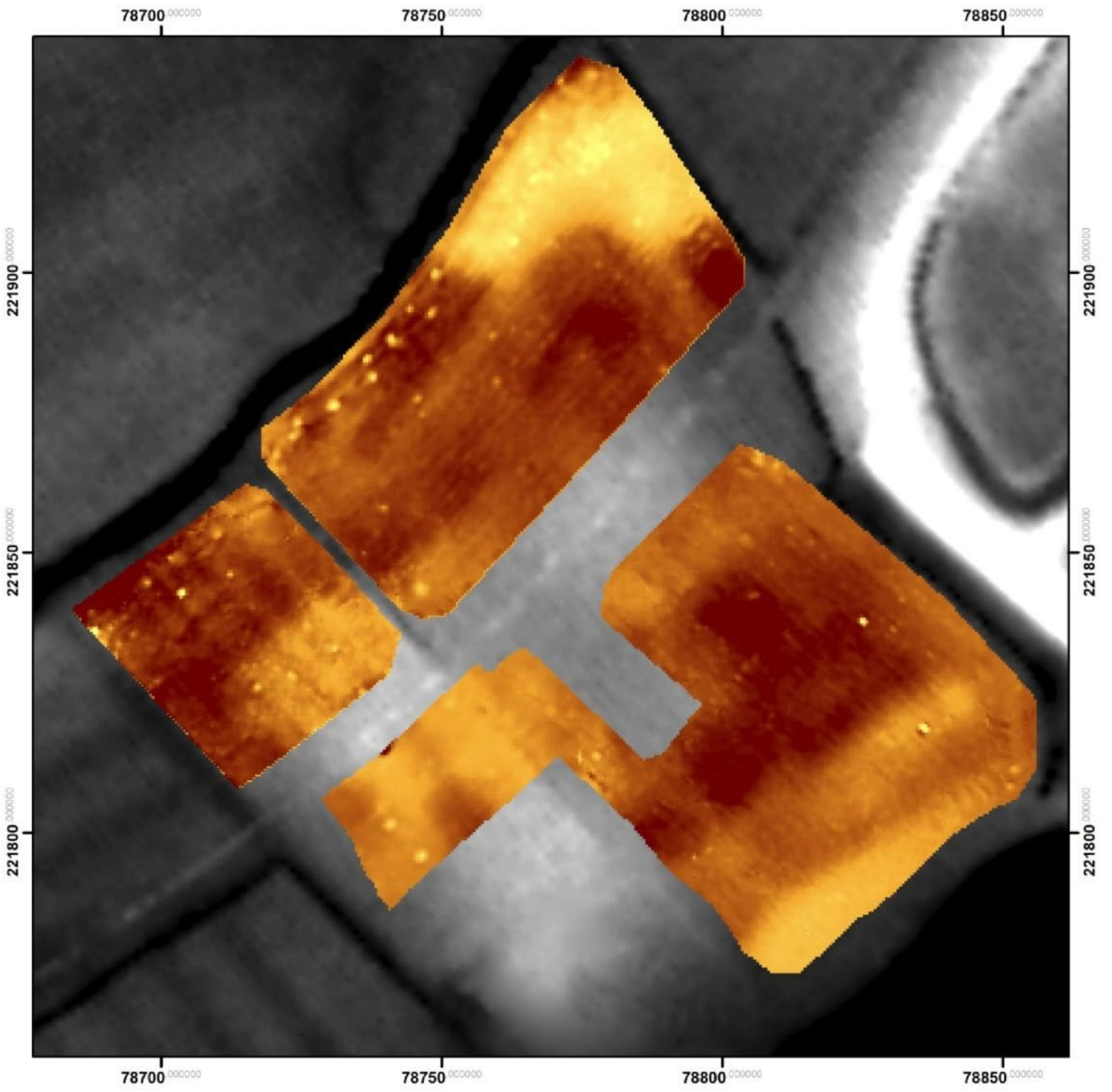
EMI – example 2: mapping conductivity and susceptibility – Spanish Fort 17th Century (Belgium)

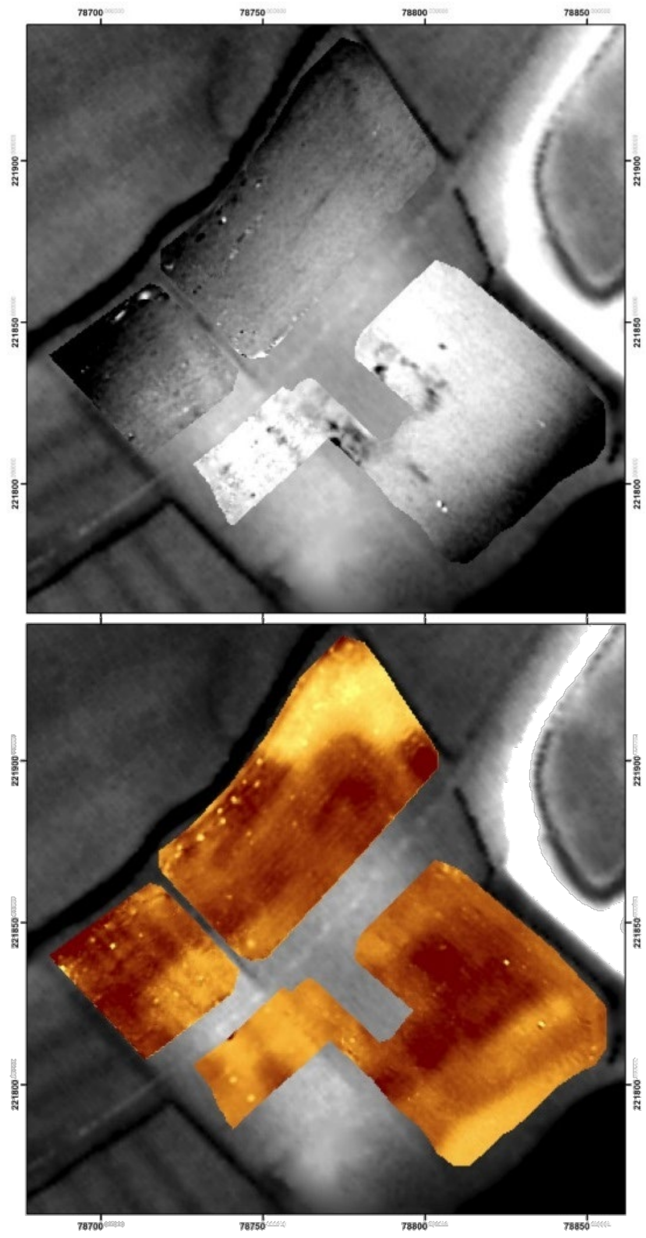


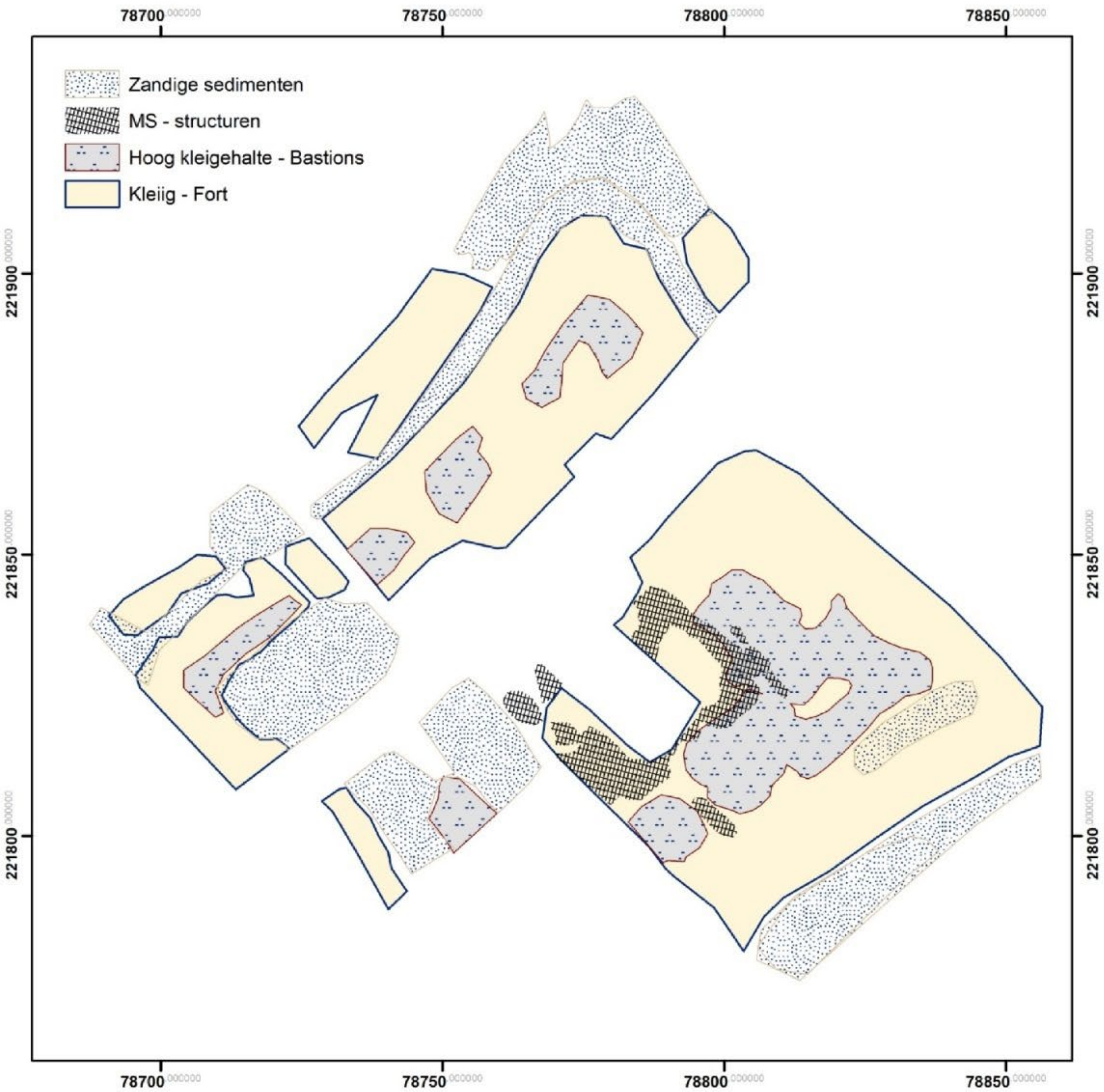
In-phase susceptibility



ECa







78700
78750
78800
78850
221900
221850
221800
Zandige sedimenten
MS - structuren
Hoog kleigehalte - Bastions
Kleiig - Fort

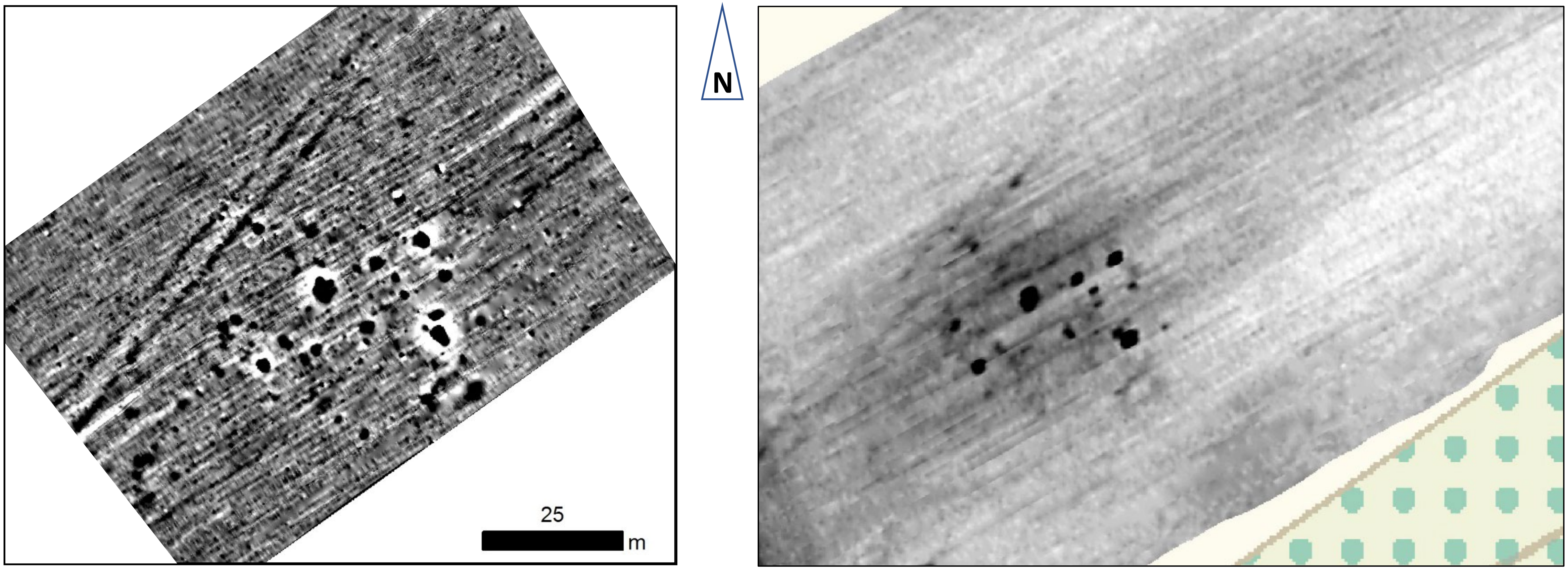
Magnetic prospection with magnetometry vs EMI

MAGNETOMETRY

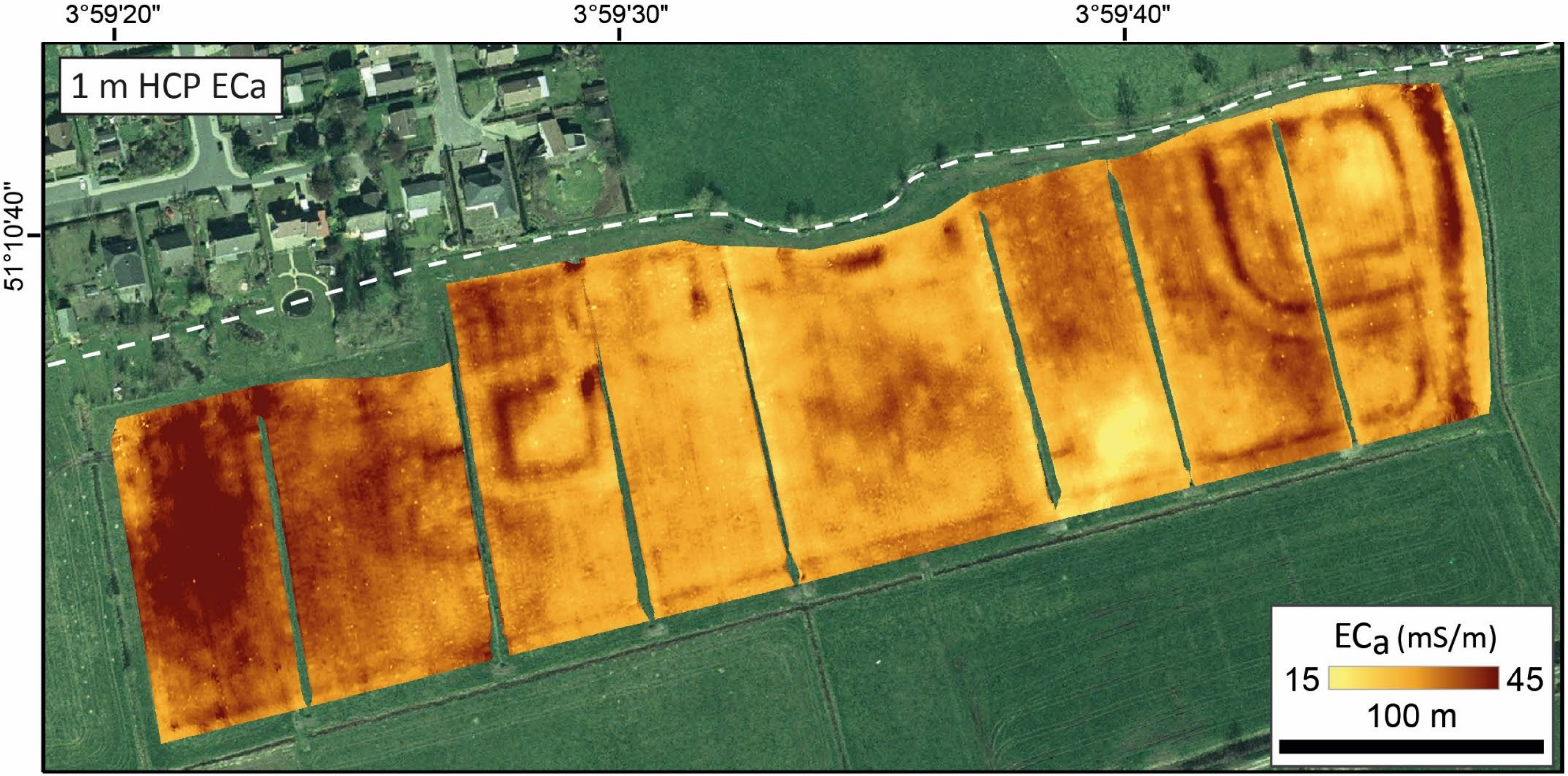
- Monitoring fluxdensity $\vec{\boldsymbol{B}}$
- Registration of **dipoles**
- Discrimination between **induced** and **remanent** magnetisaton
- Independent from electrical soil variations
- Influence of earth magnetic field

EMI

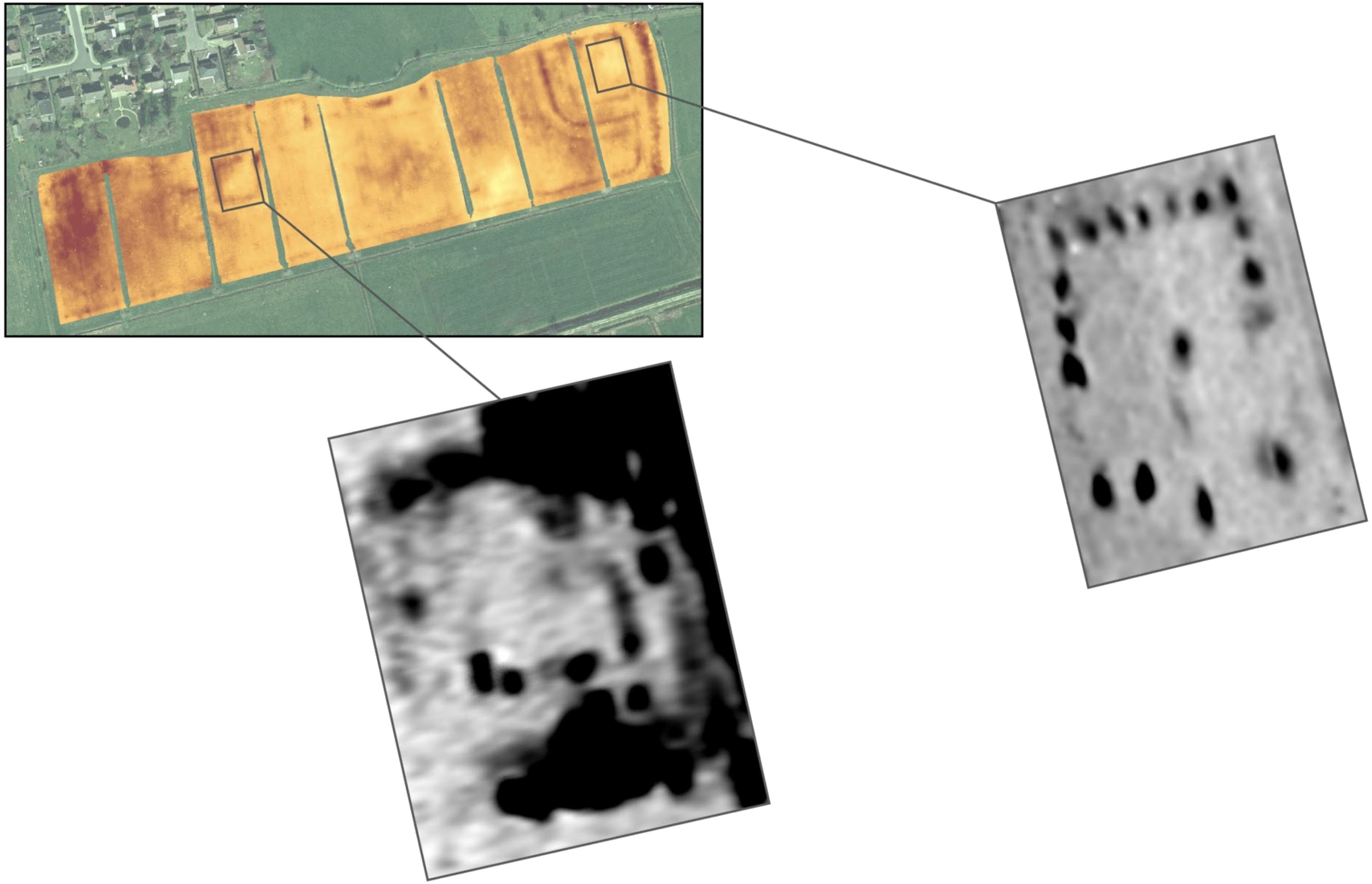
- Recording magnetic susceptibility ($\boldsymbol{\kappa}$) through the induced field $\vec{\boldsymbol{H}}_p$
- Recording of **field strength** (ppt)
- Only information on **induced** magnetisation
- At high conductivity (saline conditions): EC dominates the IP response
- No influence of earth magnetic field

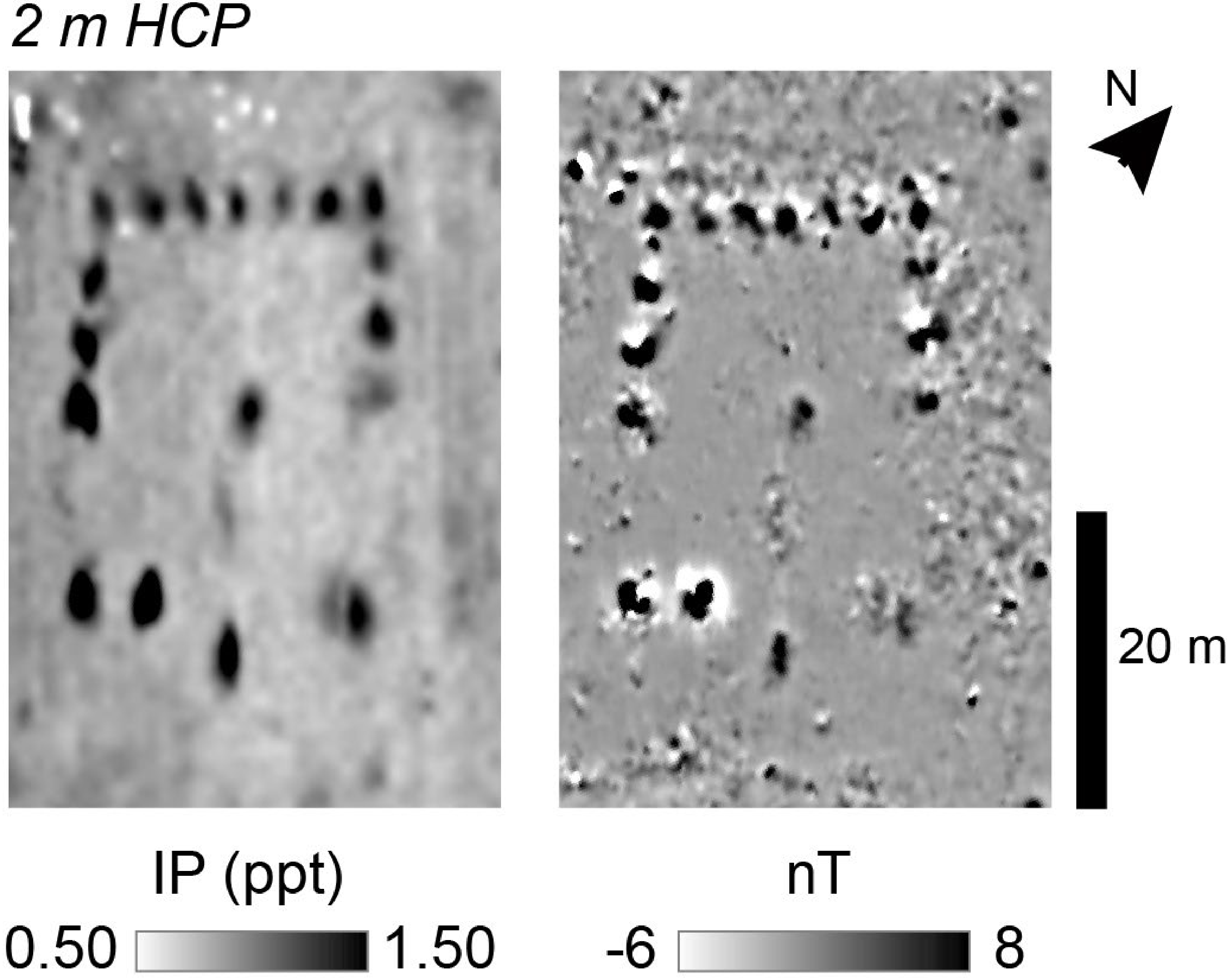

25
m
N

EMI – example 3: medieval wetland site (Belgium)

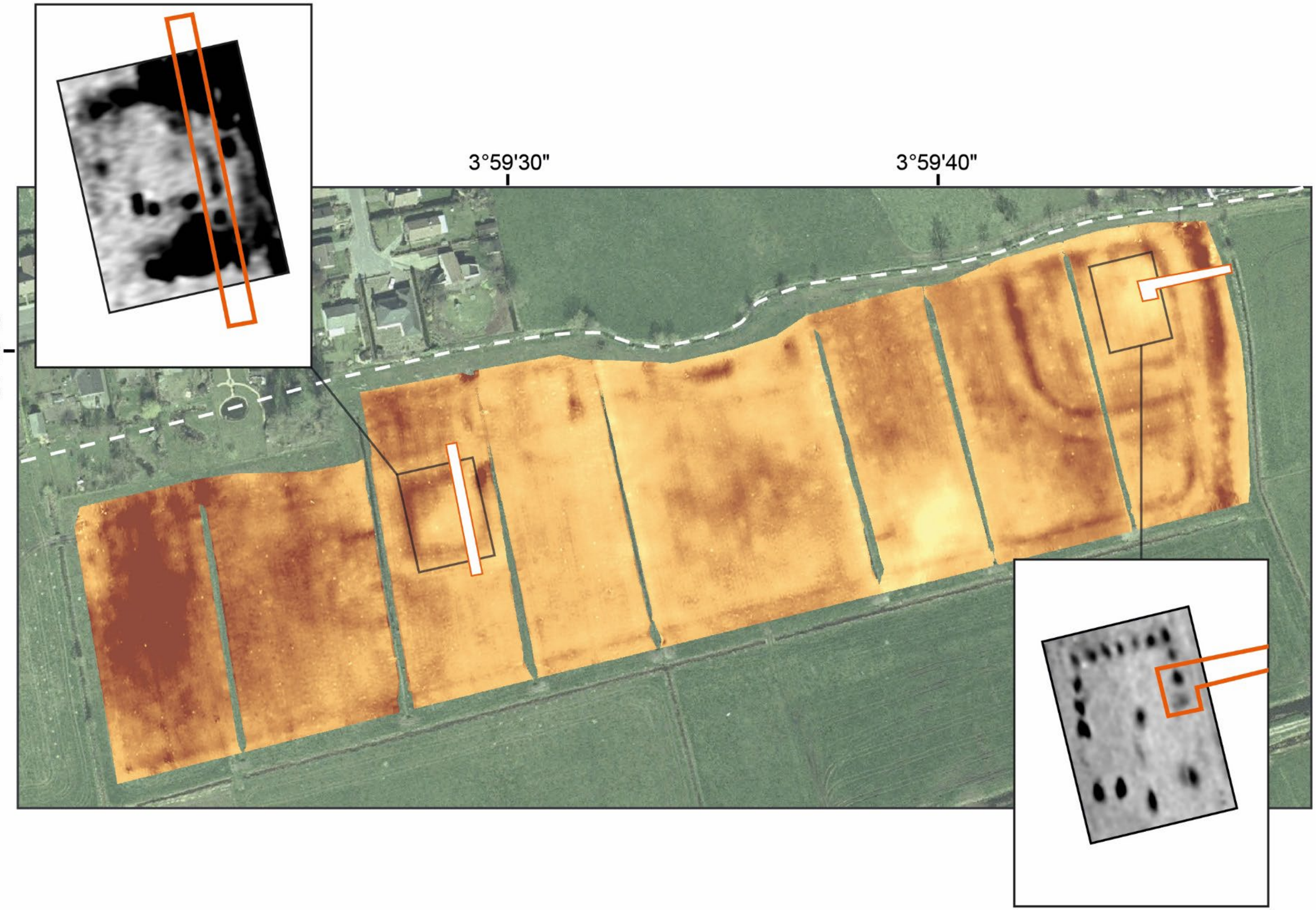


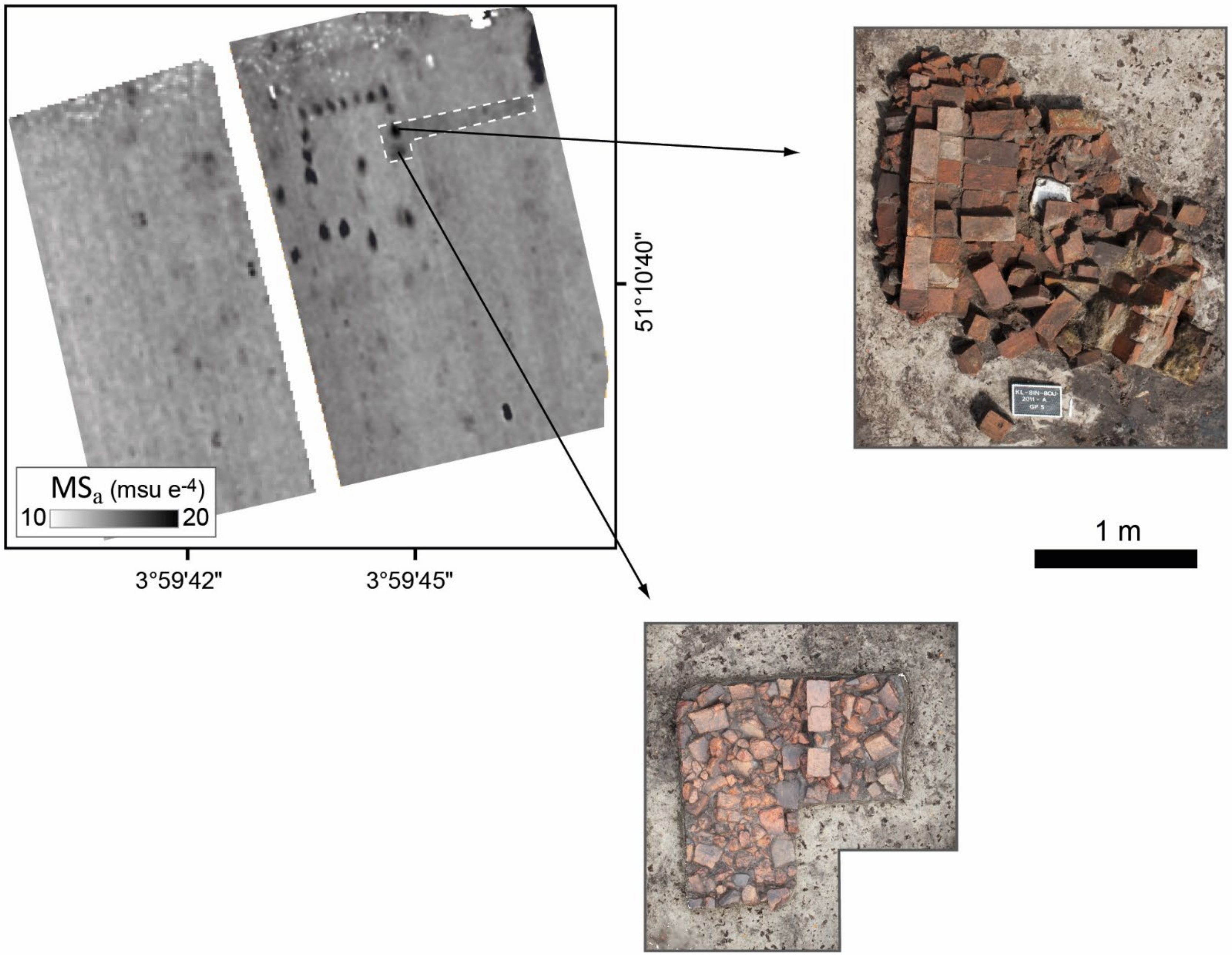
In-phase susceptibility



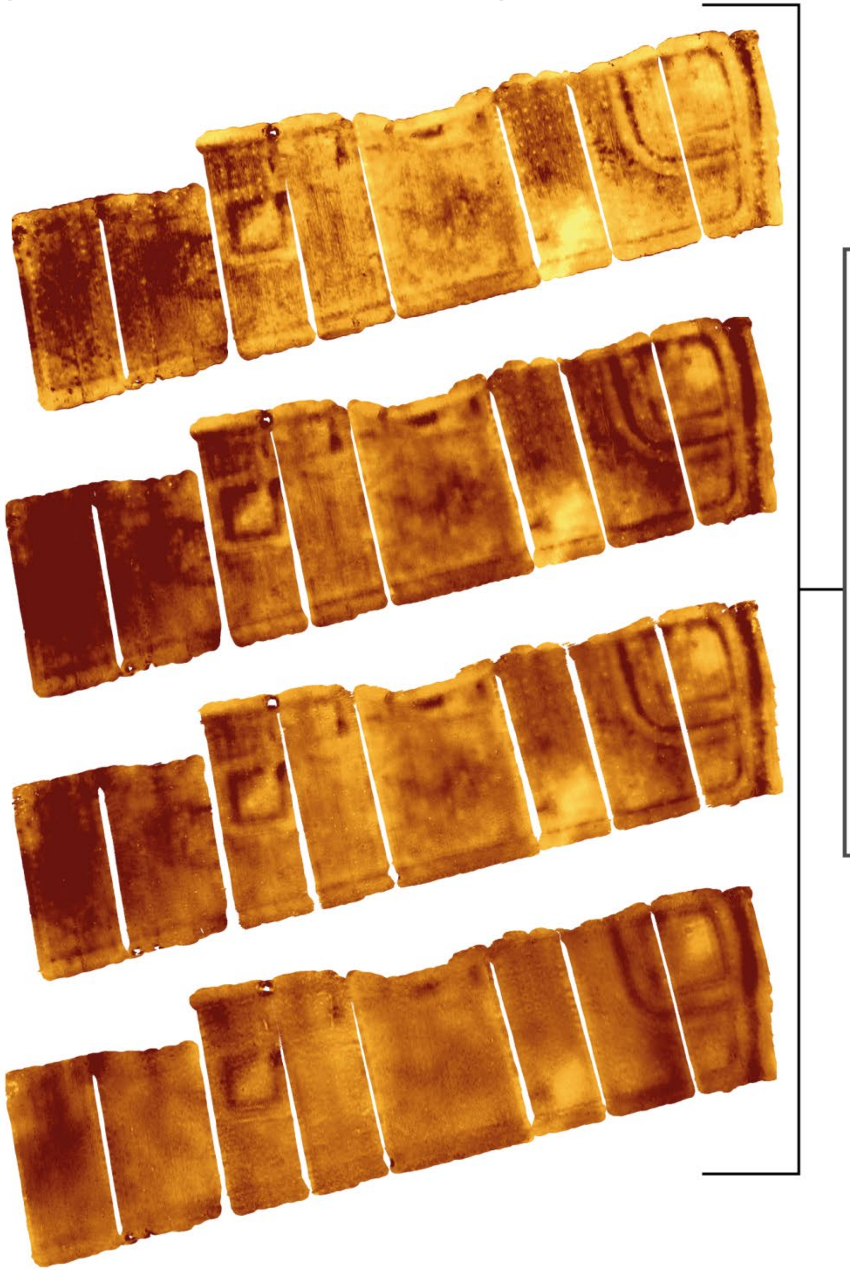


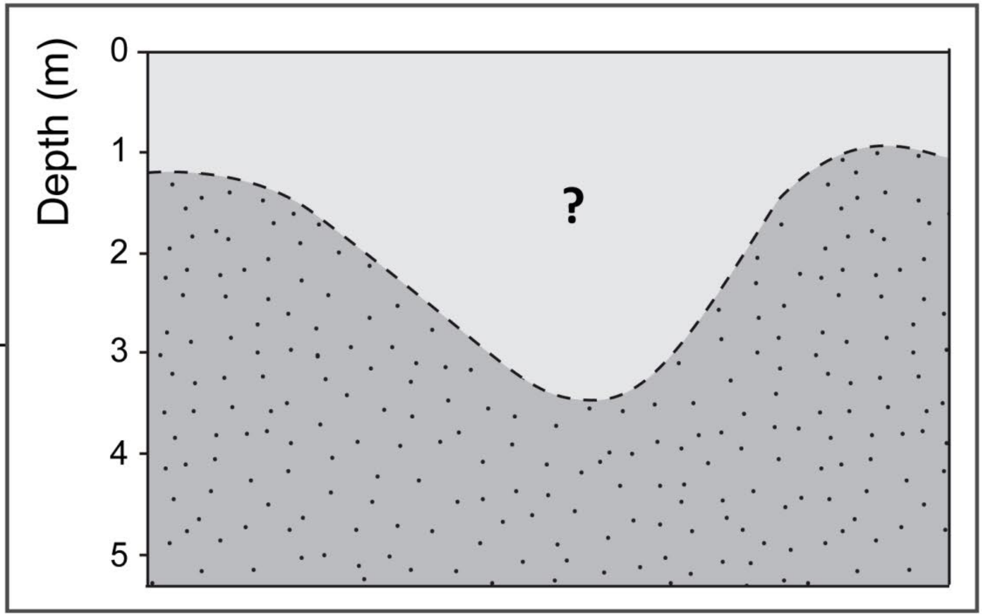
2 m HCP
N
20 m
IP (ppt)
0.50
1.50
nT
-6
8


3°59'30"
3°59'40"
51°10'40"

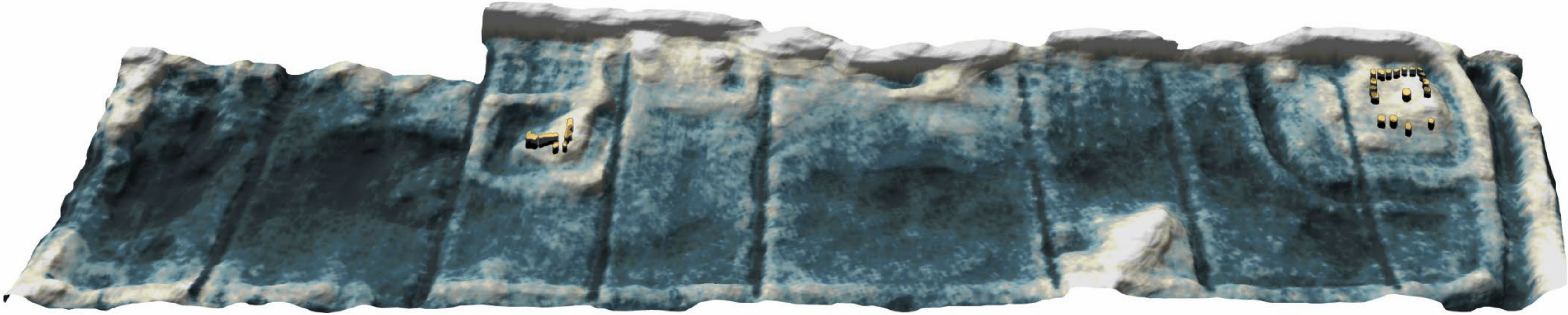

MSa (msu e-4)
10
20
51°10'40"
3°59'42"
3°59'45"
1 m

Reconstructing subsurface morphology

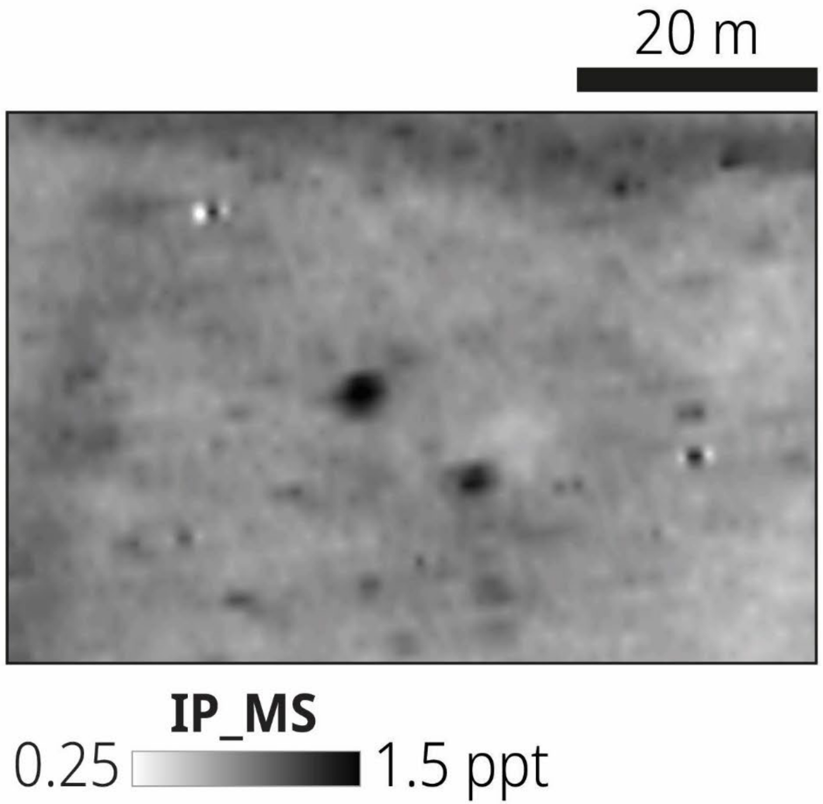


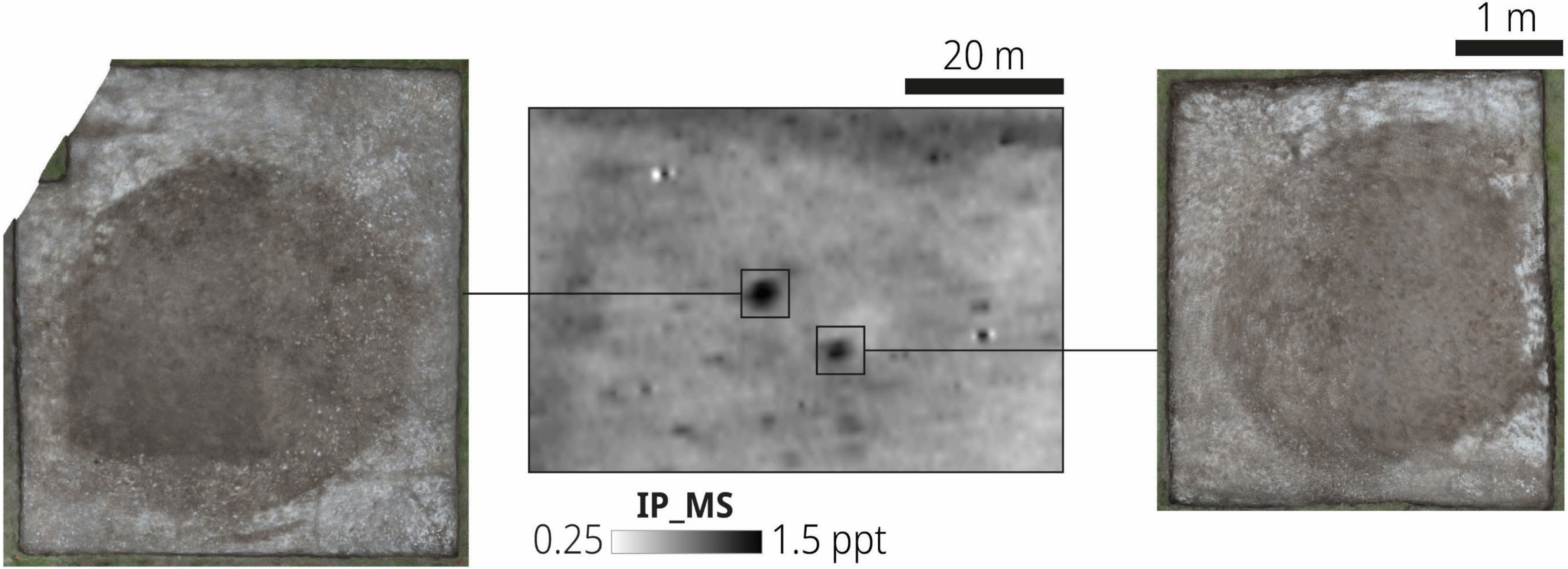


Buried surface topography + magnetic structures

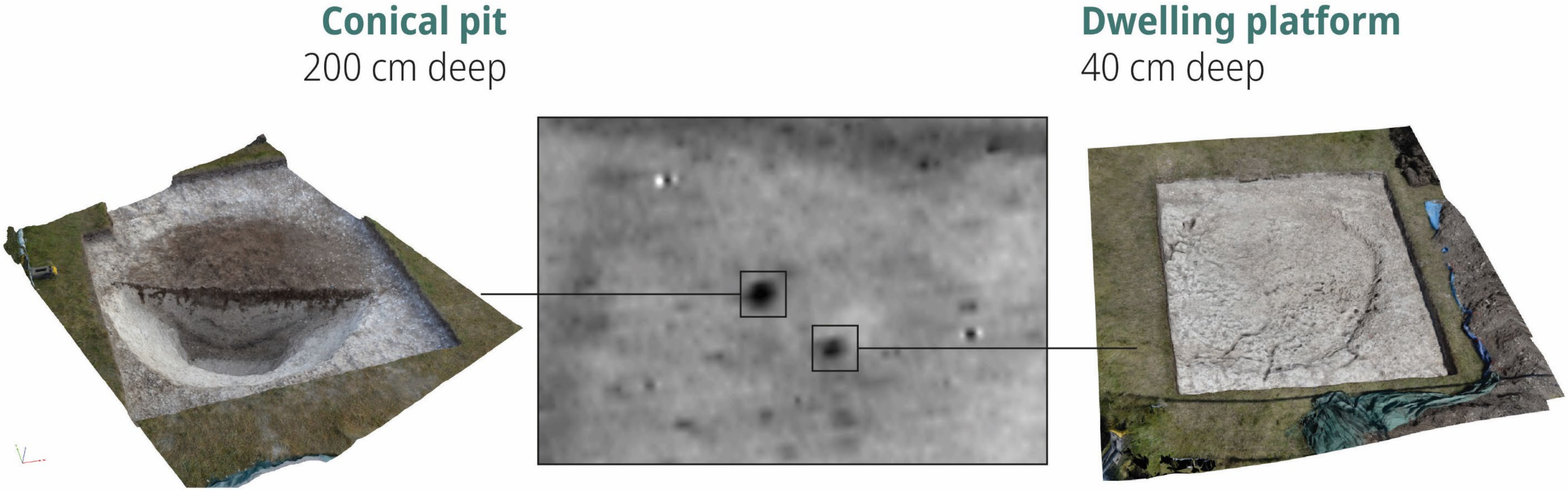


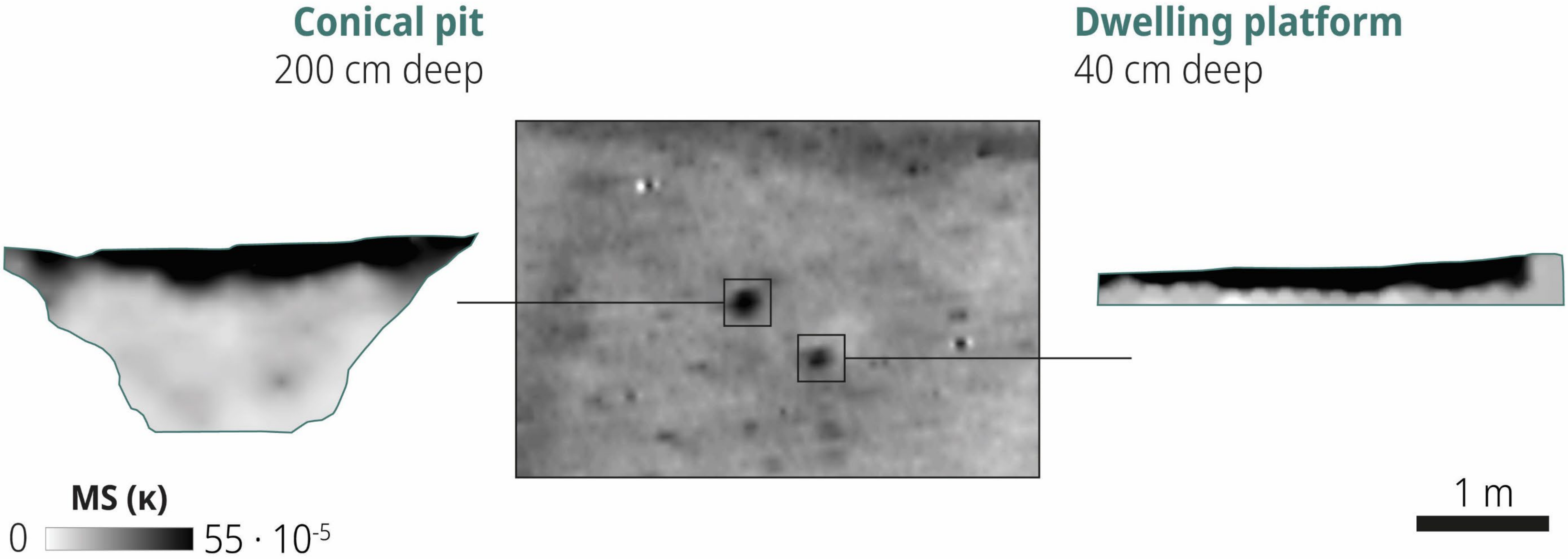
EMI – example 4: multi-variate characterisation of pits



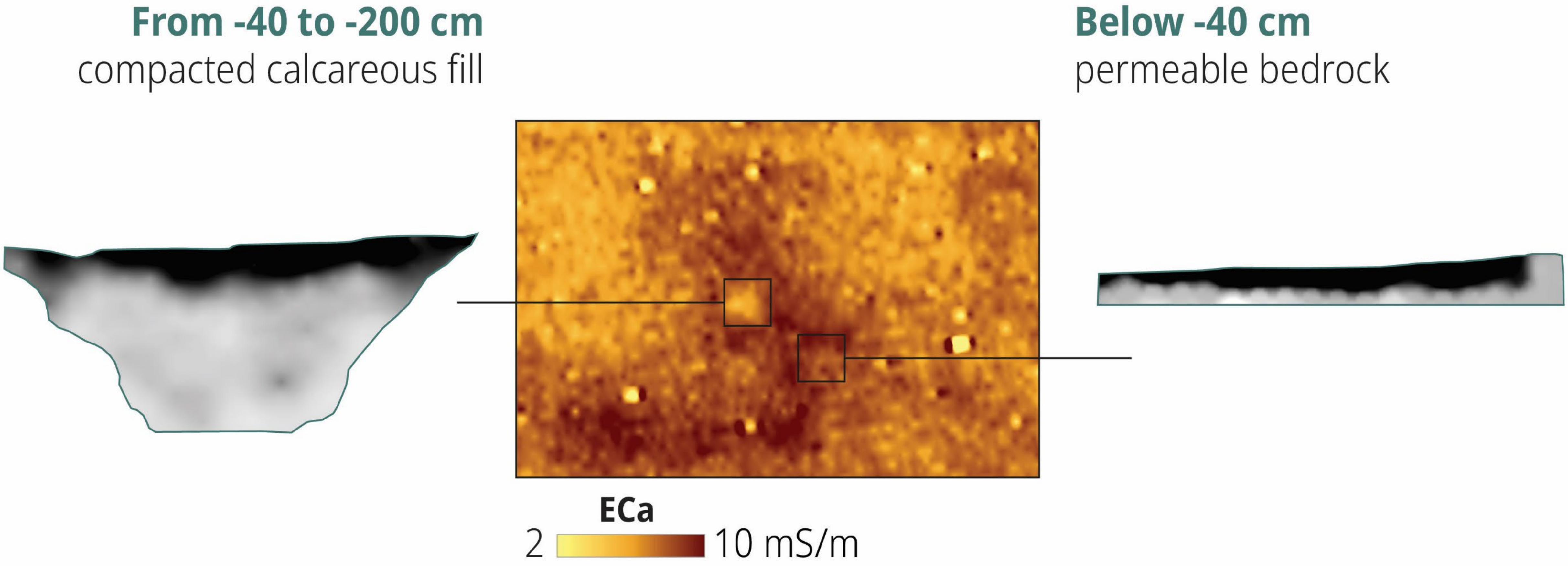


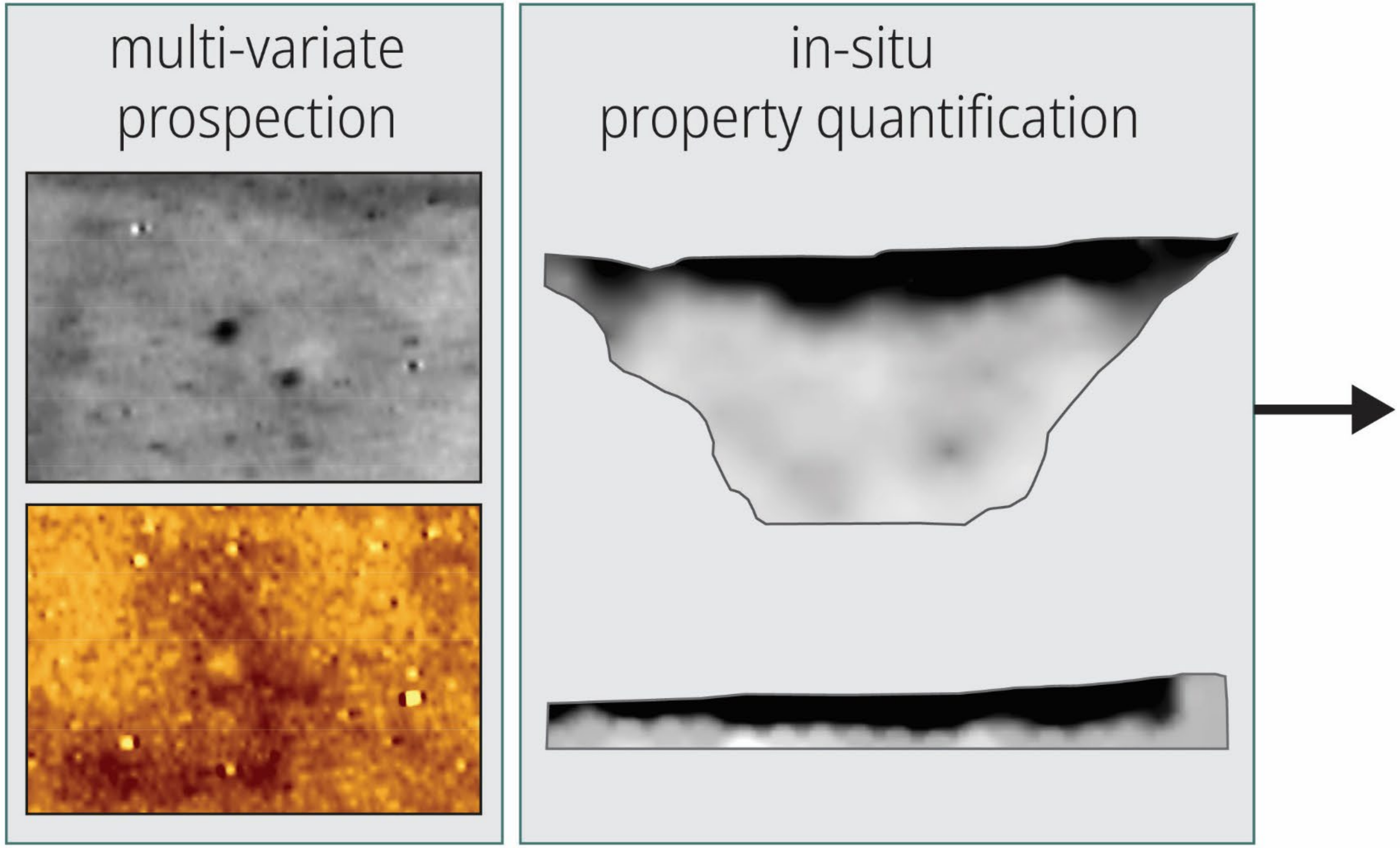
20 m
1 m
IP_MS
0.25
1.5 ppt


Conical pit
200 cm deep
Dwelling platform
40 cm deep



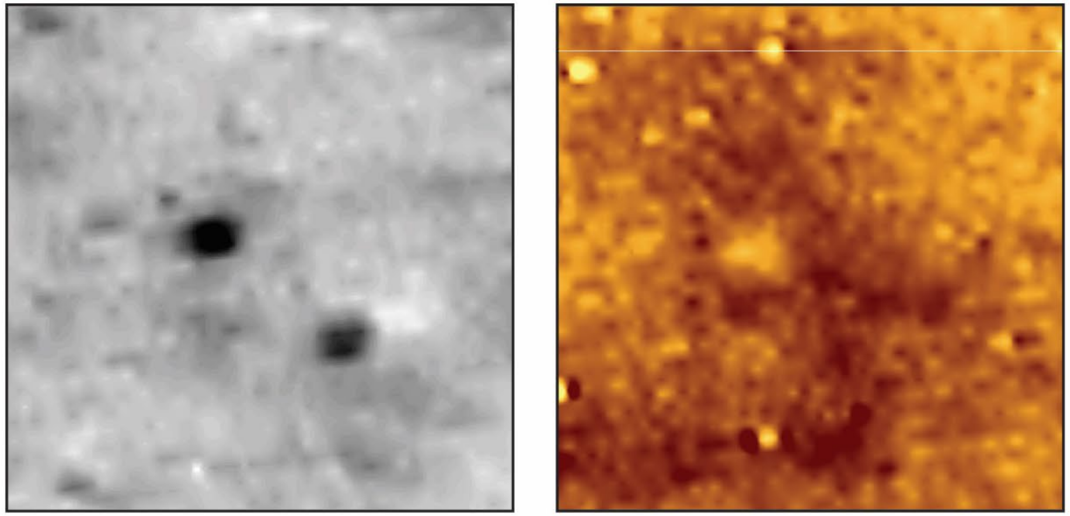
Conical pit
200 cm deep
Dwelling platform
40 cm deep
MS (κ)
0
55 · 10-5
1 m


From -40 to -200 cm
compacted calcareous fill
Below -40 cm
permeable bedrock
ECa
2
10 mS/m

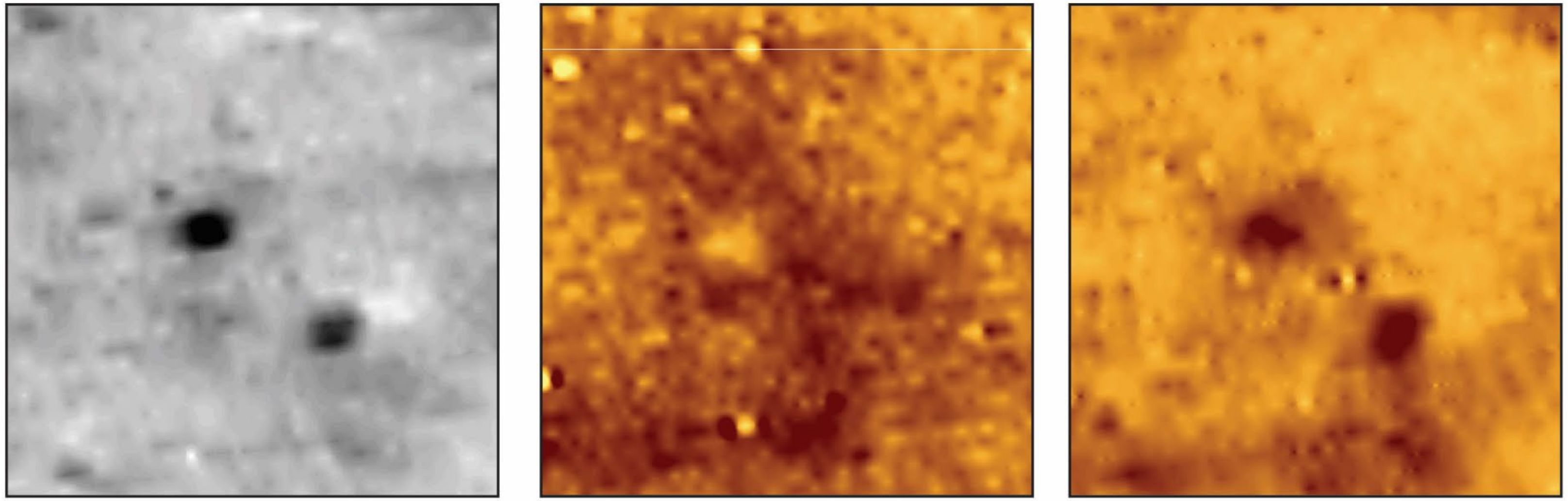


more reliable interpretation and classification

Electrical conductivity of soils: **the importance of moisture balance**



Electrical conductivity of soils: **the importance of moisture balance**

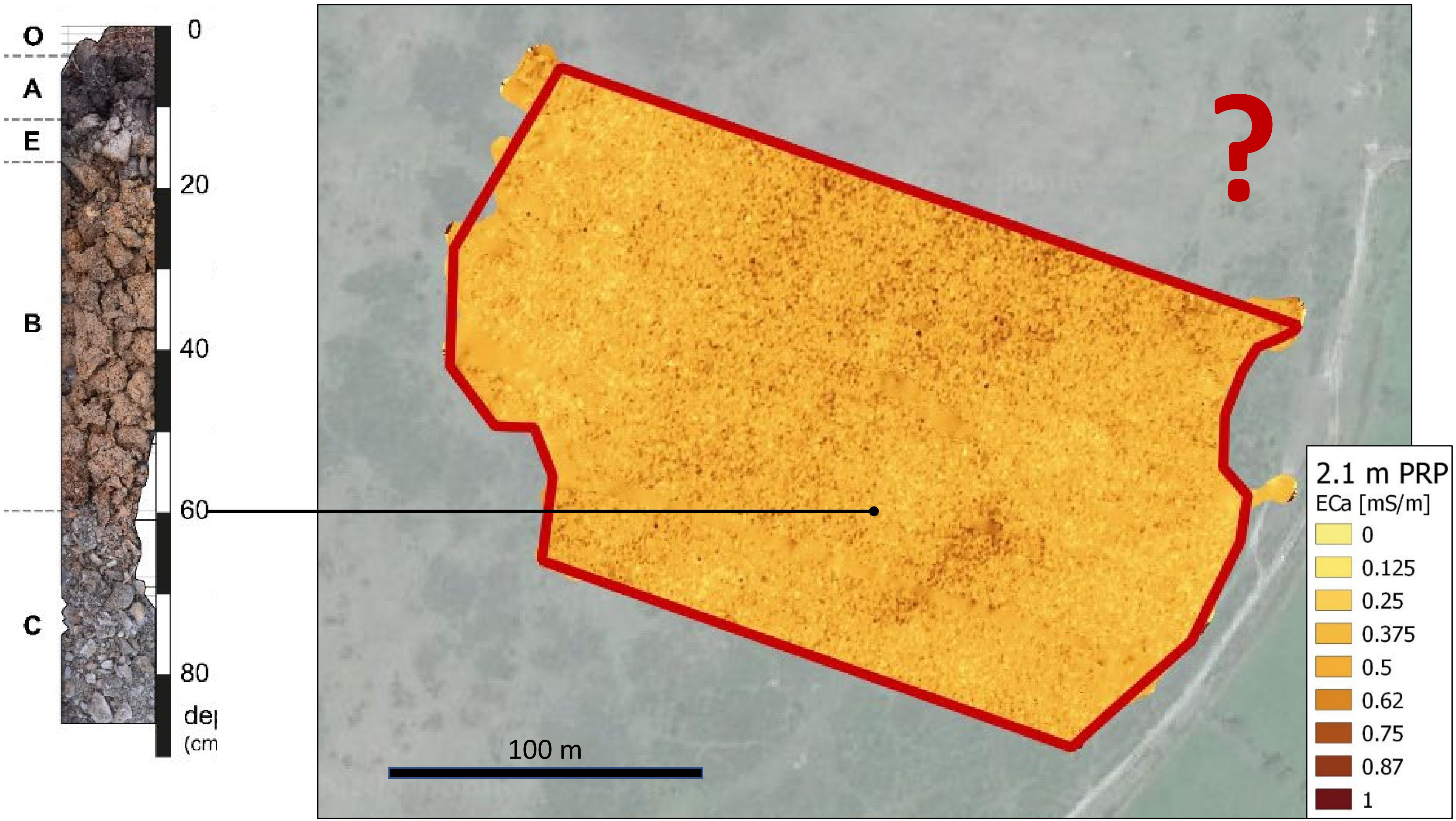


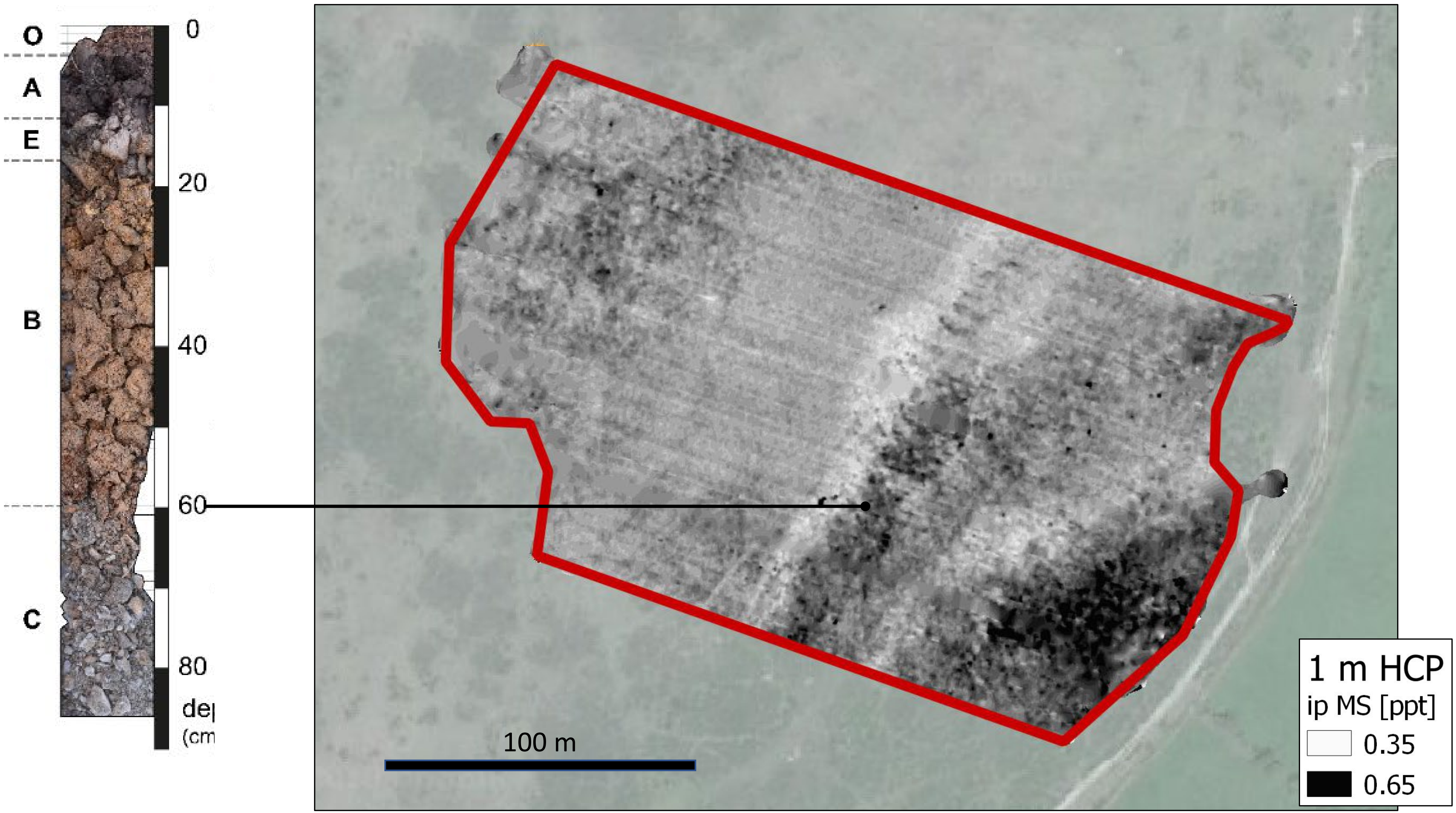
EMI – working principle overview

- Potential to **simultaneously investigate electrical conductivity and magnetic susceptibility**
    - QP and IP response: ECa and in-phase susceptibility
    - Limiting conditions: saline environments (> 100 mS/m)

- Observations of a **soil volume**
    - Influence size and shape of investigated soil volume by different **Tx – Rx** configurations.
    - **Simultaneous investigation of multiple soil volumes** with multi-receiver/multi configuration instrumentation

- Inductive method: **requires no contact with the soil**


O
A
E
B
C
0
20
40
60
80
de
(cm
?
2.1 m PRP
ECa [mS/m]
0
0.125
0.25
0.375
0.5
0.62
0.75
0.87
1
100 m



O
A
E
B
C
0
20
40
60
80
dep
(cm
100 m
1 m HCP
ip MS [ppt]
0.35
0.65