EPOS
EUROPEAN PLATE OBSERVING SYSTEM

VINNOVA
Sweden's Innovation Agency

D-REX

# DEPOSIT-TO-REGIONAL SCALE EXPLORATION
# D-REX PROJECT

***Maxim Yu. Smirnov***, *Graham Hill, Jochen Kamm, Jan Vozar, Pankaj Mishra, Oskar Rydman, Tobias Bauer*

*and DREX WG*

ERA·MIN 2

Co-funded by the Horizon 2020 programme of the European Union

LULEÅ UNIVERSITY OF TECHNOLOGY

# DREX WG

M.Yu. Smirnov, T.M. Rasmussen, T. Bauer, O. Rydman, G. Hill, S. Kovachikova, J. Puente, G. Donoso, N. Hassan, N. Najafipour, J. Kamm, P. Mishra, C. Patzer, U. Autio, A.Voutilainen, J. Jokinen, J. Luukas, J. Jäsberg , J. Vozar , J. Madzin, L. Ondrášová, P. Vajda, T. Hermansson, K. McGimpsey, J. Kaukolinna, K. Vaittinen, N. Juhojuntti, H. Van Den Berg, S. Gradmann, J. Gellein

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Consortium

https://mt.research.ltu.se/web/

LULEÅ TEKNISKA UNIVERSITET

D-REX

GTK

INSTITUTE OF GEOPHYSICS
OF THE CZECH ACADEMY OF SCIENCES

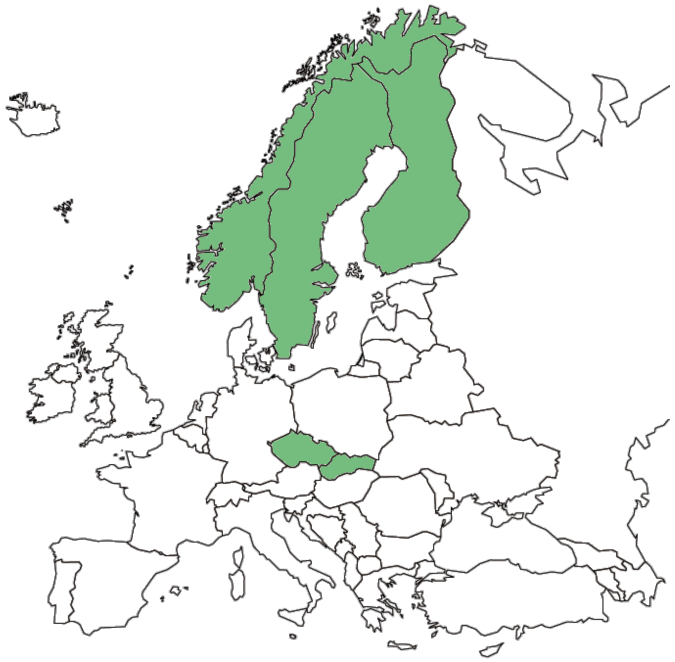
EARTH SCIENCE INSTITUTE
SLOVAK ACADEMY OF SCIENCES

LKAB

NEW BOLIDEN

LoopandLine

NORGES GEOLOGISKE UNDERSØKELSE
- NGU -



D-REX

Co-funded by the Horizon 2020
programme of the European Union

EU co-funded ERA-MIN Joint Call 2019
Raw Materials for the Sustainable Development
and the Circular Economy

LULEÅ UNIVERSITY OF TECHNOLOGY

# Summary

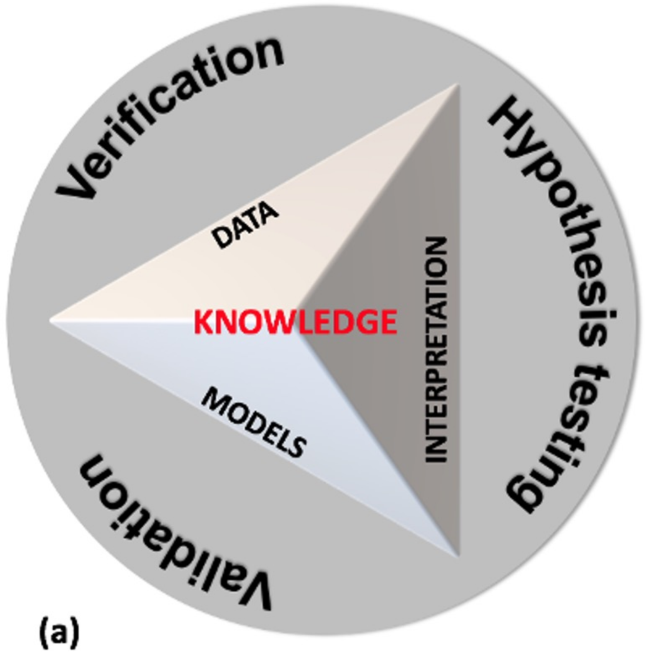
- DREX project
  - Concept
  - Tectonic settings
- Magnetotellurics in Fennoscandia
- New regional and deposit scale MT surveys
  - Data processing
  - 3D MT inversion
- Magnetotelluric models + potential fields
- Joint inversion ->

LULEÅ UNIVERSITY OF TECHNOLOGY

# Basic concept

The **D-Rex** project addresses the ERA-MIN Joint Call 2019 "Raw materials for sustainable development and the circular economy", topic 1: "***Supply of raw materials from exploration and mining***".

Mineral deposits are often described with reference to a ***mineral system concept*** as the end products of complex geological processes. Unification, optimum integration and visualization of geological and geophysical data are important steps towards understanding **how a deposit was formed**. **D-REX** builds on this paradigm and the research is exemplified with new **Magnetotelluric data** combined with available geophysics from prospective areas in Sweden, Finland and Norway




(a)

# Objectives

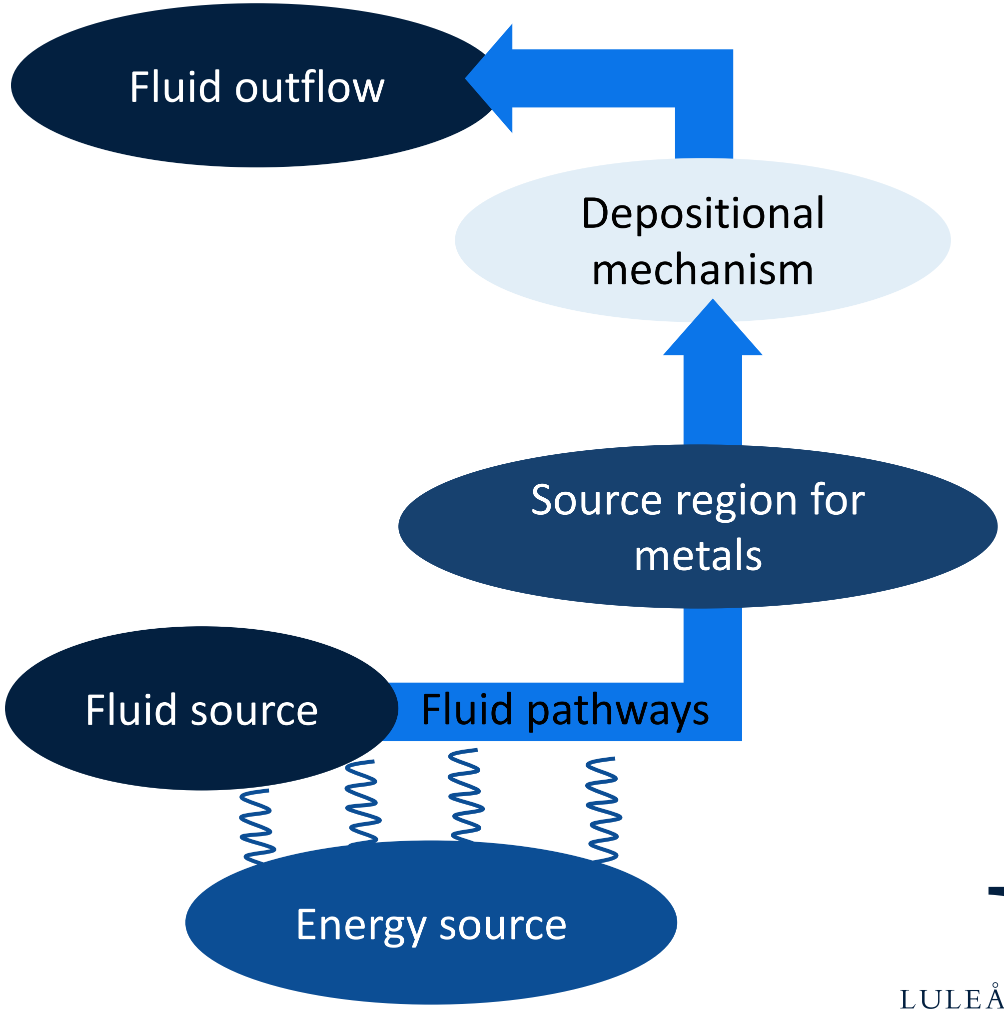
- The ***first objective of D-Rex*** is to build onto new paradigm of ***mineral systems*** with data from three prospective areas in *Sweden, Norway and Finland* and leverage its potential for large scale mineral systems characterisation by regional **magnetotelluric surveys** combined with available regional data (gravity, magnetics)

- The ***second objective of D-Rex*** is the integration of multi-facetted geophysical data sets

- The ***third objective of D-Rex*** is the unification, optimum integration and visualization of geological and geophysical data on the basis of the **Common Earth Modelling** (CEM) concept

# Mineral system concept

- Mineral deposits are a small part of large and often deep geological context: **the mineral system**
- **Magnetotellurics** is an important tool for characterizing the entire mineral system




*EMinars:*

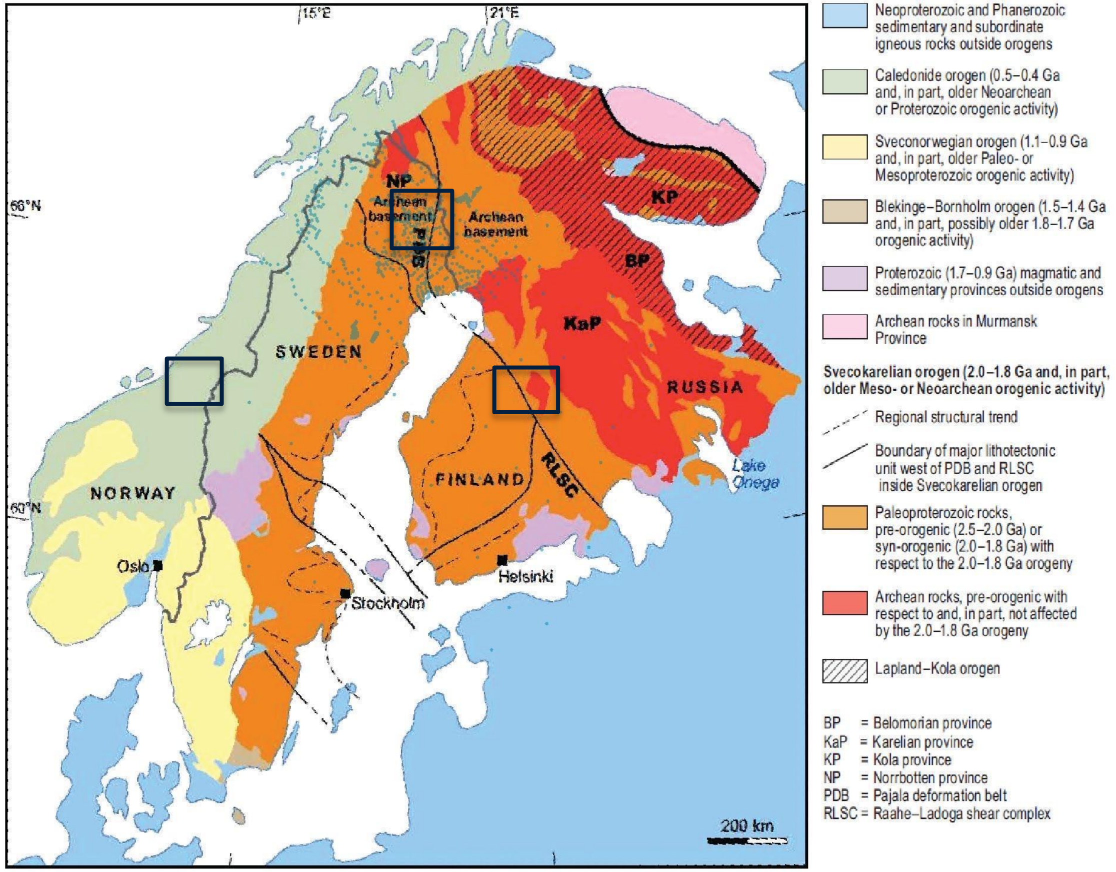
*Graham Heinson, Graham Begg, Phil Wannamaker,….*

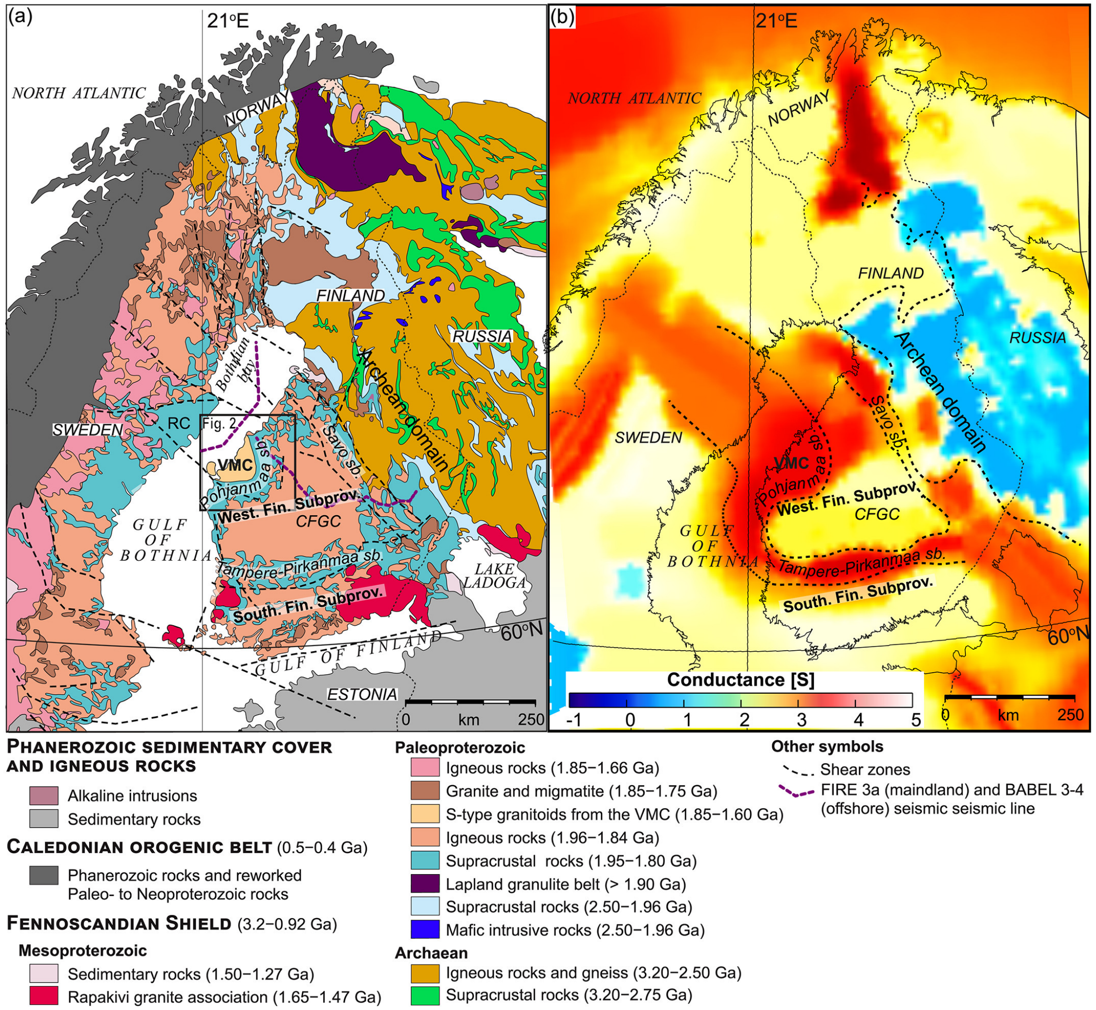
*Wyborn et al., 1994; McCuaig et al., 2010*
*J.M. A. Hronsky & D. I. Groves, 2008)*

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

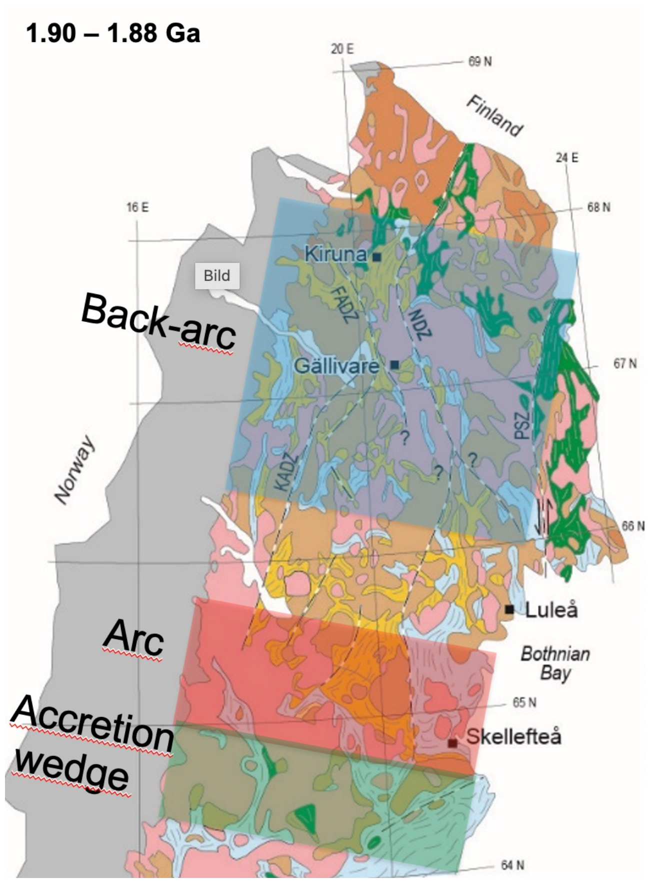
# Tectonic settings



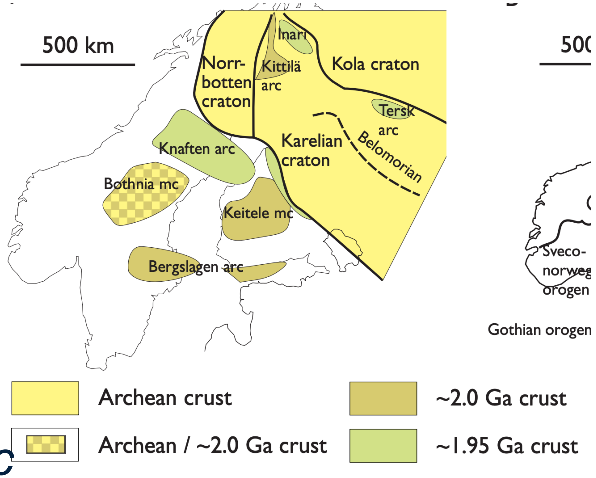

*F.Chopin, A.Korja, KcNikkilä, P.Hölttä, T.Korja, M.Zaher, M.Kurhila, O.Eklund, O.T.Rämö 2020*

# Tectonic settings

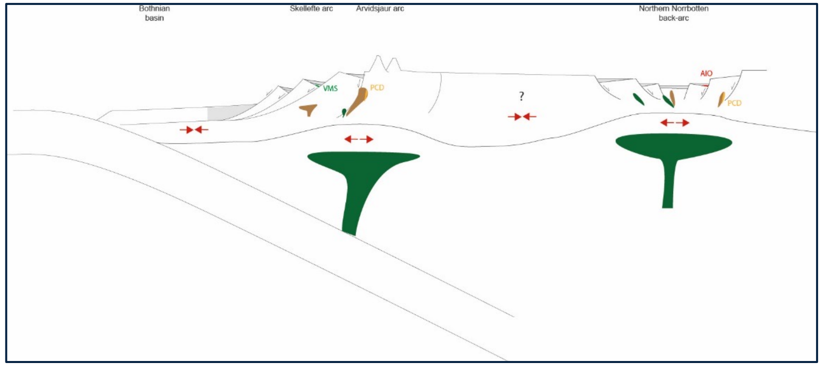



T.Bauer (2020, in prep)

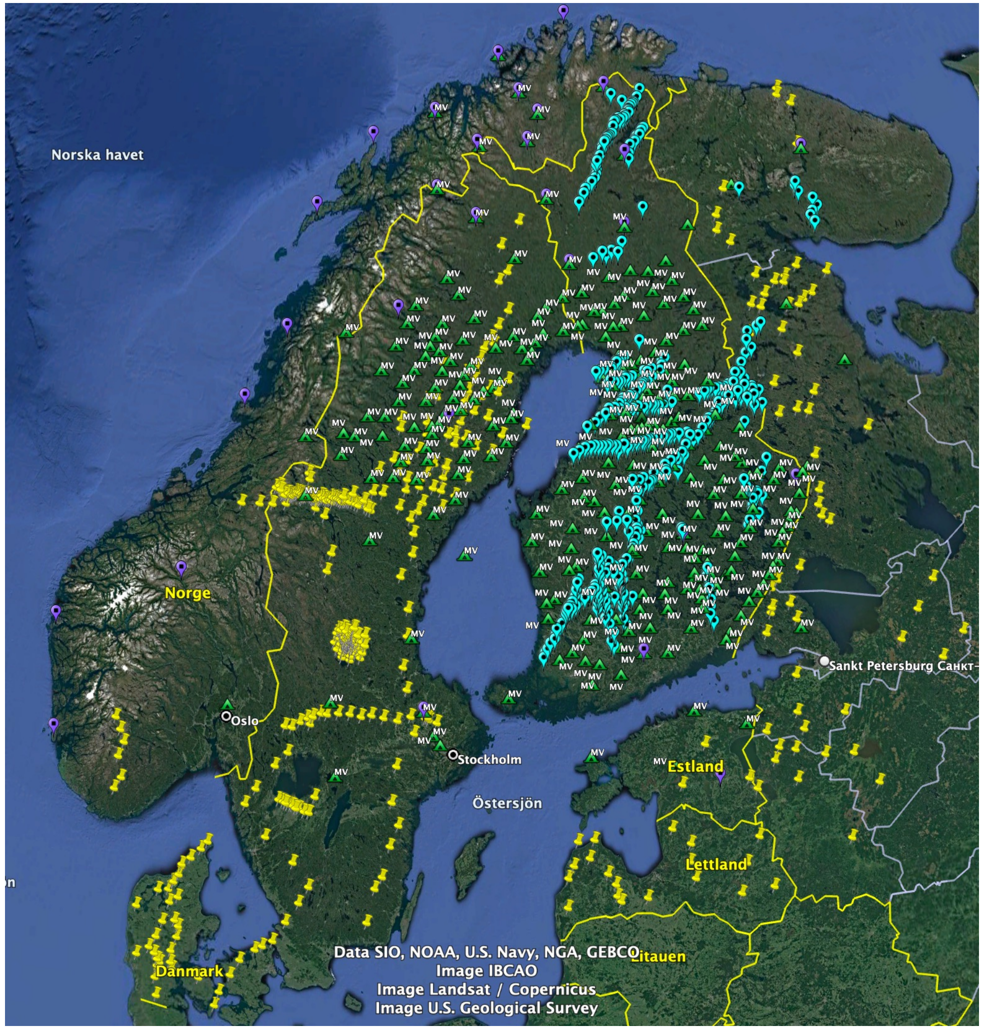
- Svecofennian orogeny 1.92–1.79 Ga
- Several accretionary events
- One-two subduction events (1.9 -1.82 Ga)
- Gällivare area is in back-arc settings
- Two major ore forming phases (hydrothermal activity)
  - *First one during extension. Formation of arc and back arc. (VMS, porphyry, IOA)*
  - *Second during the last accretionary phase (1.8Ga) (IOCG, Orogenic gold)*




*Lantinen et al. 2005*



# Pre BEAR project < 1997




***1980th***

Kovtun, A. A., Induction studies in stable shield and platform areas, Acta Geod. Geophys. Mont., Acad. Sci. Hung., 11, 333–346, 1976.

AG. Jones, 1982 Observations of the electrical asthenosphere beneath Scandinavia, Tectonophysics, v.90

K. Pajunpää and others, Crustal conductivity anomalies in central Sweden and southwestern Finland, GJI, 2002 (1983)

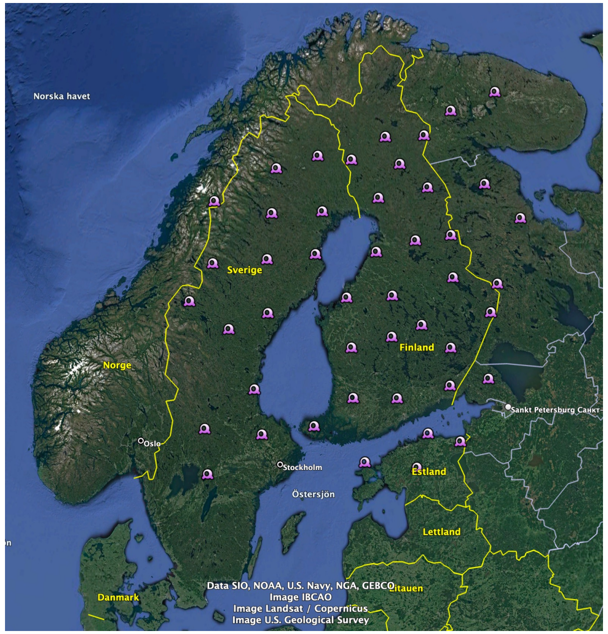
T. M. Rasmussen, R. G. Roberts, L. B. Pedersen 1987 (FENNOLORA) Magnetotellurics along the Fennoscandian Long Range profile

Korja, T., Hjelt, S.-E., Koivukoski, K., Rasmussen, T. M., & Roberts, R. G. (1989). The geoelectric model of the POLAR Profile, Northern Finland. Tectonophysics, 162(1–2),

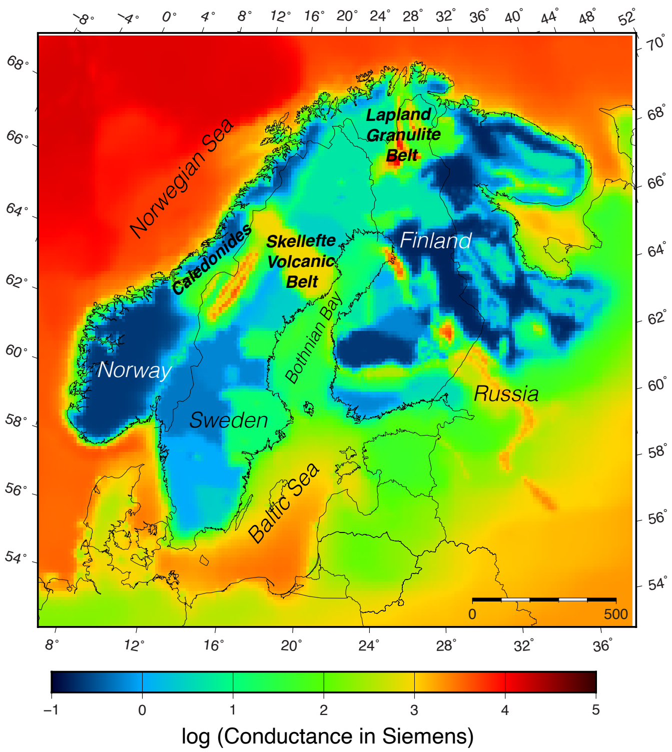
D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

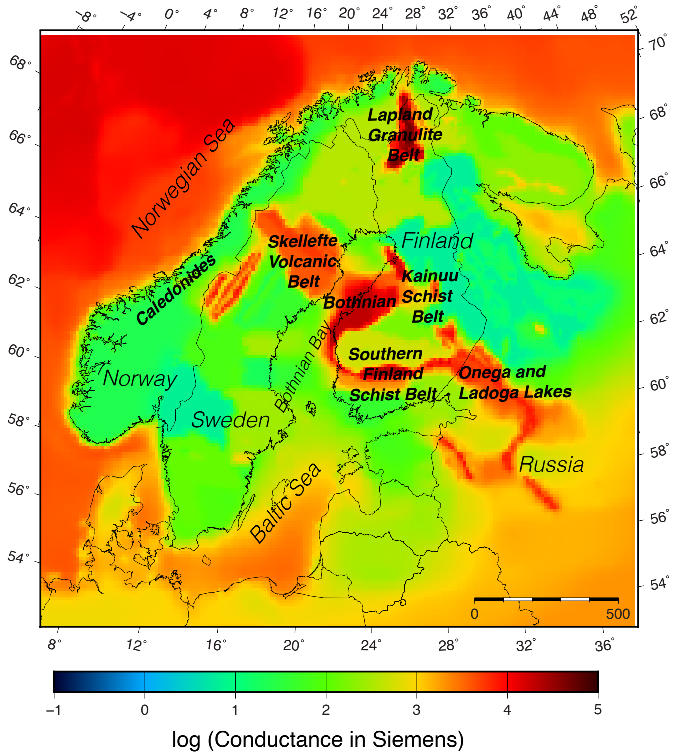
# BEAR project 1997




Conductance: upper crust 0–10 km



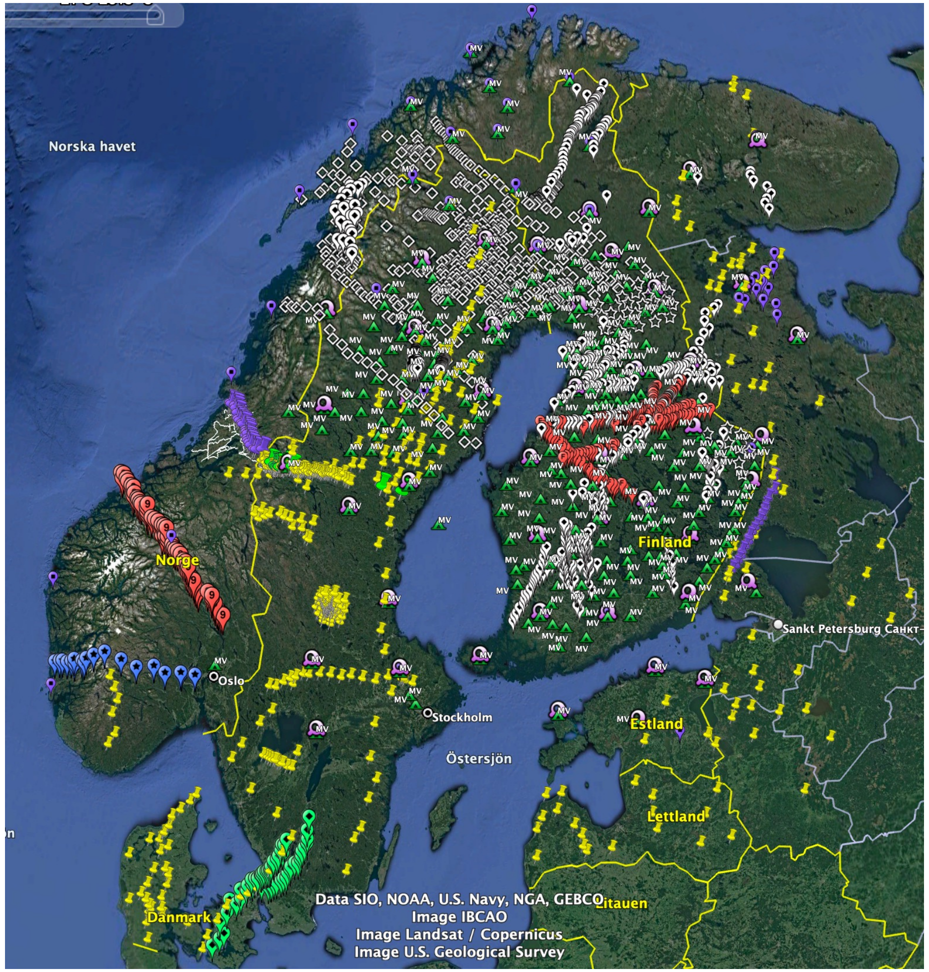

Conductance: crust 0–60 km




*T. Korja, M. Engels, A. A. Zhamaletdinow, A. A. Kovtun, N. A. Palshin, M. Y. Smirnov, A. D. Tokarev, V. E. Asming, L. L. Vanyan, I. L. Vardaniants, and the BEAR Working Group. 2003 Crustal conductivity Map of the Fennoscandian Shield.*

LULEÅ UNIVERSITY OF TECHNOLOGY

# Magnetotellurics in Fennoscandia



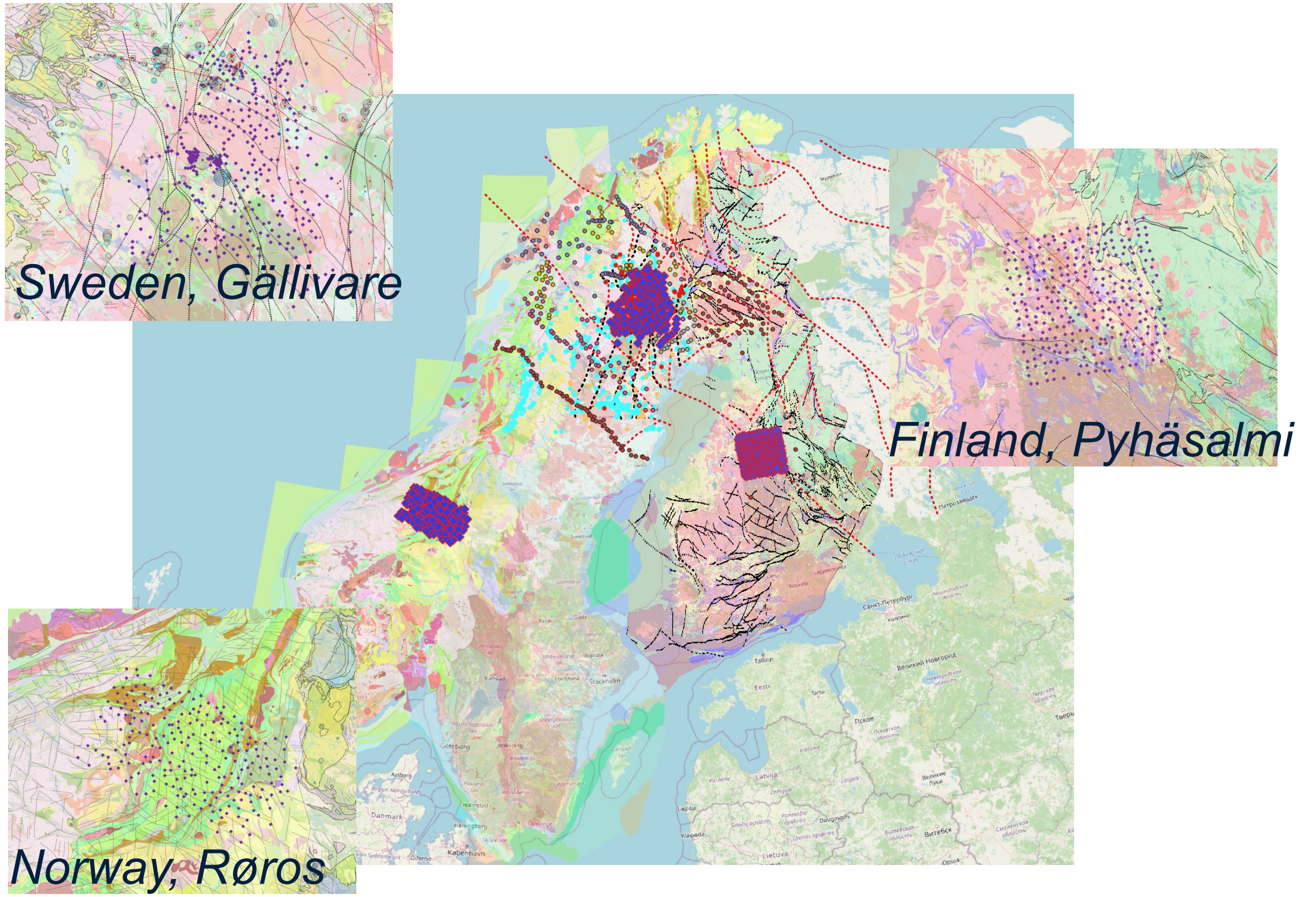

I.Lahti 2005,
T.Korja, 2008,
M.Smirnov 2009,
K.Vaittinen 2012,
M.Cherevatova 2015,
P.Yan 2017,
U.Autio 2020

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# D-Rex regional magnetotelluric measurements

*Location of Broadband Magnetotelluric sites acquired in period range (0.001 – 1000 s). Magnetotelluric measurements at all three areas were completed in the summers 2021-2022. All the data are processed using robust multi remote reference approaches.*




D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

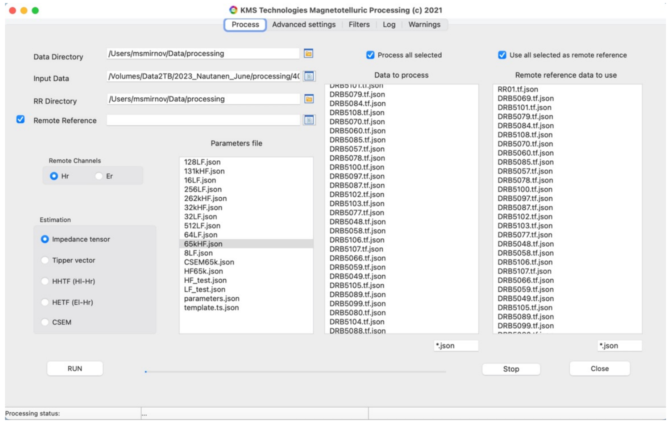
# Field campaigns

- Broadband MagnetoTelluric (BMT) data were acquired during several field campaigns (ongoing efforts)
- Most of the data were measured during summer time with some measurements during winters
- Data recorded for at least **1 day (continuous sampling 128 Hz)** and simultaneous **burst recording at 4096 Hz for 2h starting midnight** to increase signal/noise ratio

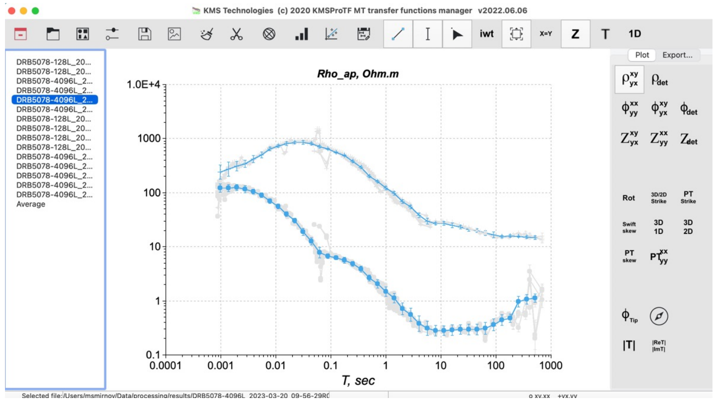
D-REX

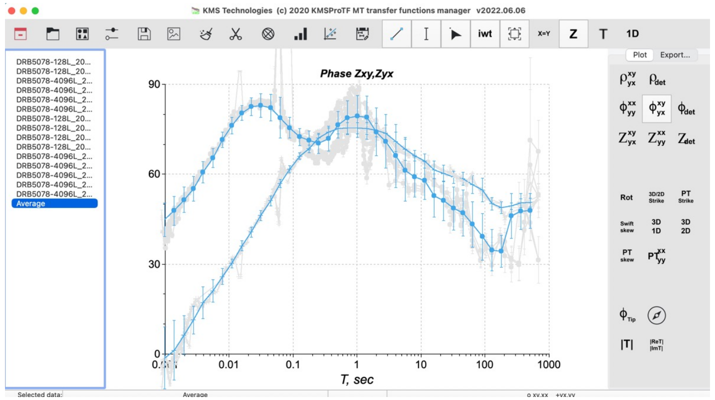
LULEÅ UNIVERSITY OF TECHNOLOGY

# Magnetotelluric Data processing



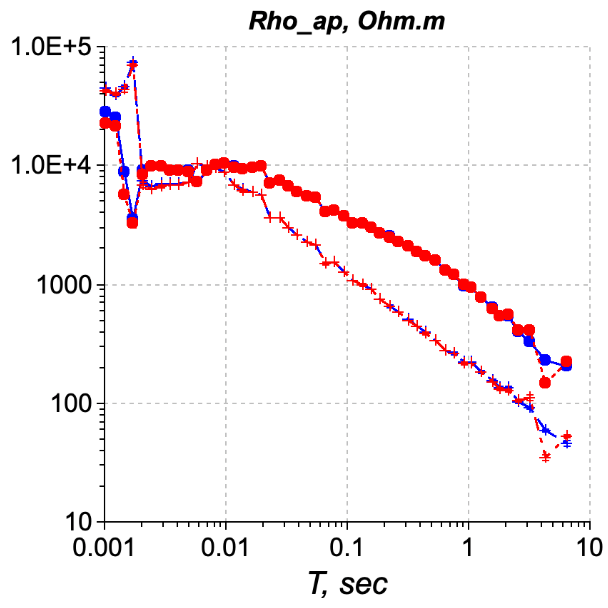

- Robust remote reference (Smirnov 2003)
- Multi-remote reference final transfer functions. All mutual referencing and remote reference assembled
- Power harmonics filtering in frequency domain combined with coherence thresholding

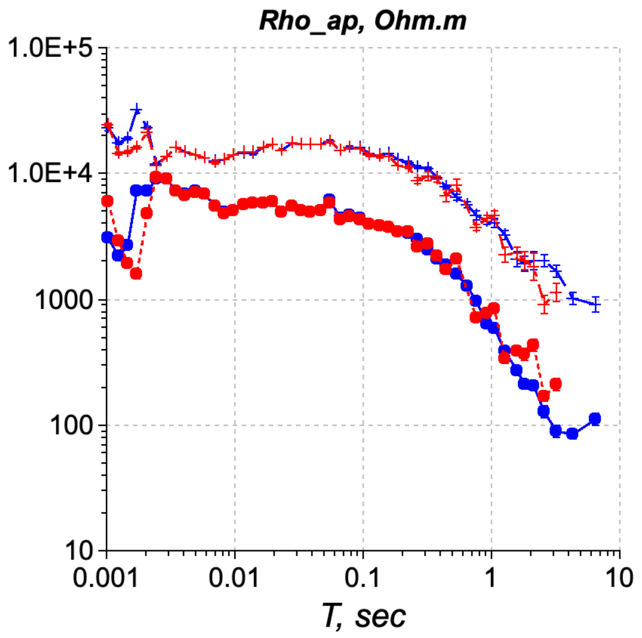


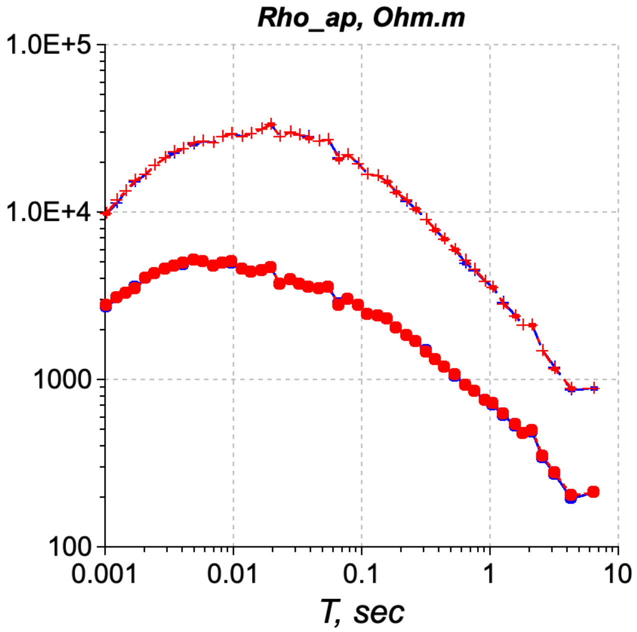



# Remote referencing

## RR electric vs magnetic field as a reference



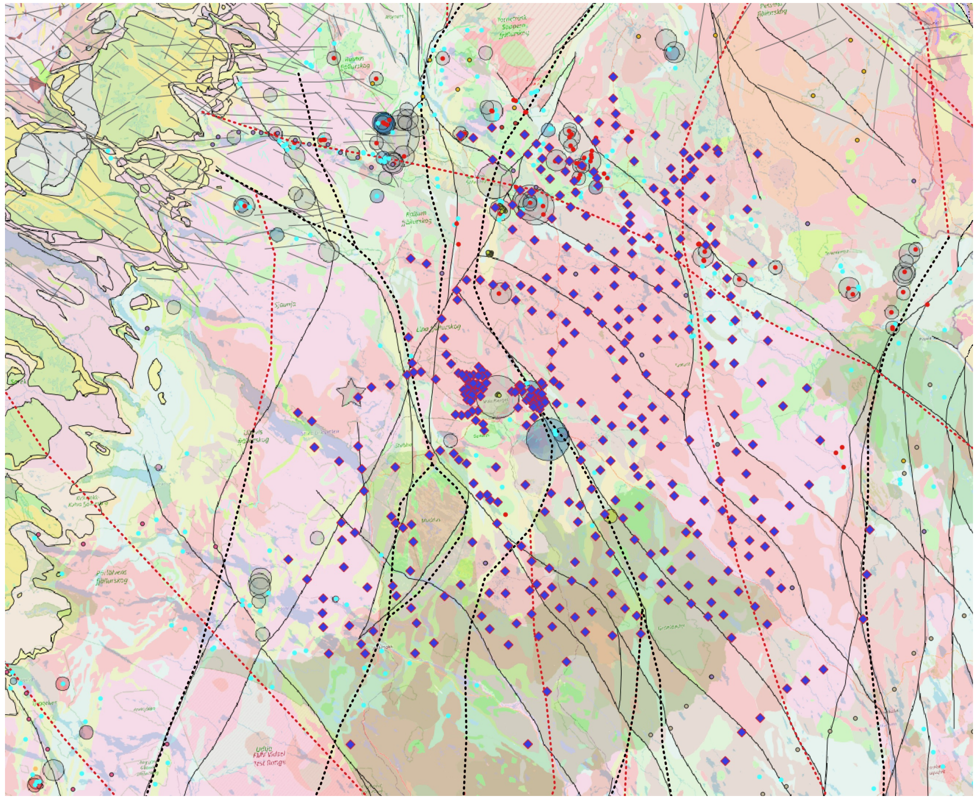




RRE estimates are in blue, RRH are in red (Zxy circles, Zyx crosses)

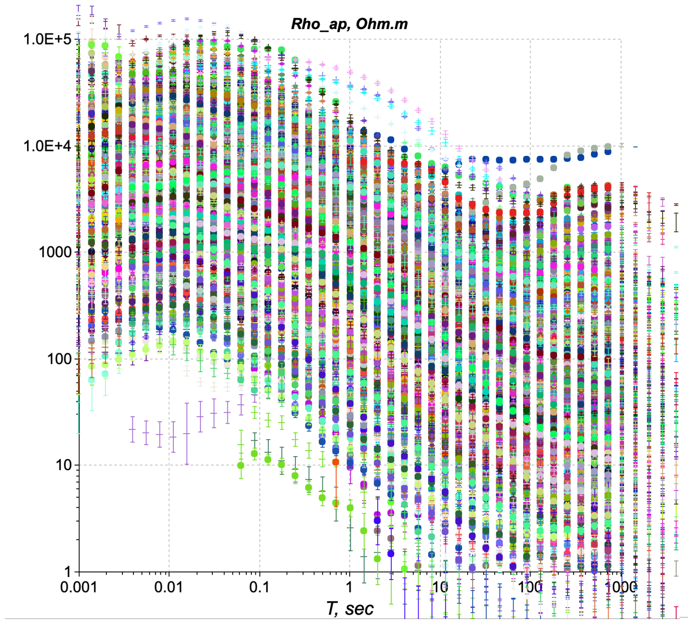
D-REX

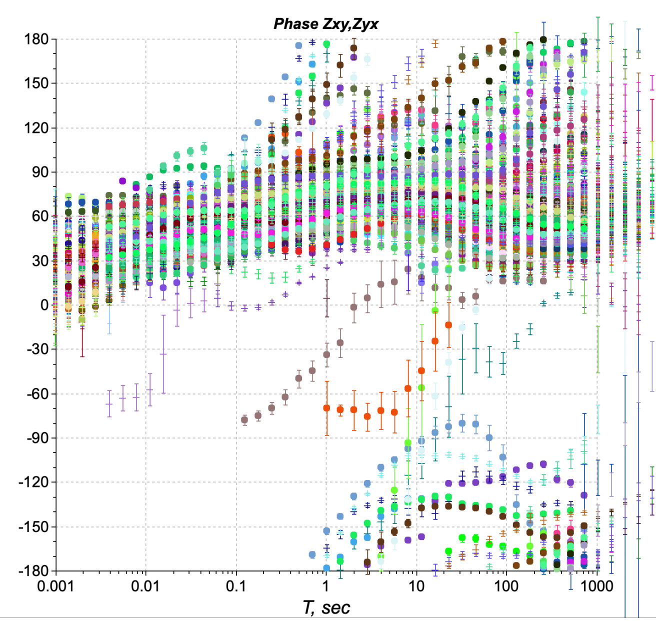
LULEÅ UNIVERSITY OF TECHNOLOGY

# MT survey in Sweden



Locations of 399 MT sites on top of geological map



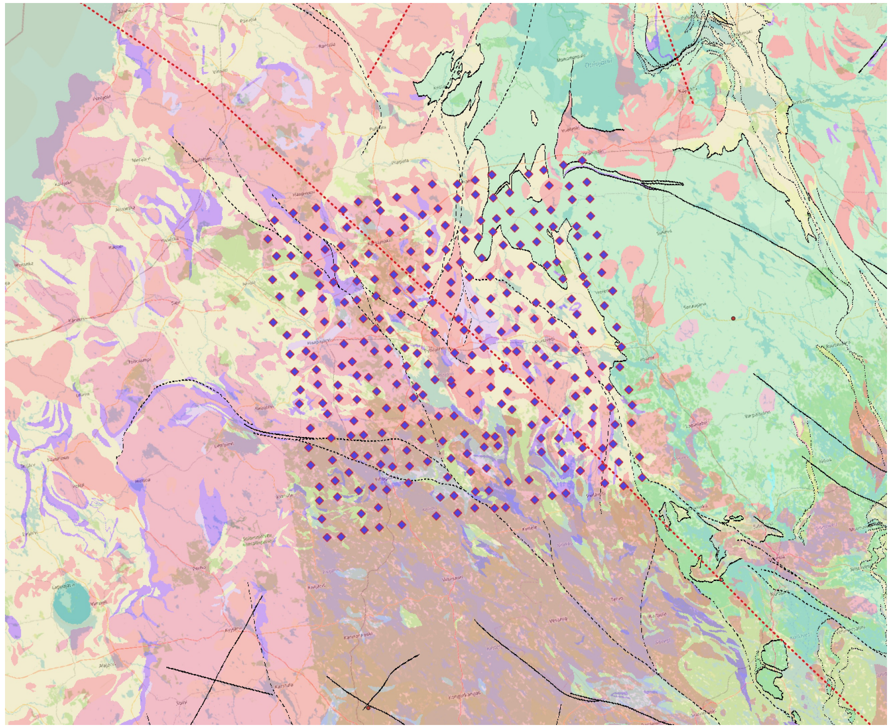



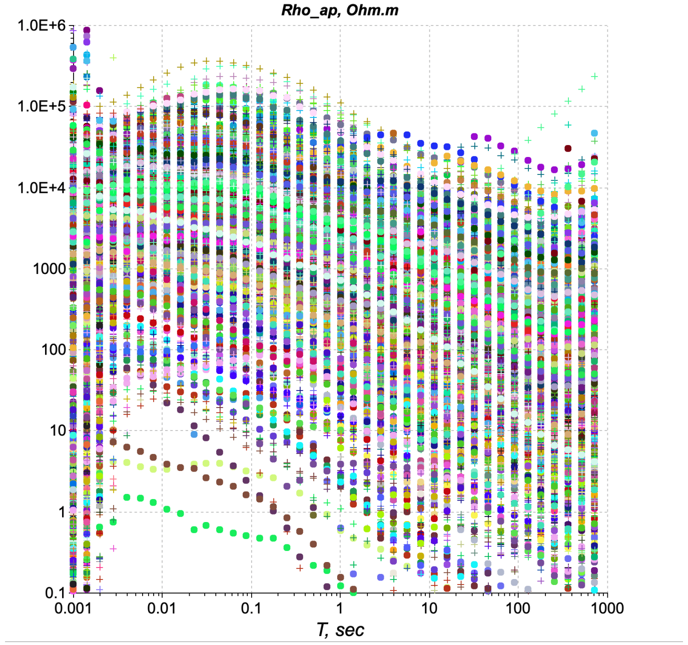

Main impedance components for all sites

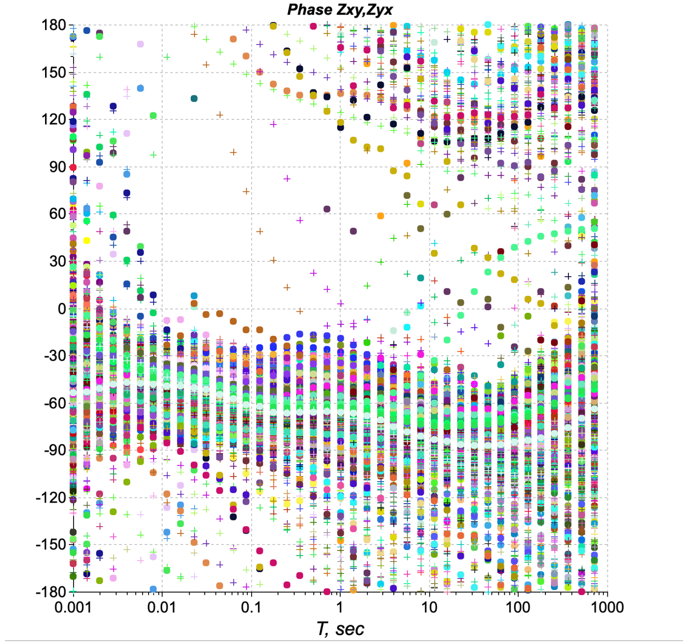
D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# MT survey in Finland





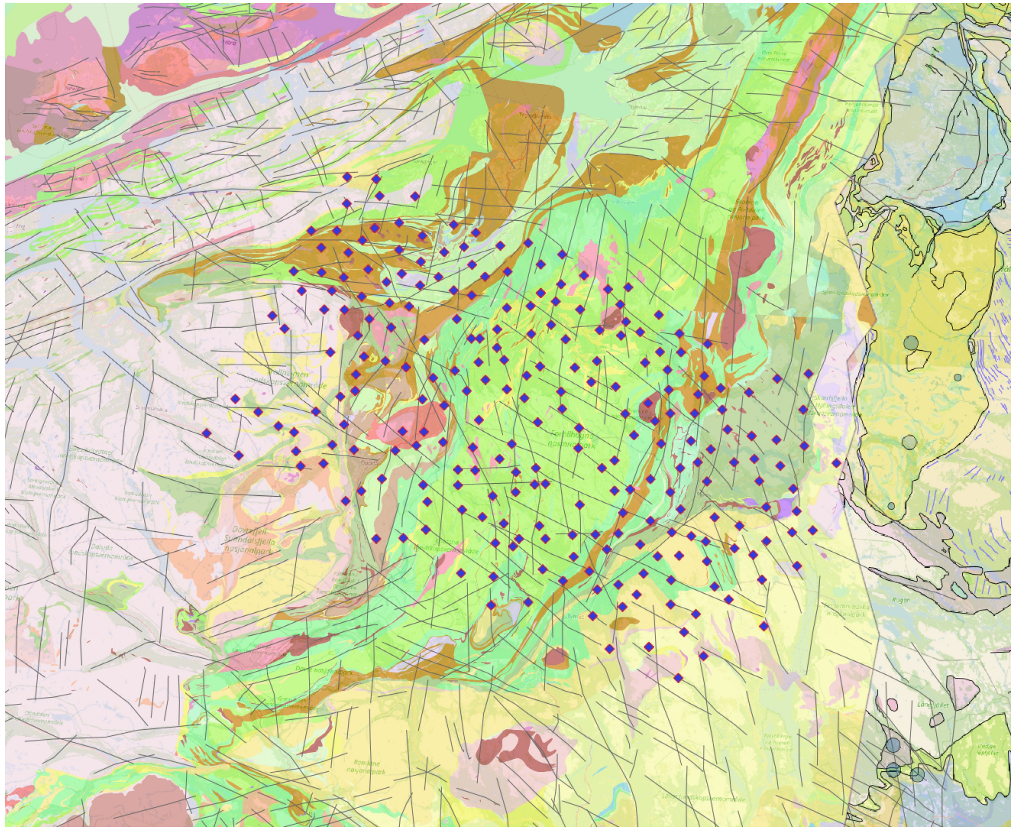

Main impedance components for all sites

Locations of 324 MT sites on top of geological map

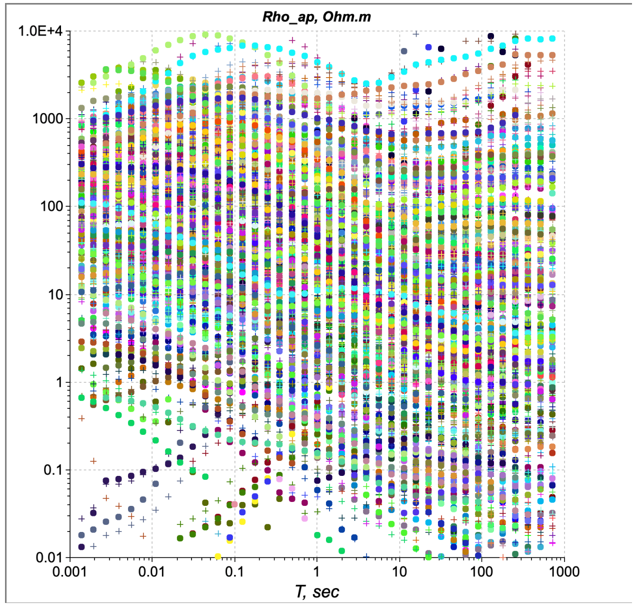
D-REX

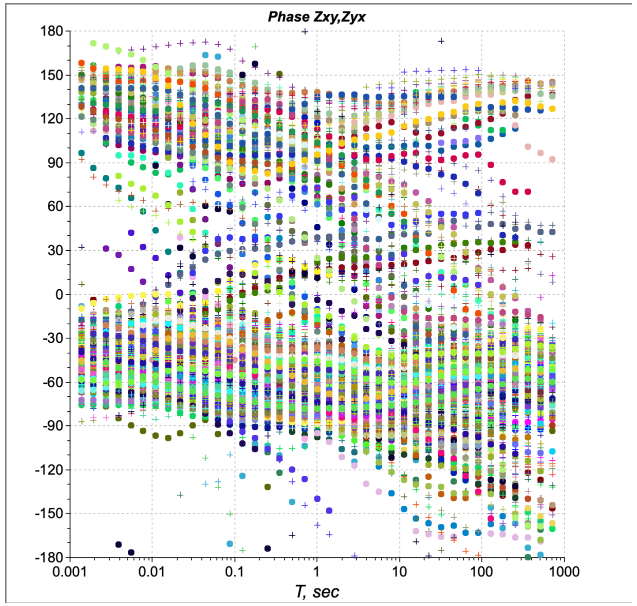
LULEÅ UNIVERSITY OF TECHNOLOGY

# MT survey in Norway



Locations of 255 MT sites on top of geological map



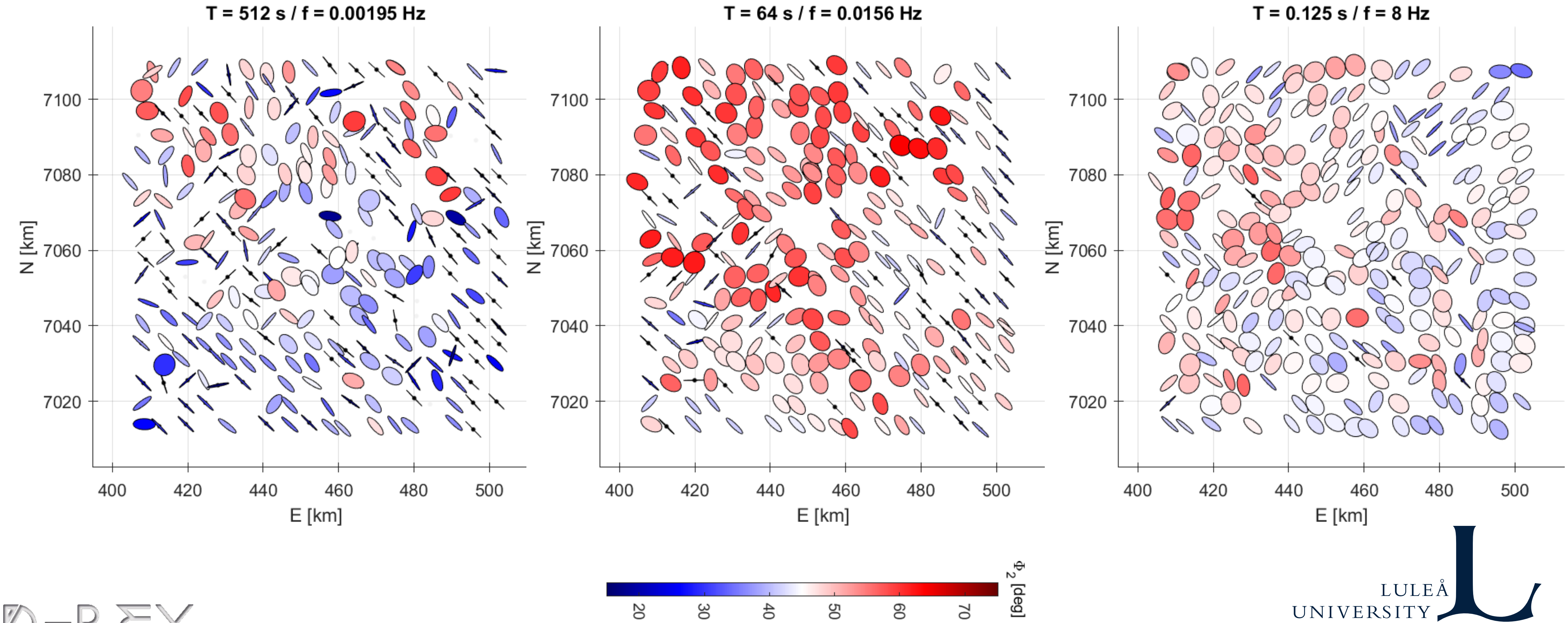




Main impedance components for all sites

D-REX

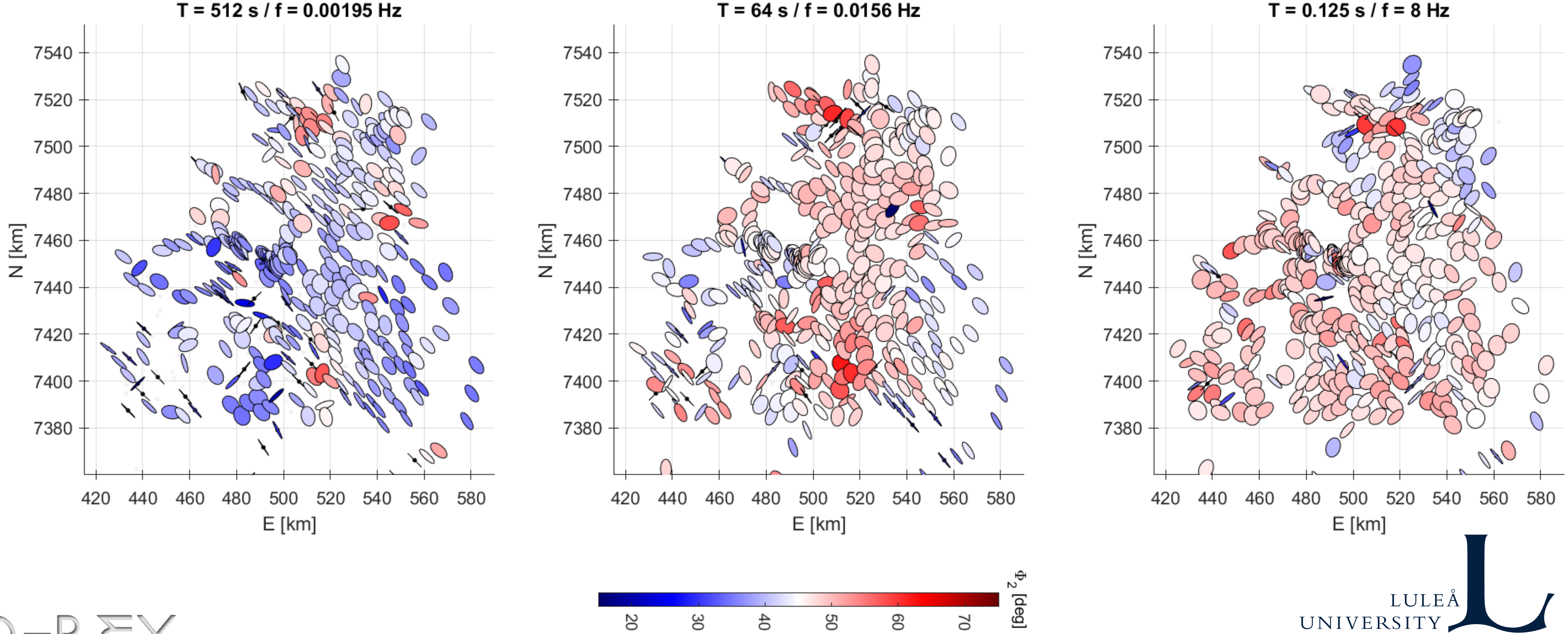
LULEÅ UNIVERSITY OF TECHNOLOGY

# Phase tensors (Finland)




LULEÅ
UNIVERSITY
OF TECHNOLOGY

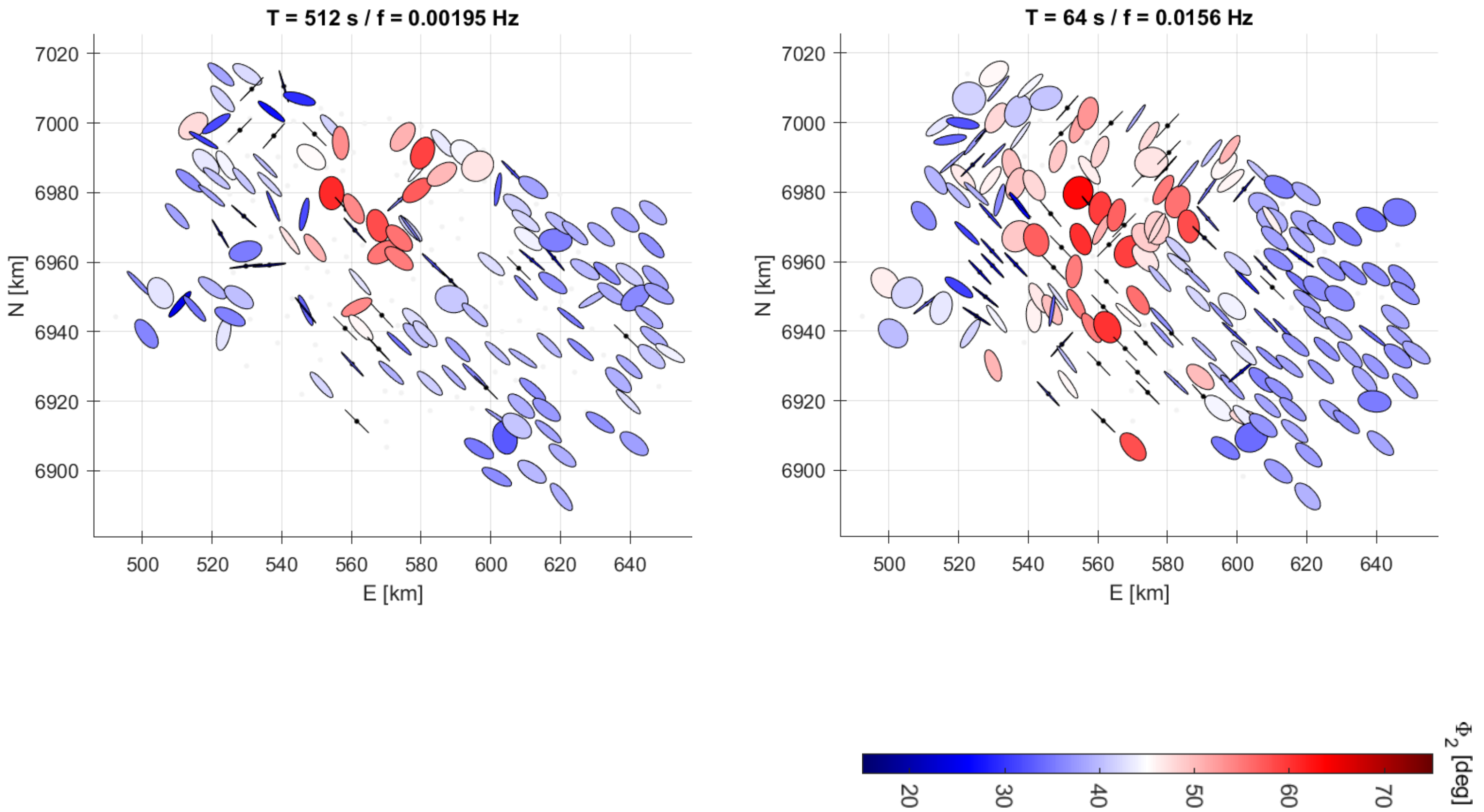
# Phase tensors (Sweden)




D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

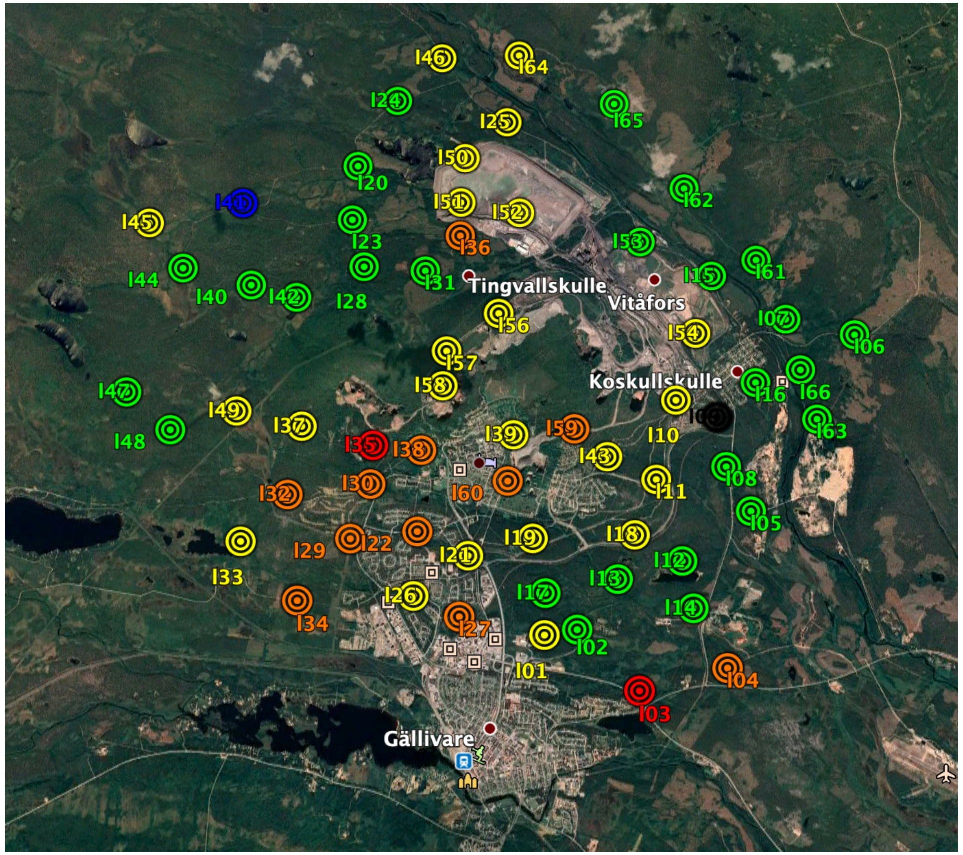
# Phase tensors (Norway)




D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Malmberget deposit scale




Color of the symbol indicates data quality

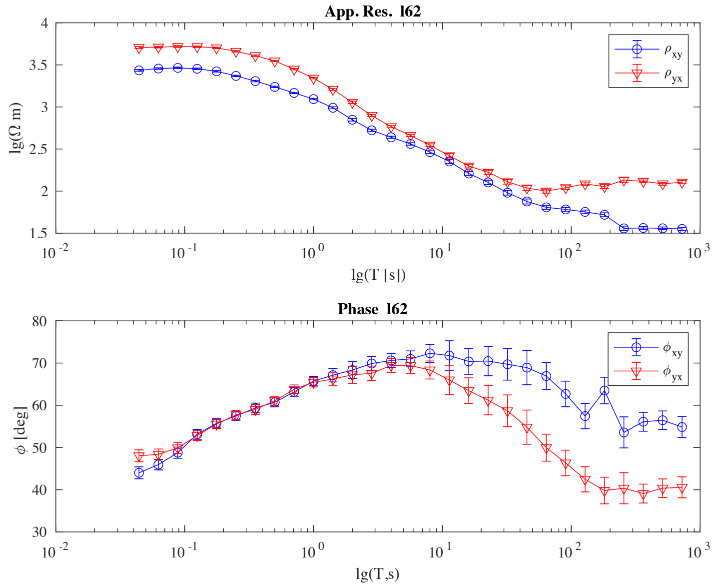
***Remote*** (60 km) remote reference site is used.

Magnetic and electric components are used as reference.

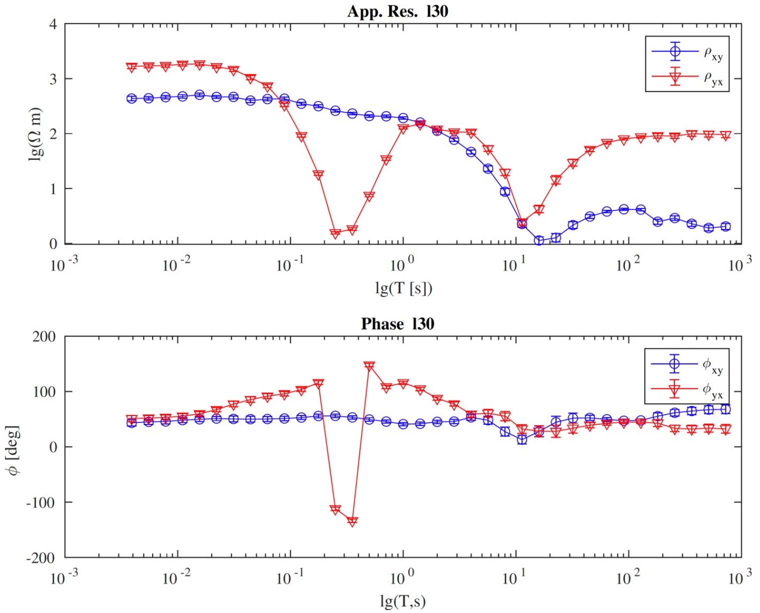
LULEÅ
UNIVERSITY
OF TECHNOLOGY

# Data quality

- **Green** sites good to excelent quality




- **Orange** sites are just acceptable




There is clear consistency between majority of the sites with some sites (marked orange on the map) deviating from physical behavoir in the part of the frequency range

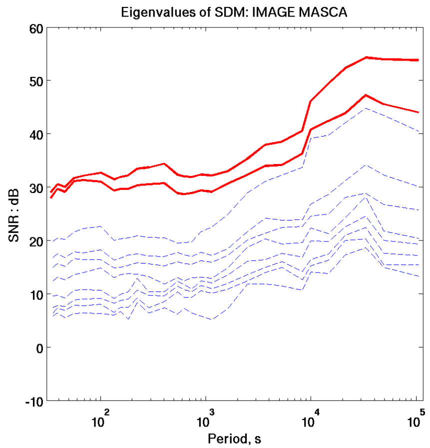
# Robust Multivariate data analysis (MsDEMPCA)

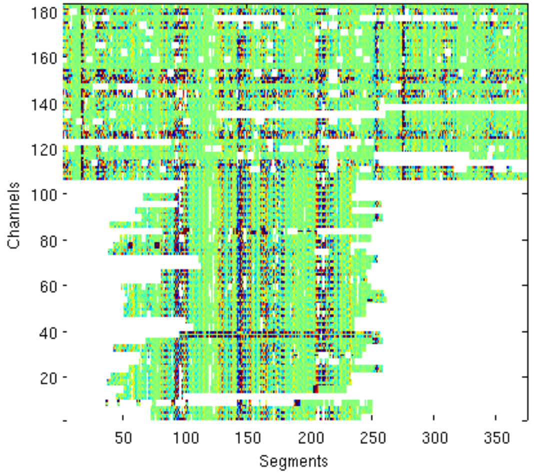
*See Eminar: Gary Egbert*

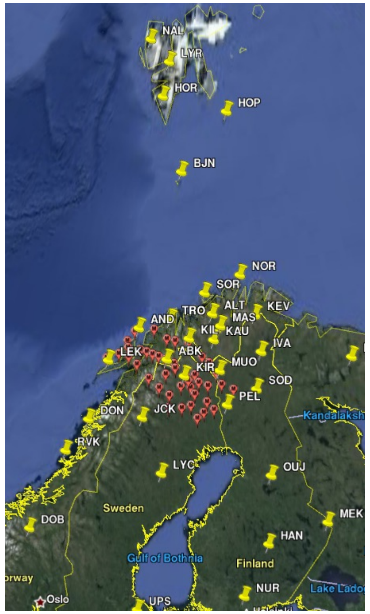
*Smirnov&Egbert, 2012*

$$\mathbf{X} = \mathbf{U}\mathbf{a},$$

$$\begin{pmatrix} E_{1i} \\ H_{1i} \\ \cdot \\ \cdot \\ \cdot \\ E_{Ji} \\ H_{Ji} \end{pmatrix} = \begin{pmatrix} U_{11} \\ U_{21} \\ \cdot \\ \cdot \\ \cdot \\ U_{N1} \end{pmatrix} a_{1i} + \begin{pmatrix} U_{12} \\ U_{22} \\ \cdot \\ \cdot \\ \cdot \\ U_{N2} \end{pmatrix} a_{2i} + \cdots + e_i$$



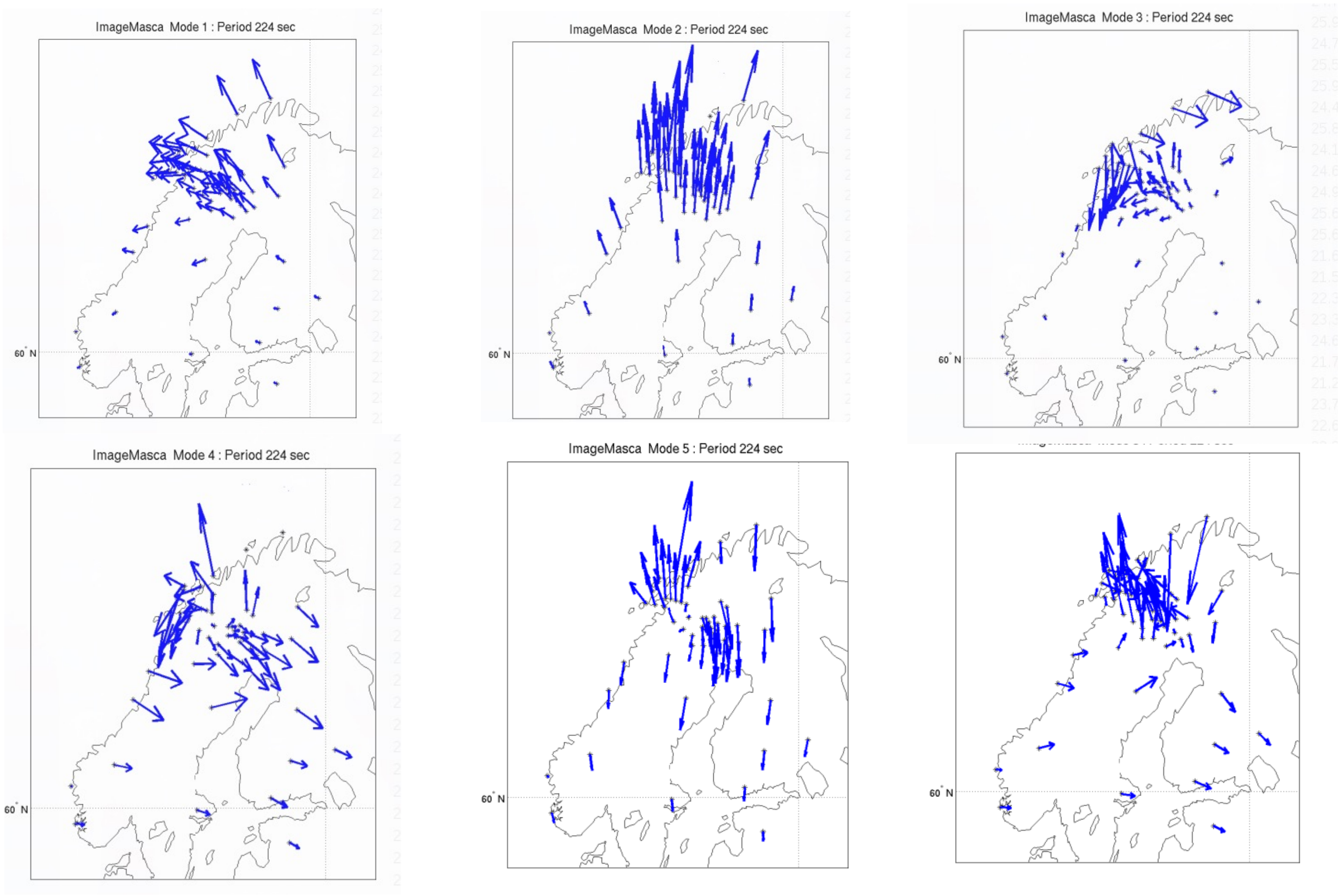




OOP Matlab framework → OOP Python package

LULEÅ UNIVERSITY OF TECHNOLOGY

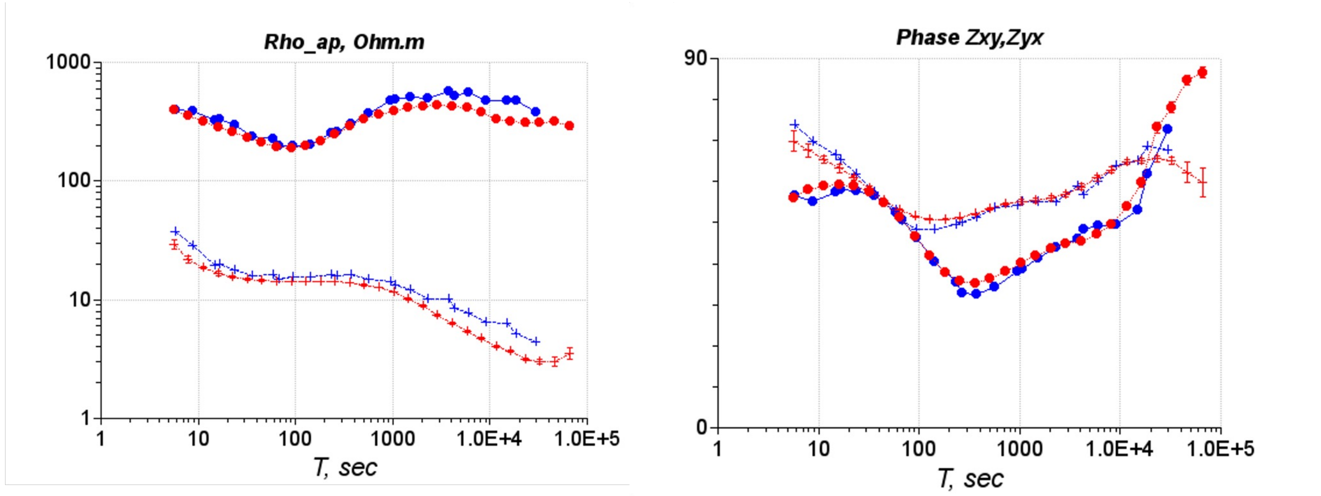
# The first 6 modes



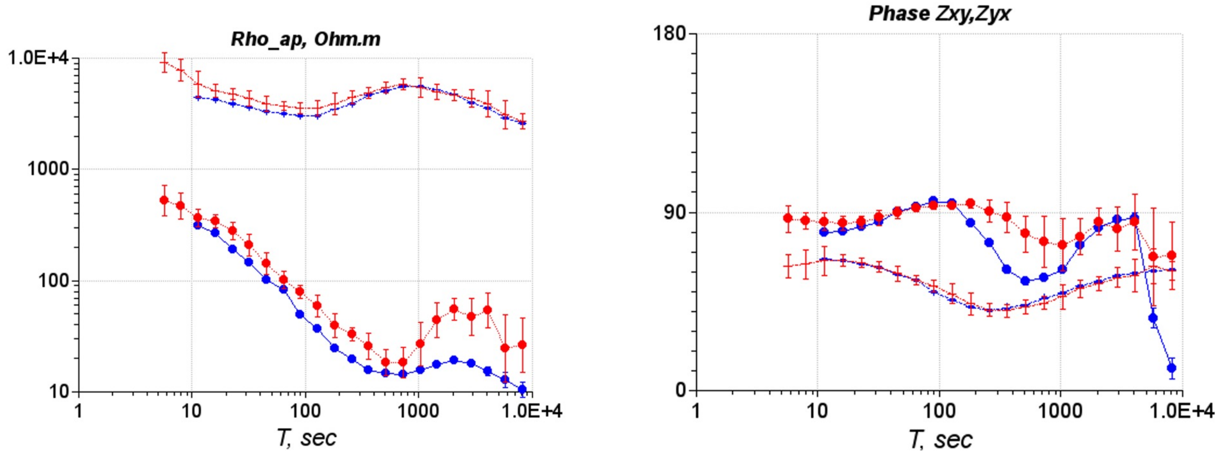

Real part of horizontal magnetic field

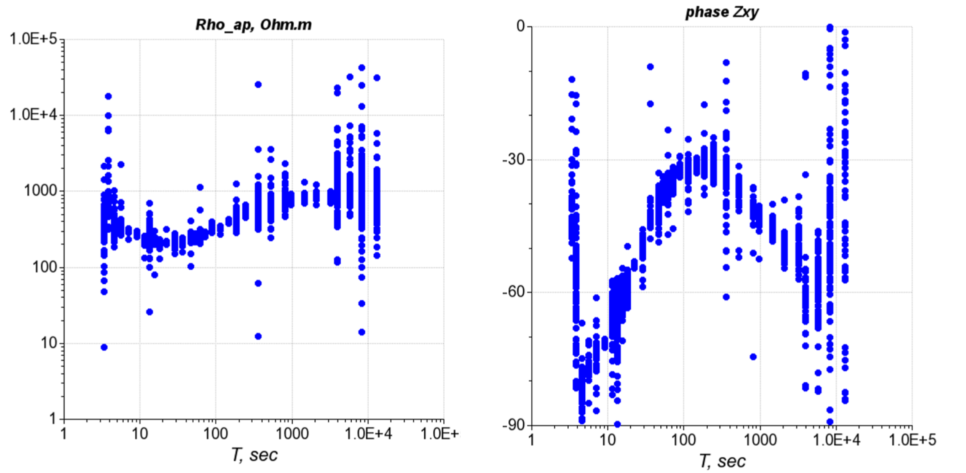
First two modes represents mostly plane wave components. The other components are very closely resambles gradient modes.

# MV “plane wave” impedances




*MV estimates are shown in blue and standard robust estimates in red*




*Exploring the effect of spatial modes by random mode mixing.*

Large scatter due to the source effects.

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Magnetotelluric 3D inversion

We seek to minimise objective function:

$$\varphi(m) = \varphi_d(\boldsymbol{d}, \boldsymbol{m}, \boldsymbol{C}_d) + \alpha^2 \varphi_m\left(\boldsymbol{m}, \boldsymbol{m_0}, \boldsymbol{C}_{m_{prior}}\right) =$$

$$\left\| \boldsymbol{C}_d^{-1/2} (d - \boldsymbol{G}(\boldsymbol{m})) \right\|_{\boldsymbol{p}}^{p} + \left\| \boldsymbol{C}_{m,priori}^{-1/2} (\boldsymbol{m} - \boldsymbol{m_0}) \right\|_{\boldsymbol{q}}^{q} =$$

Usual L2 norm:

$$\varphi(m) = (\boldsymbol{d} - \boldsymbol{G}(\boldsymbol{m}))^{\boldsymbol{T}} \boldsymbol{C}_d^{-1} (\boldsymbol{d} - \boldsymbol{G}(\boldsymbol{m})) + \alpha^2 (\boldsymbol{m} - \boldsymbol{m_0})^{\boldsymbol{T}} \boldsymbol{C}_{m_{prior}}^{-1} (\boldsymbol{m} - \boldsymbol{m_0})$$

What if we have noisy data and inconsistent model (some data can not be fit)

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Choose robust norm of residuals

We can use L1 norm of residuals or for example Huber's loss function:

$$\varphi(m) = \left\| \boldsymbol{C}_d^{-1/2}(d - \boldsymbol{G}(\boldsymbol{m})) \right\|_{\boldsymbol{1}} + \left\| \boldsymbol{C}_{m,priori}^{-1/2}(\boldsymbol{m} - \boldsymbol{m_0}) \right\|_{\boldsymbol{2}}^2$$

Can be solved using iteratively reweighted least squares (IRL):

$$\varphi(m) = \left\| \boldsymbol{W}_t \boldsymbol{C}_d^{-1/2}(\boldsymbol{d} - \boldsymbol{G}(\boldsymbol{m})) \right\|_{\boldsymbol{2}}^{\boldsymbol{2}} + \left\| \boldsymbol{C}_{m,priori}^{-1/2}(\boldsymbol{m} - \boldsymbol{m_0}) \right\|_{\boldsymbol{2}}^2$$

With weighting matrix $\boldsymbol{W}_t = \mathrm{diag}(1/|r_i|)$, where residuals $\boldsymbol{r} = \boldsymbol{d} - \boldsymbol{G}(\boldsymbol{m})$

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# 3D MT inversion using ModEM

Several runs with different parameters, sites selection, objective function to minimise

- Full tensor
- Error floor 5%
- Final RMS 4
- Mesh 100x100x60 (15 padding cells from each side)
- 324 sites
- AR model covariances $\boldsymbol{C_m}$
- Default smoothing

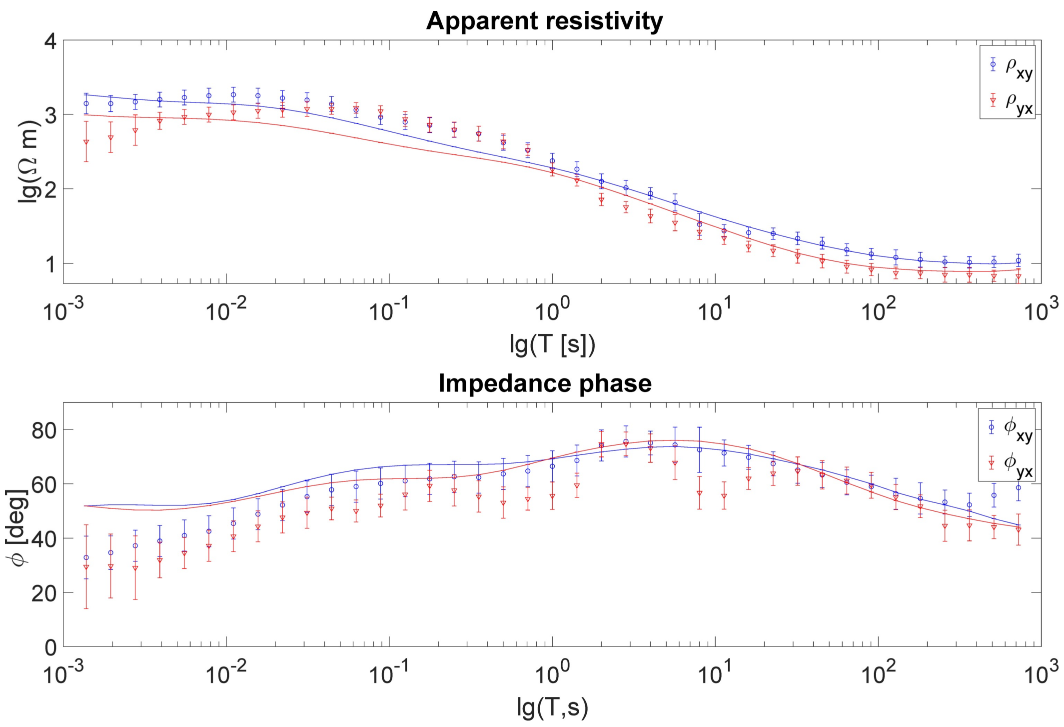
- Full tensor
- Error floor 1%
- L1 norm of residuals
- Final RMS 1.2
- Mesh 120x120x60 (10 padding cells)
- 399 sites
- Diffusion model covariances $\boldsymbol{C_m}$
- 7 periods per decade (0.001 – 1000 s)

*see Eminar: Naser Meqbel*

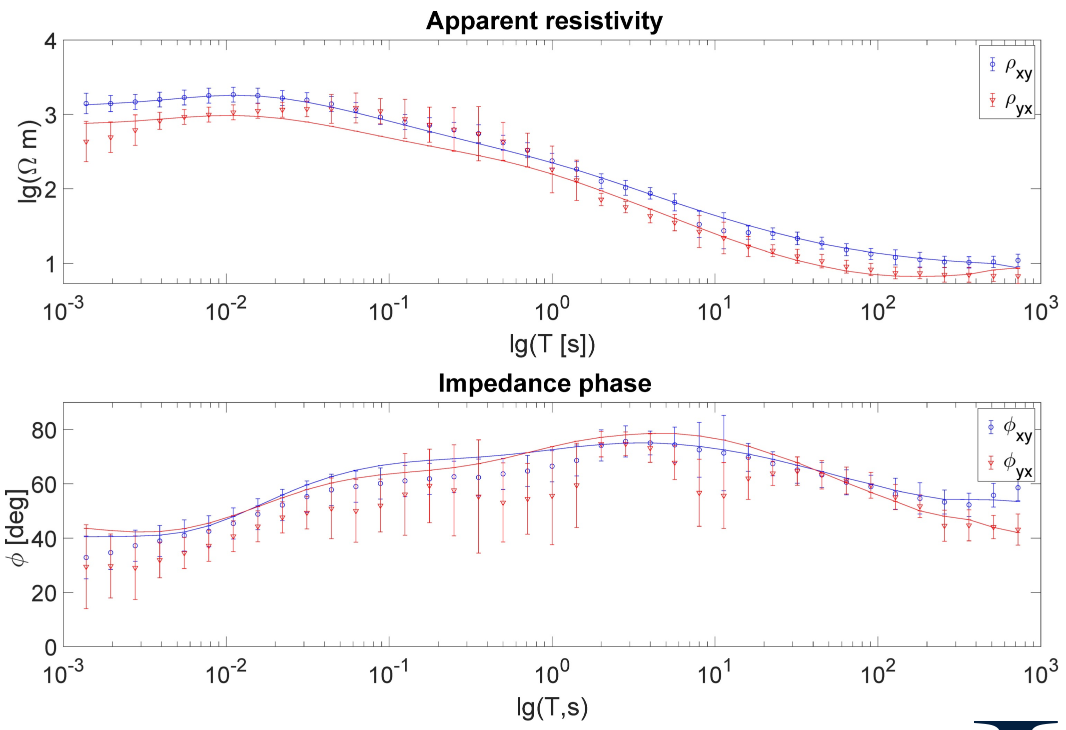
D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

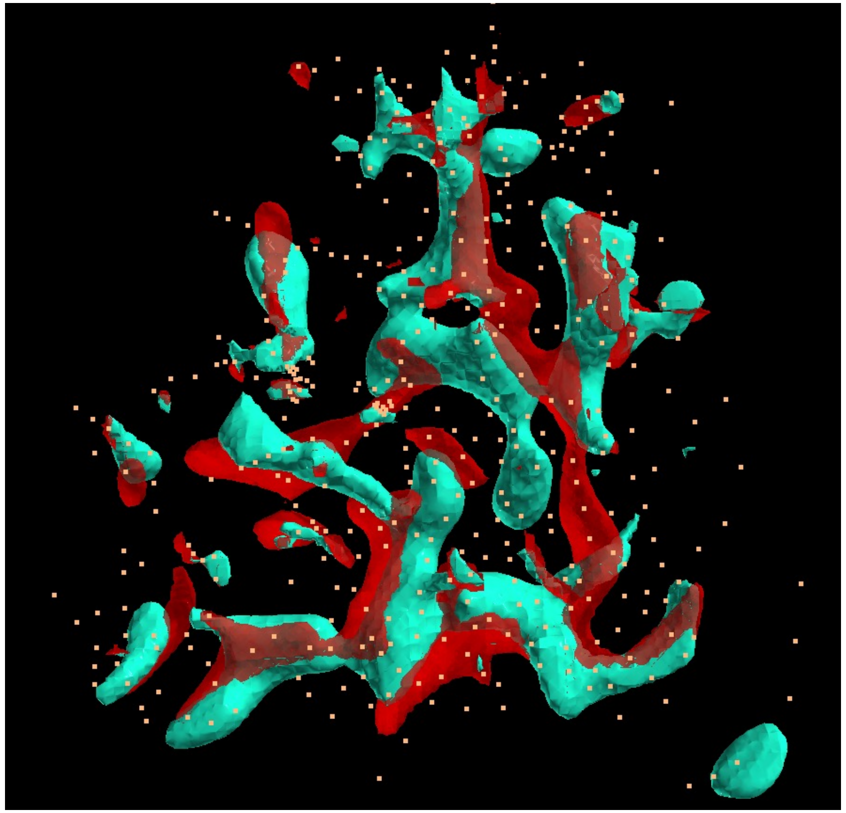
# L2 vs L1 data fit




IRL modified errors



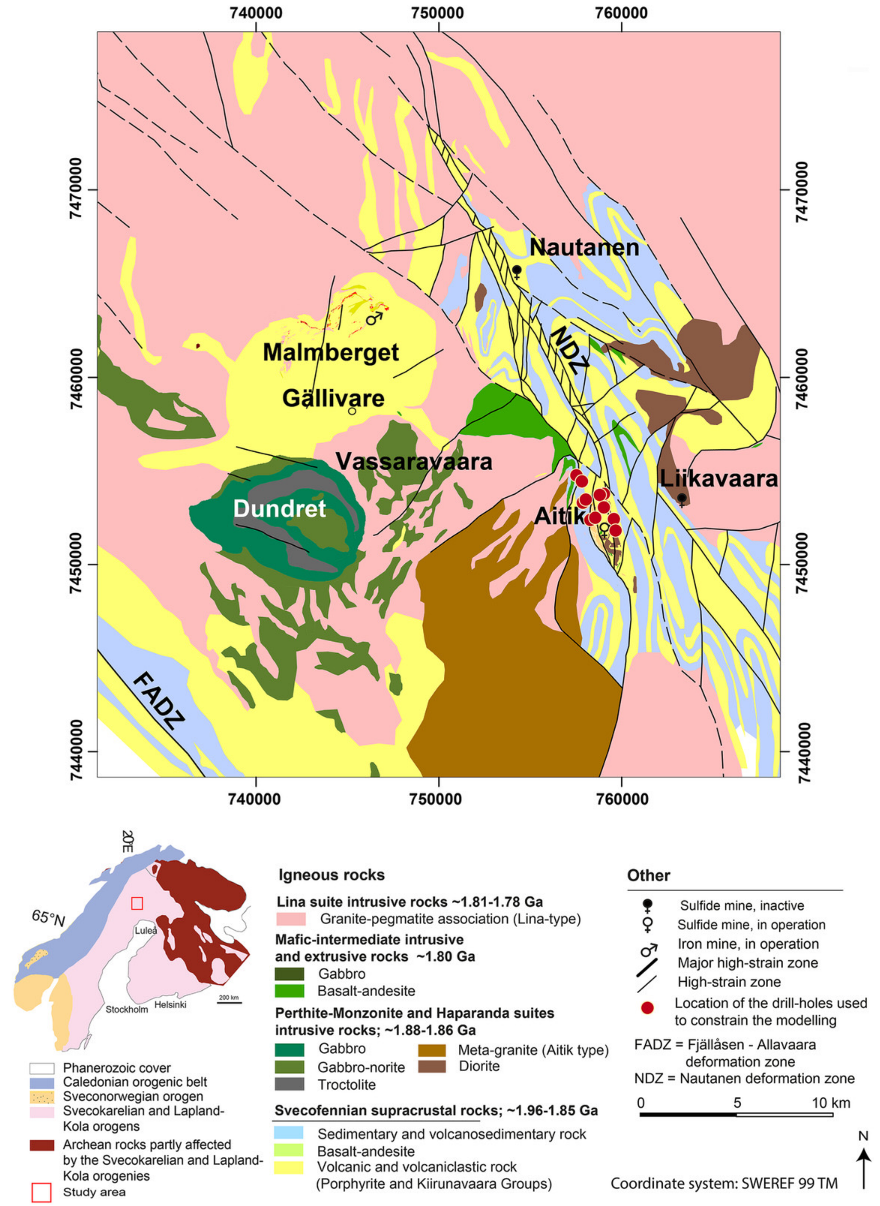
# Comparing models



Red iso-surface original inversion.

Blue iso-surface after reweighting.

# Gällivare, Sweden




- The Malmberget iron oxide-apatite (IOA) deposit in northern Sweden is one of the largest underground iron ore mine operations in the world
- Nautanen is an IOCG (Iron Oxide Copper Gold) deposit have been suggested to be formed in a continental back arc setting and is associated with the major shear zone NDZ (Nautanen Deformation Zone)

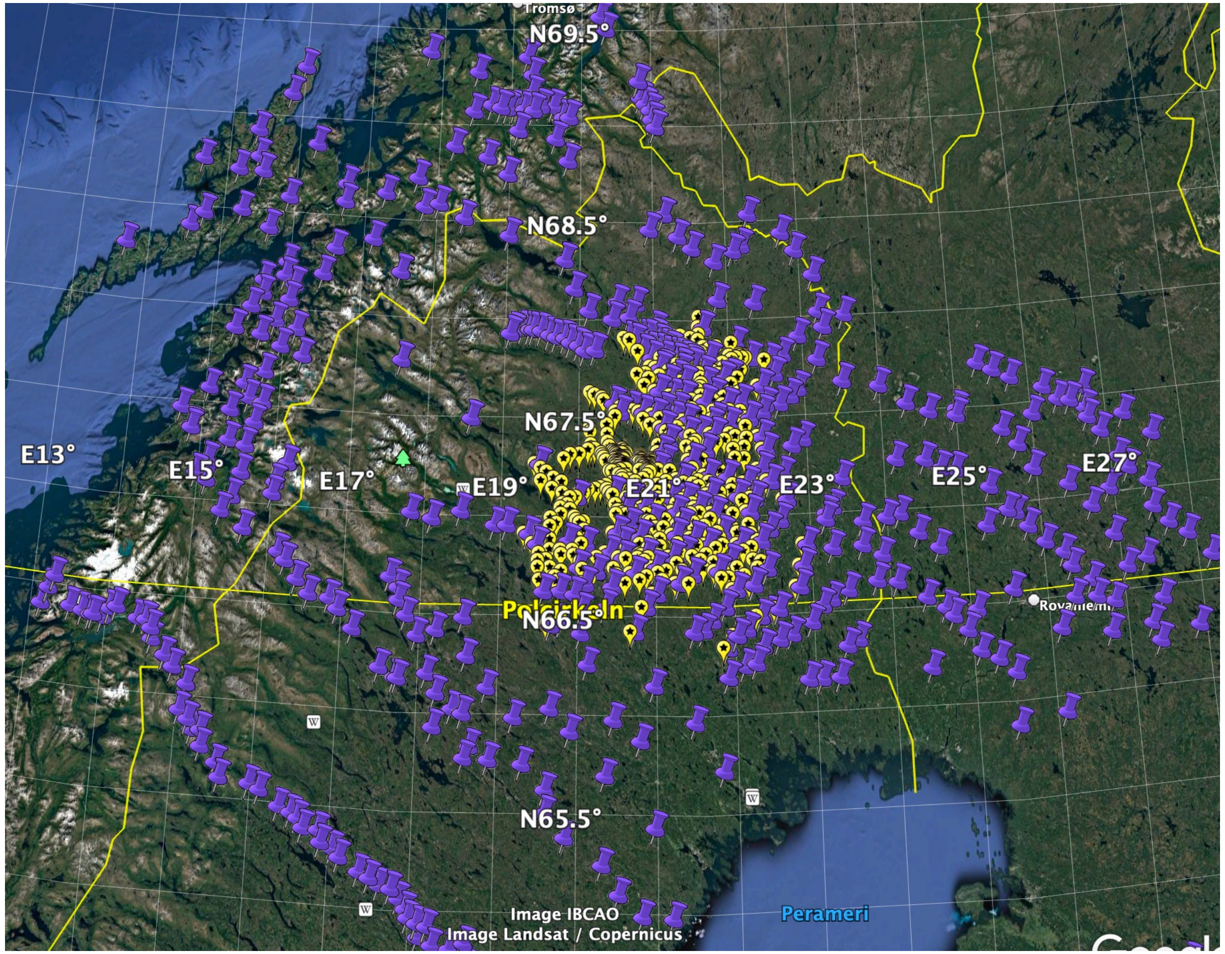
D-REX

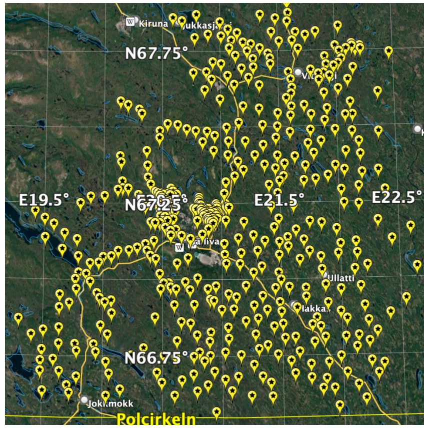
*S.Tavakoli, Z.Sarlus, I. Kronsell, T. Bauer 2021*

LULEÅ UNIVERSITY OF TECHNOLOGY

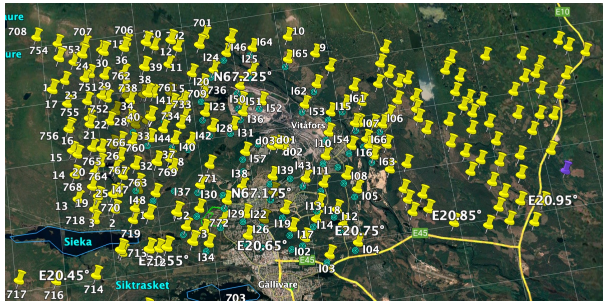
# From two regional levels to two deposit scales

**600x600 km² (*10-30 km spacing*) MT (2010-2019)**

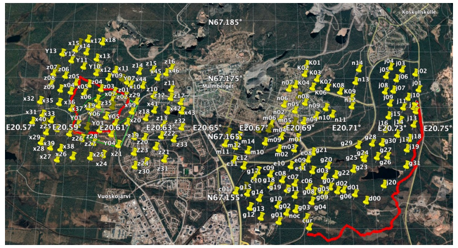



**100x100km²**
***5 km grid***
**MT D-Rex**




**15x25km²**
***1 km grid***
**MT D-Rex**

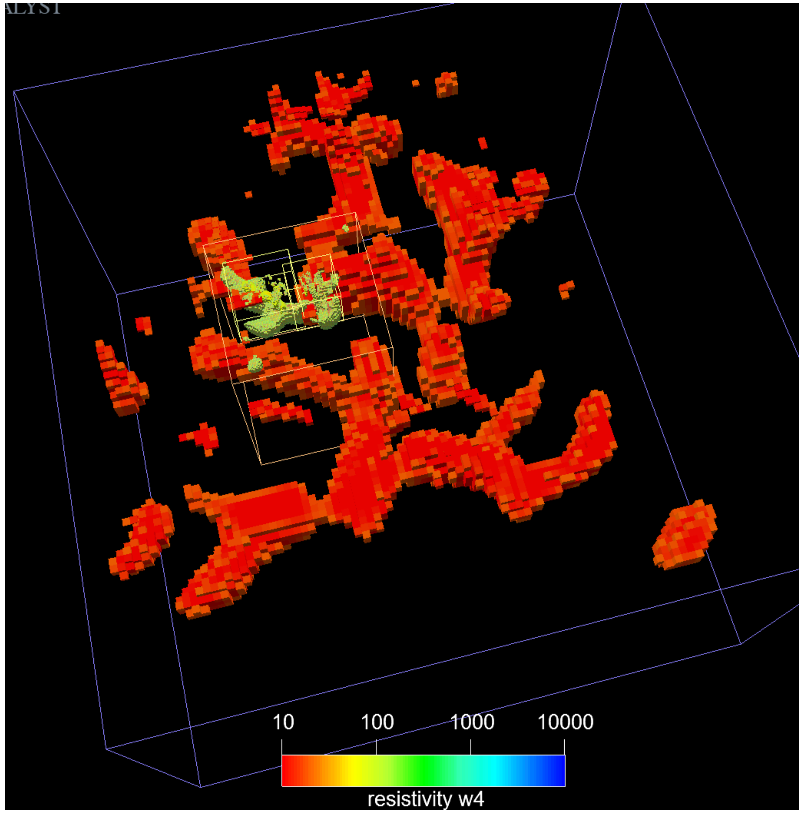


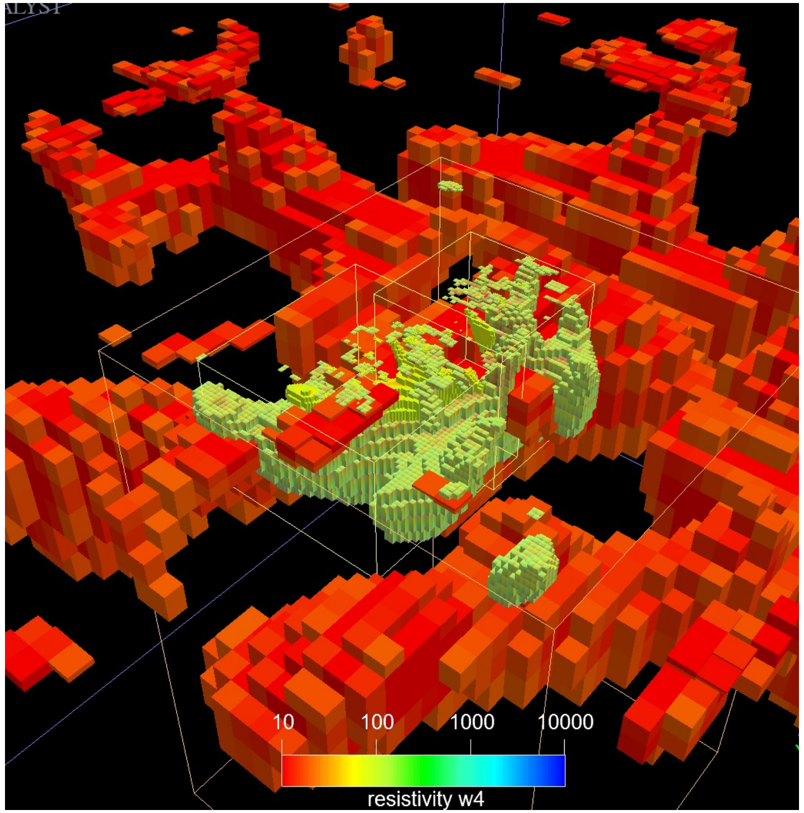
**2x2km².**
***250 m grid* (CSEM)**

LULEÅ UNIVERSITY OF TECHNOLOGY

D-REX

# From regional to deposit scale

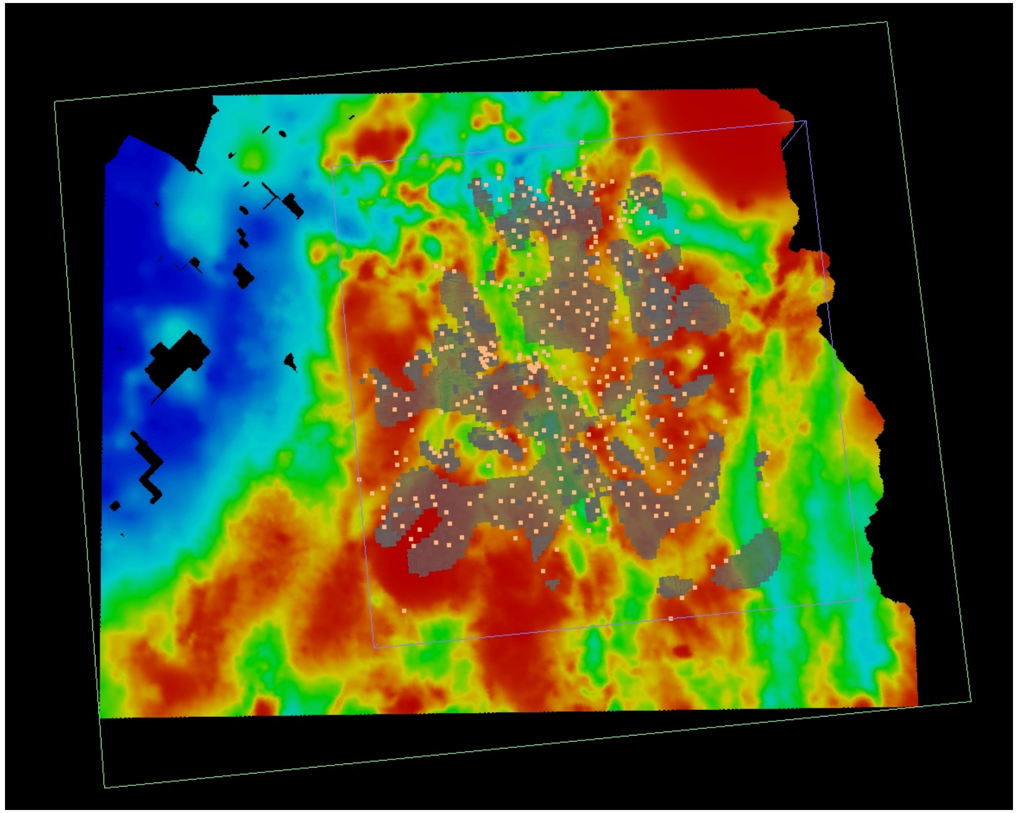


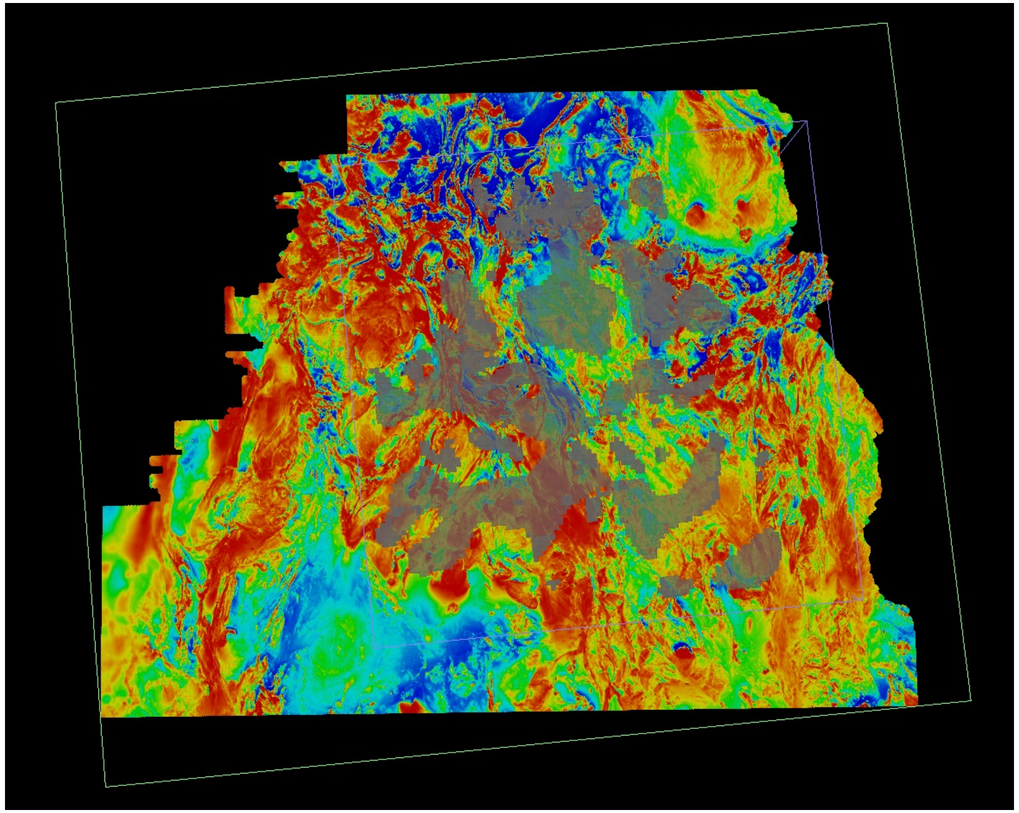

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Potential field data



Gravity

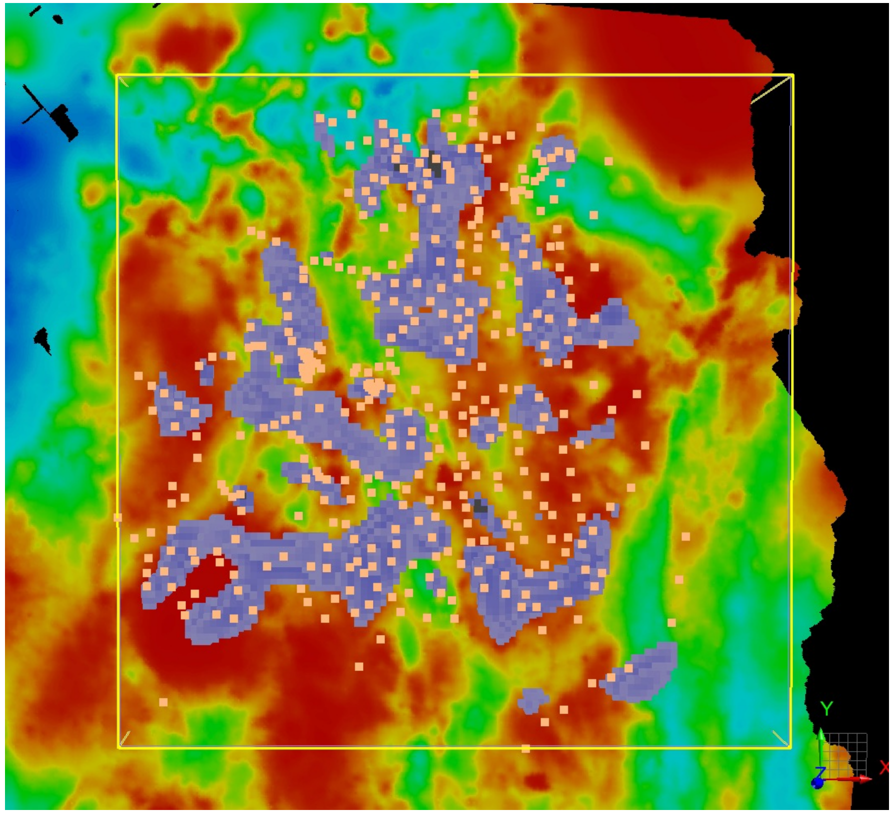


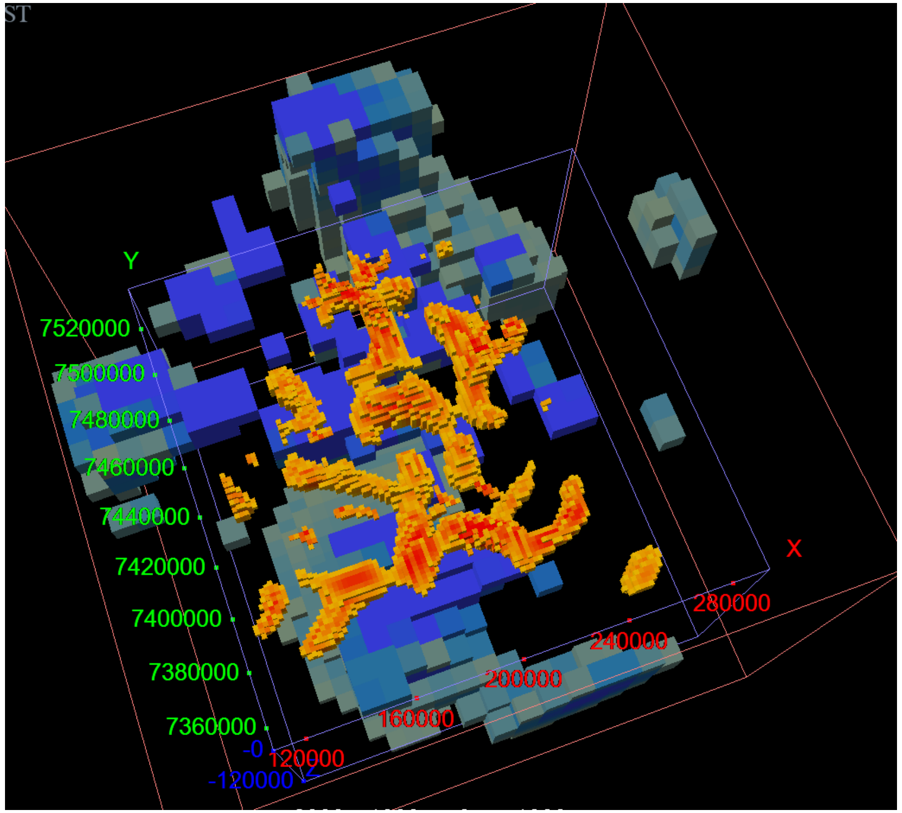
Magnetics

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Regional 3D models

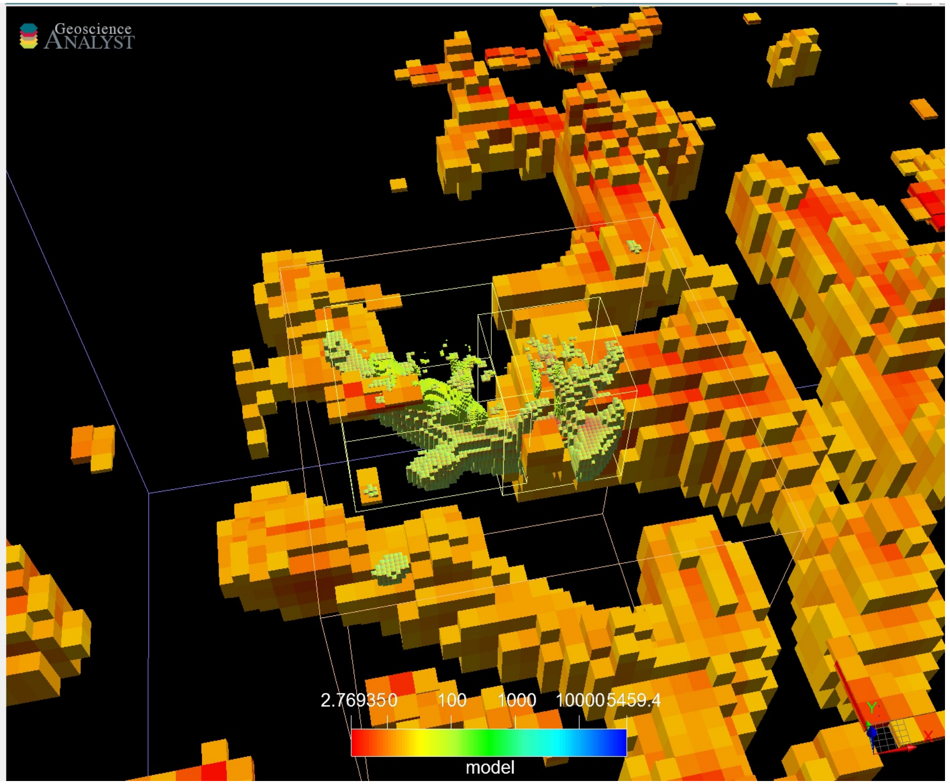


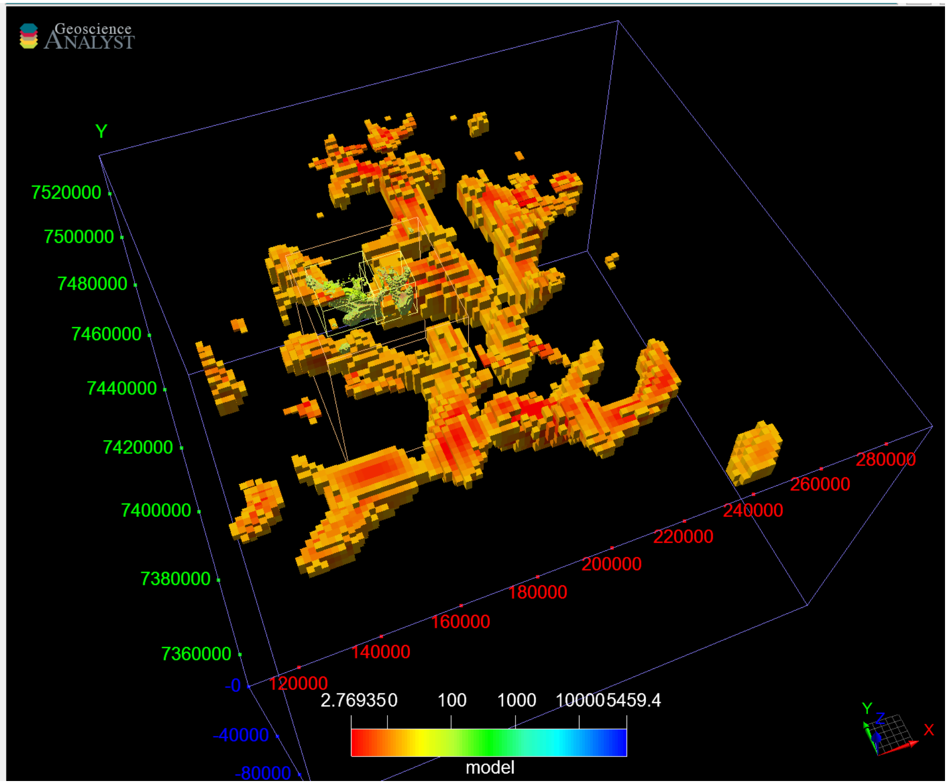




D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# DREX regional, local

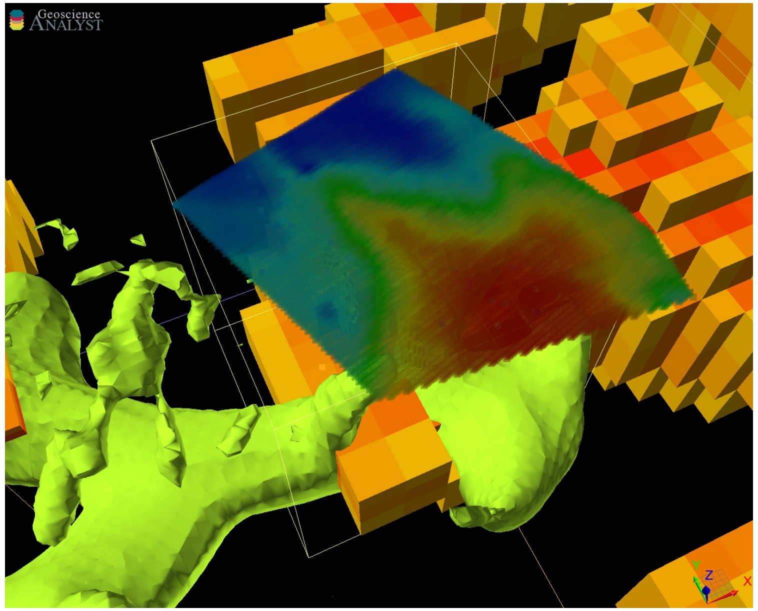


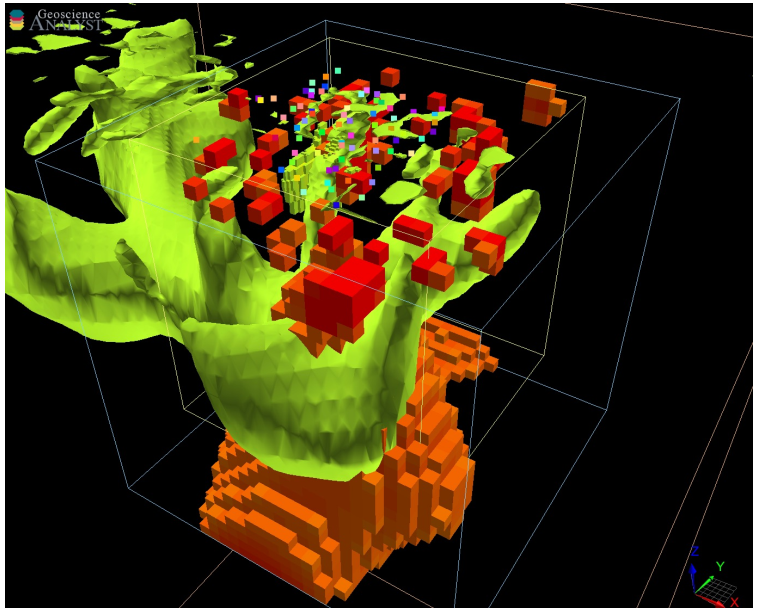



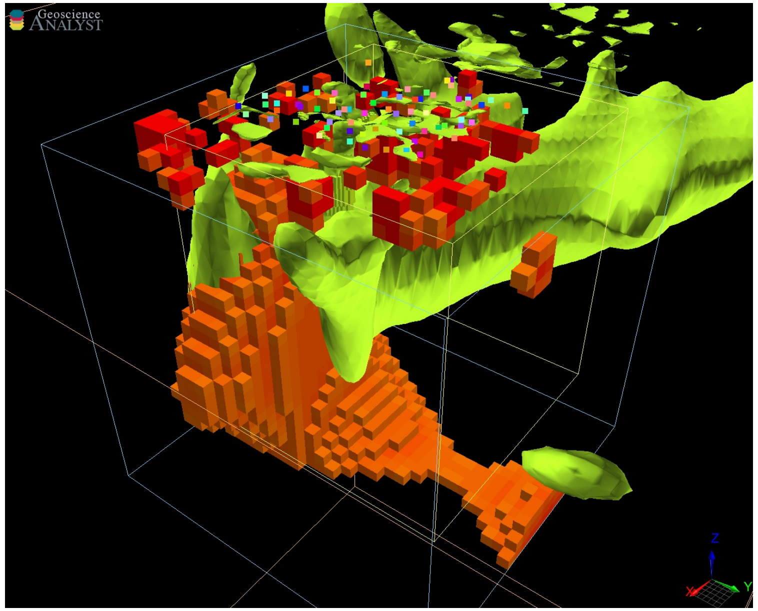

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY

# Gravity + MT (single inversions), Nautanen



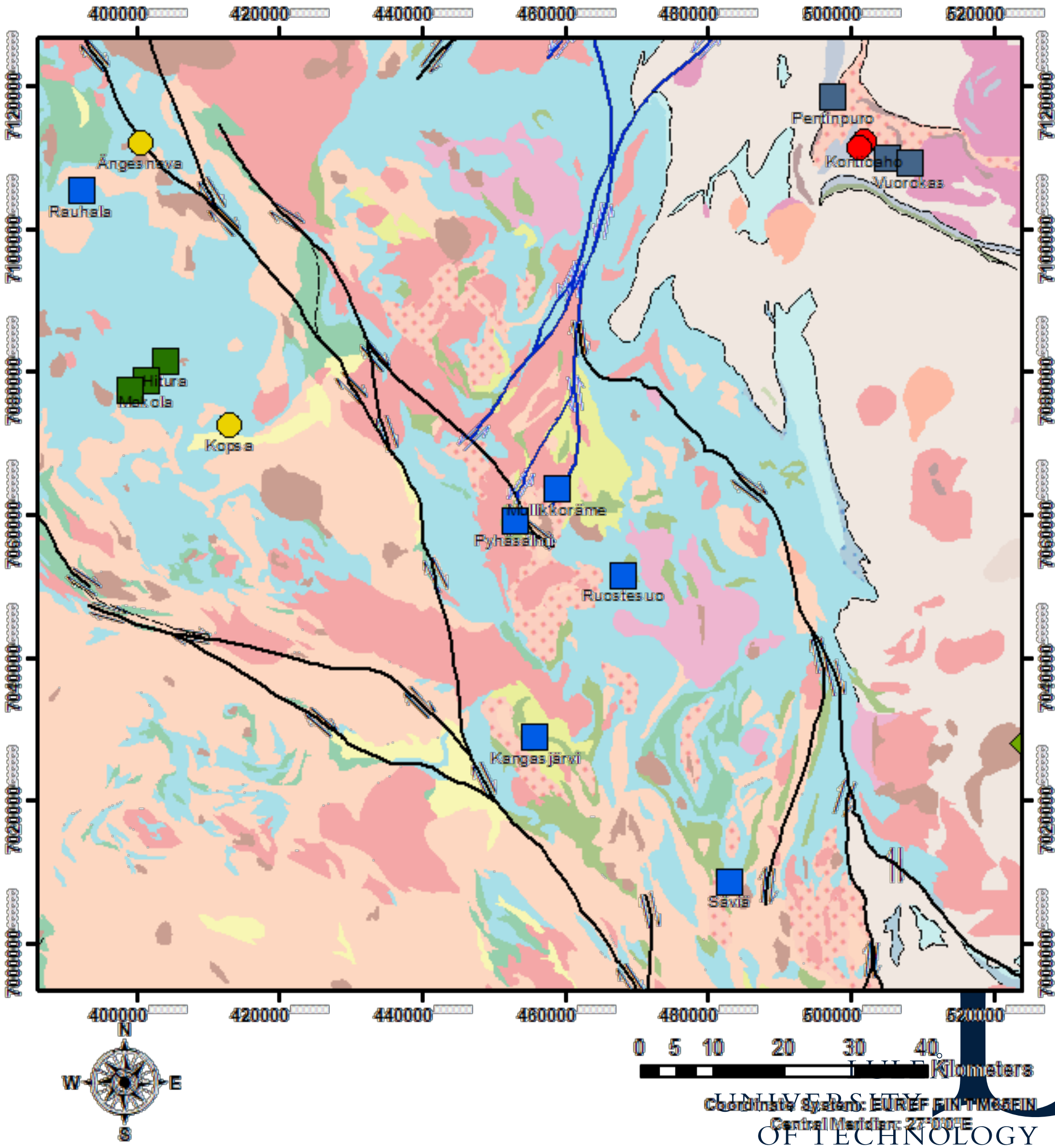




*Gravity data cortesy of Boliden*

# Pyhäsalmi, Finland

- Located at the Archean-Proterozoic boundary within the Raahe-Ladoga zone
- Finland's largest VHMS in Pyhäsalmi
- Formed through hydrothermal processes
- Metasedimentary rocks
  - contain black shales (Graphite)
  - were likely thrust over the Archean
- Deposit formation at crustal scale is not well understood

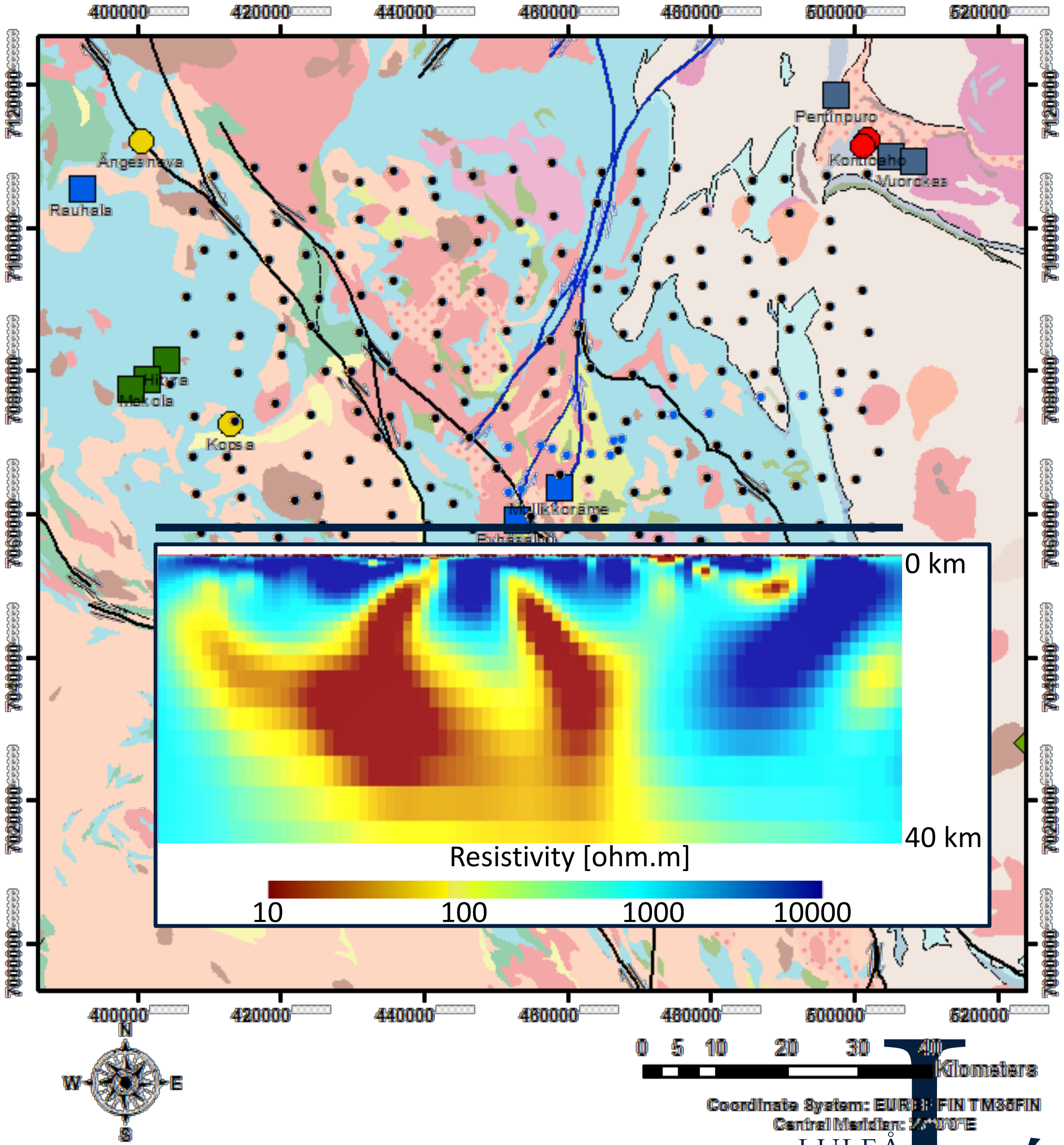


# Pyhäsalmi, Finland

- A very complicated (3D) data set
- Conductivity increases downwards
- Overall higher conductivity W and NW
- Raahe-Ladoga zone strike apparent

- Subvertical conductor below Pyhäsalmi deposit

- Depth resolution ends at ca. 30 km

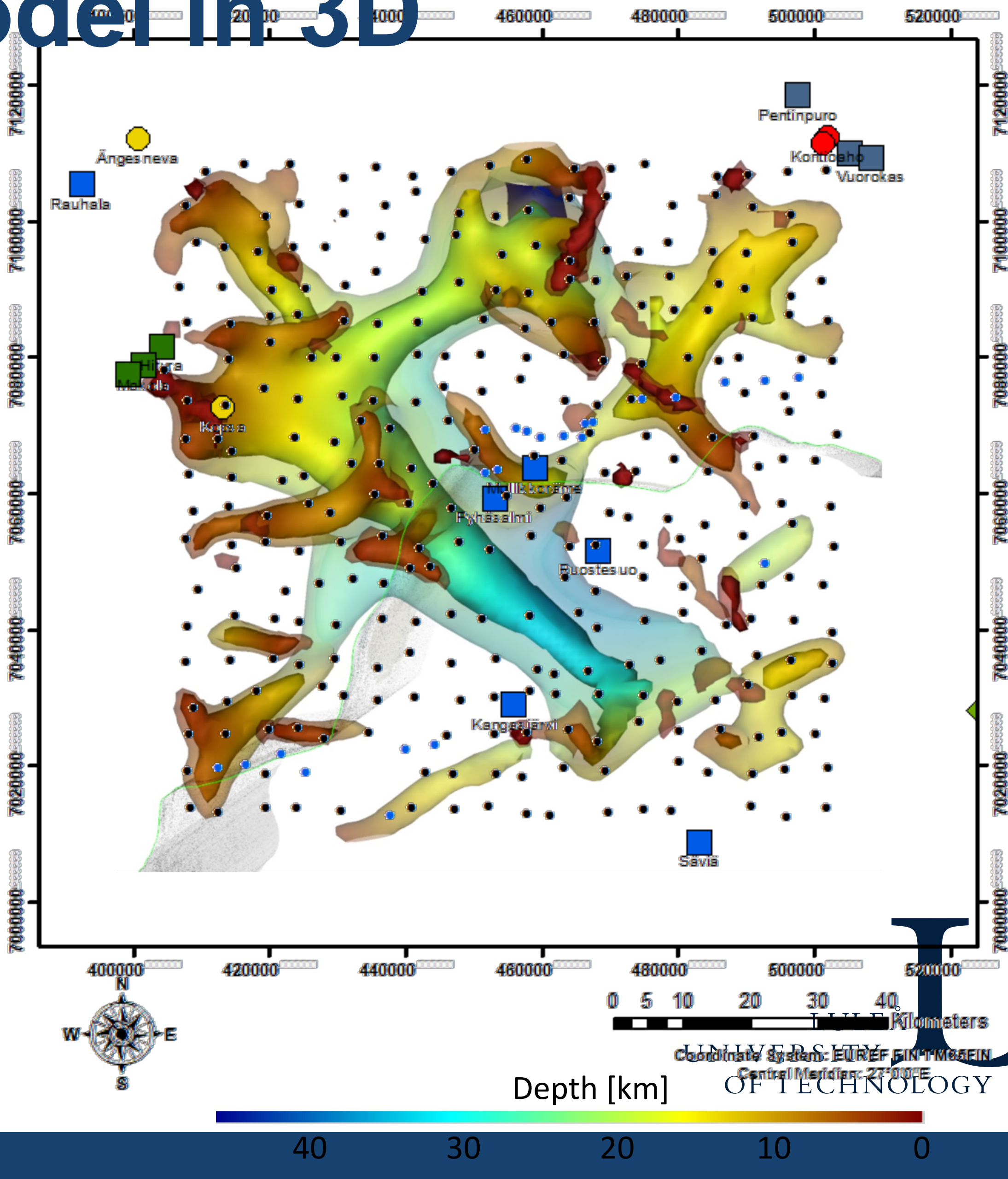



LULEÅ UNIVERSITY OF TECHNOLOGY

D-REX

# Conductivity model in 3D

- Isosurface of 10 ohm-m
- Pyhäsalmi and Mulikkoräme associated with subvertical conductor
- Kangasjärvi deposit associated with central deep conductor (better seen at 50 ohm-m)
- Nivala Ni-deposits correlate with near surface conductivity (likely intrusions piercing graphite sheets)

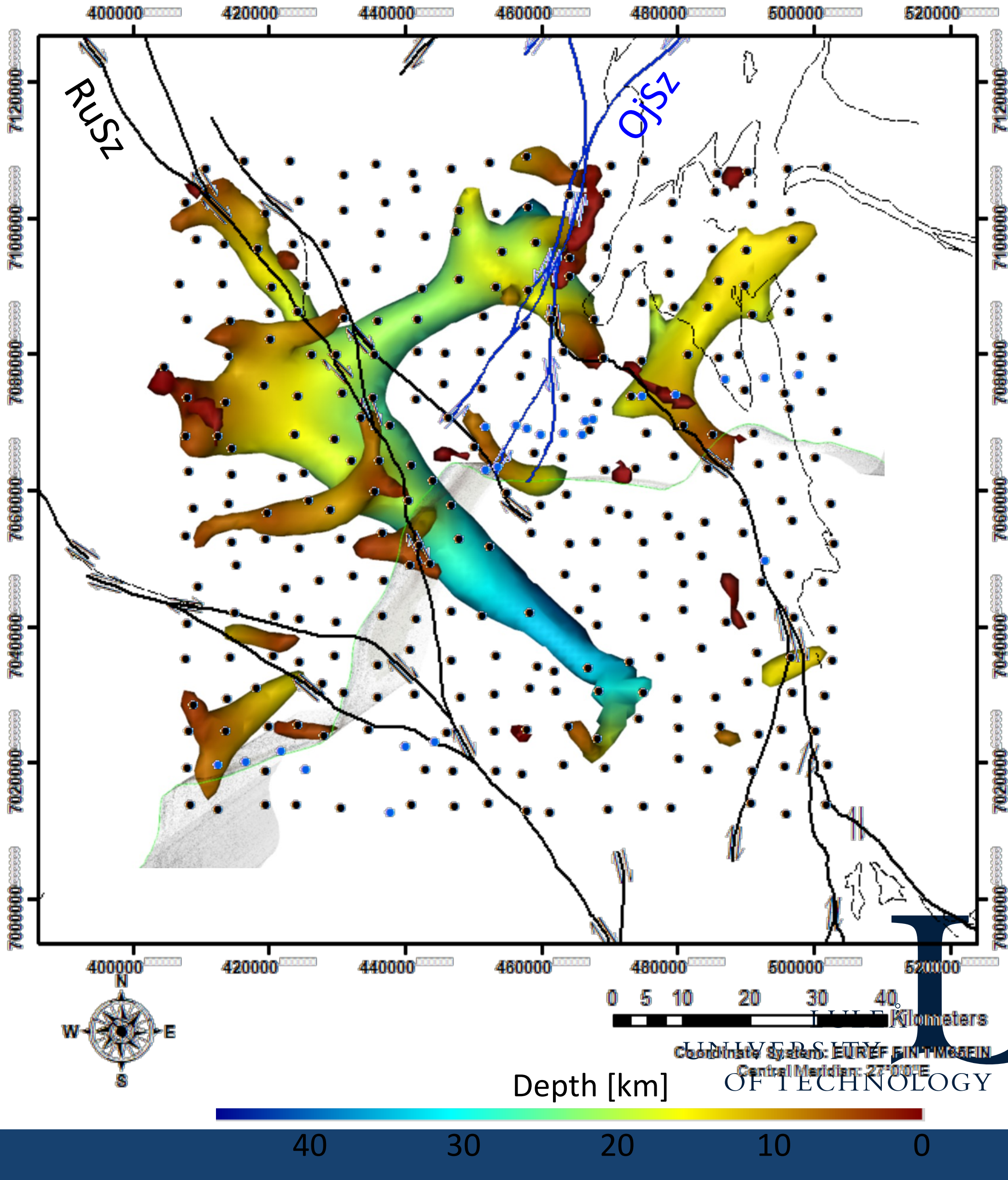



D-REX

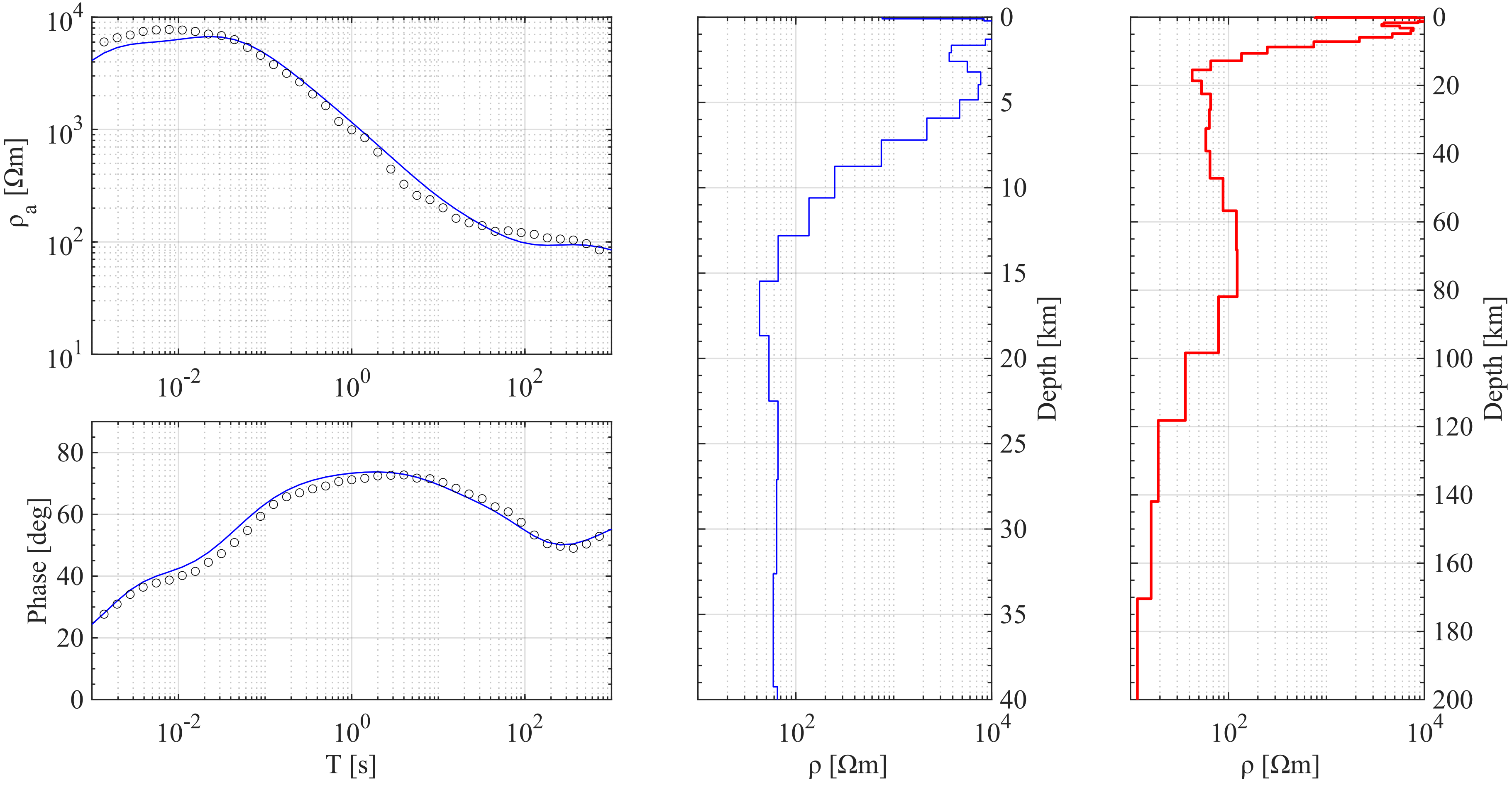
LULEÅ UNIVERSITY OF TECHNOLOGY

# Conductivity model in 3D

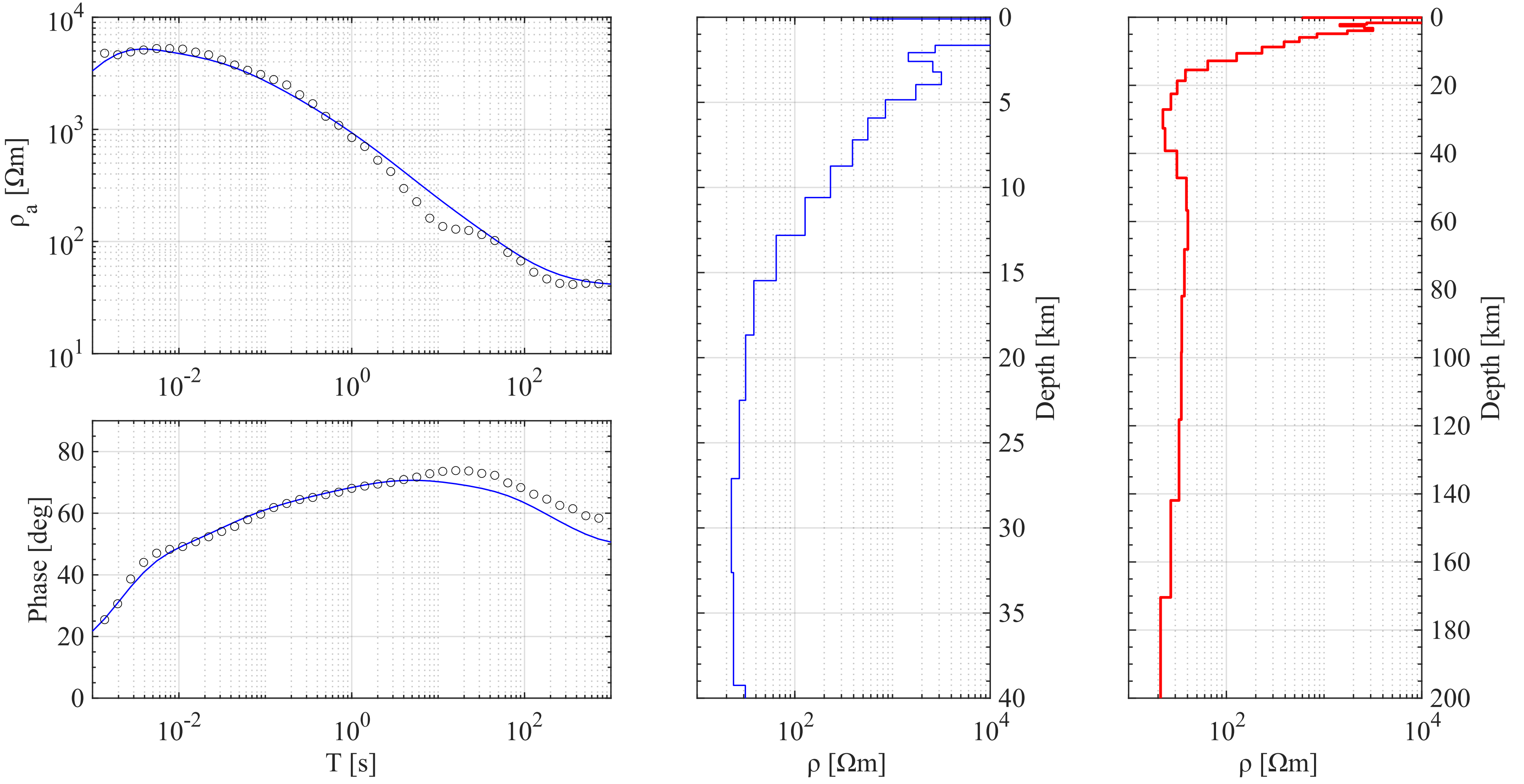
- Isosurface of 10 ohm-m
- Pyhäsalmi and Mulikkoräme associated with subvertical conductor
- Kangasjärvi deposit associated with central deep conductor (better seen at 50 ohm-m)
- Nivala Ni-deposits correlate with near surface conductivity (likely intrusions piercing graphite sheets)
- Shallow Näläntöjärvi conductors also tied to metasedimentary Graphite sheets
- Nivala conductors reach deep, Näläntöjärvi conductors isolated
- Large and deep conductors loosely follow main shear zones.



# 1D inversion of the determinant of the impedance tensor average over all sites (Sweden) Archean-Proterosoic



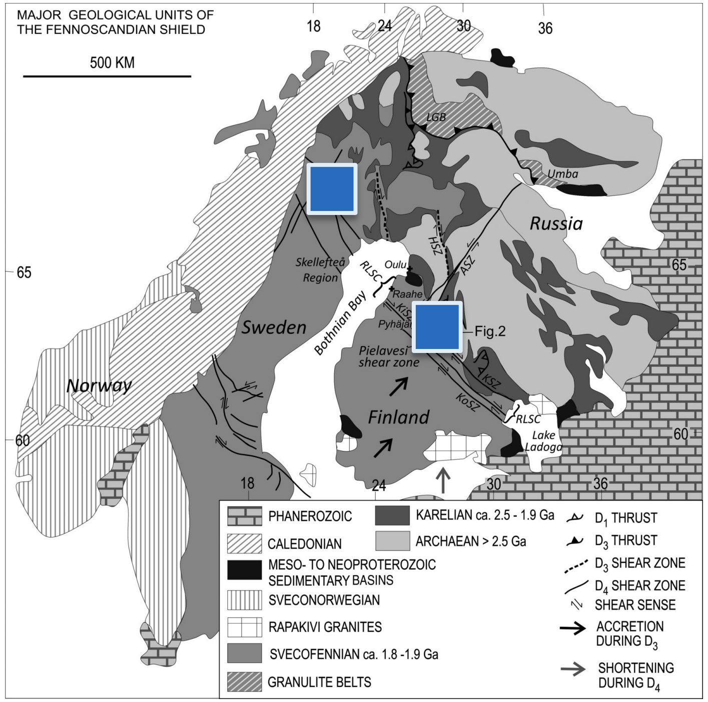
# 1D inversion of the determinant of the impedance tensor average over all sites (Finland) Archean-Proterozoic

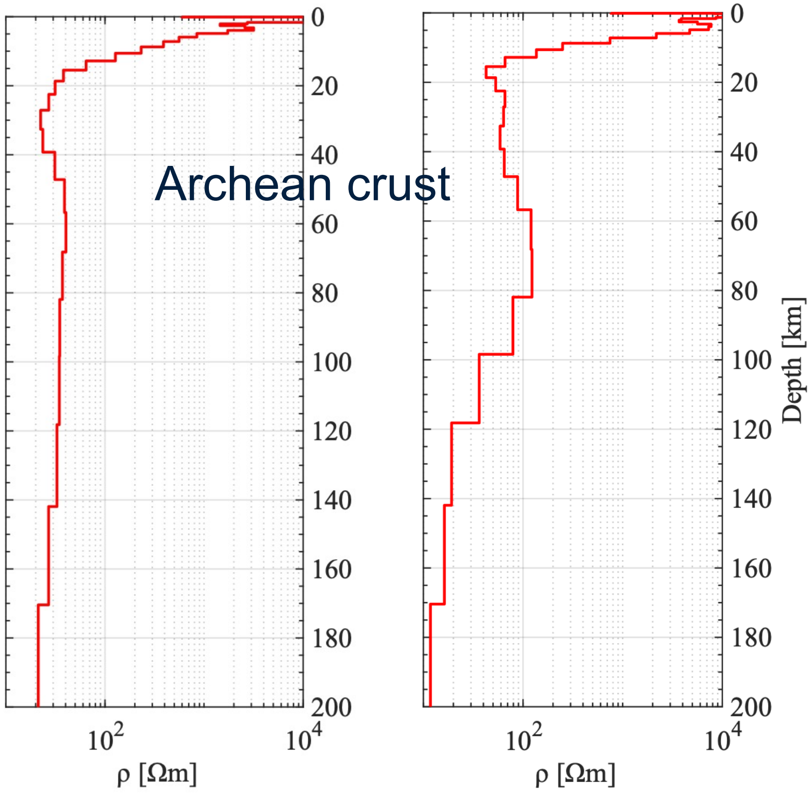



D-REX

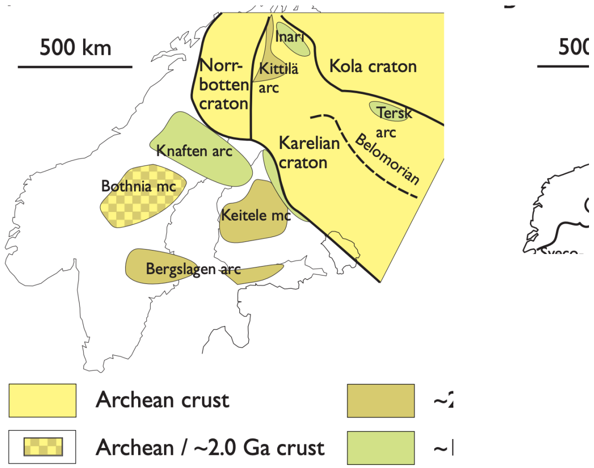
LULEÅ UNIVERSITY OF TECHNOLOGY

# Major Geological Units of The Fennoscandian shield

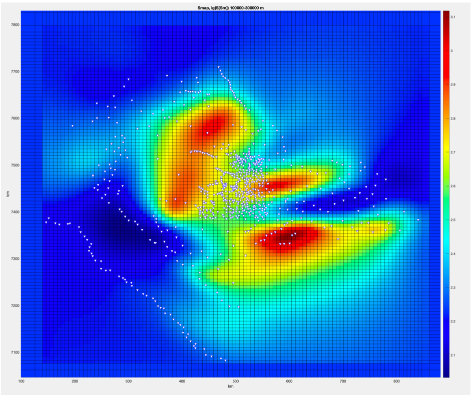



Archean crust

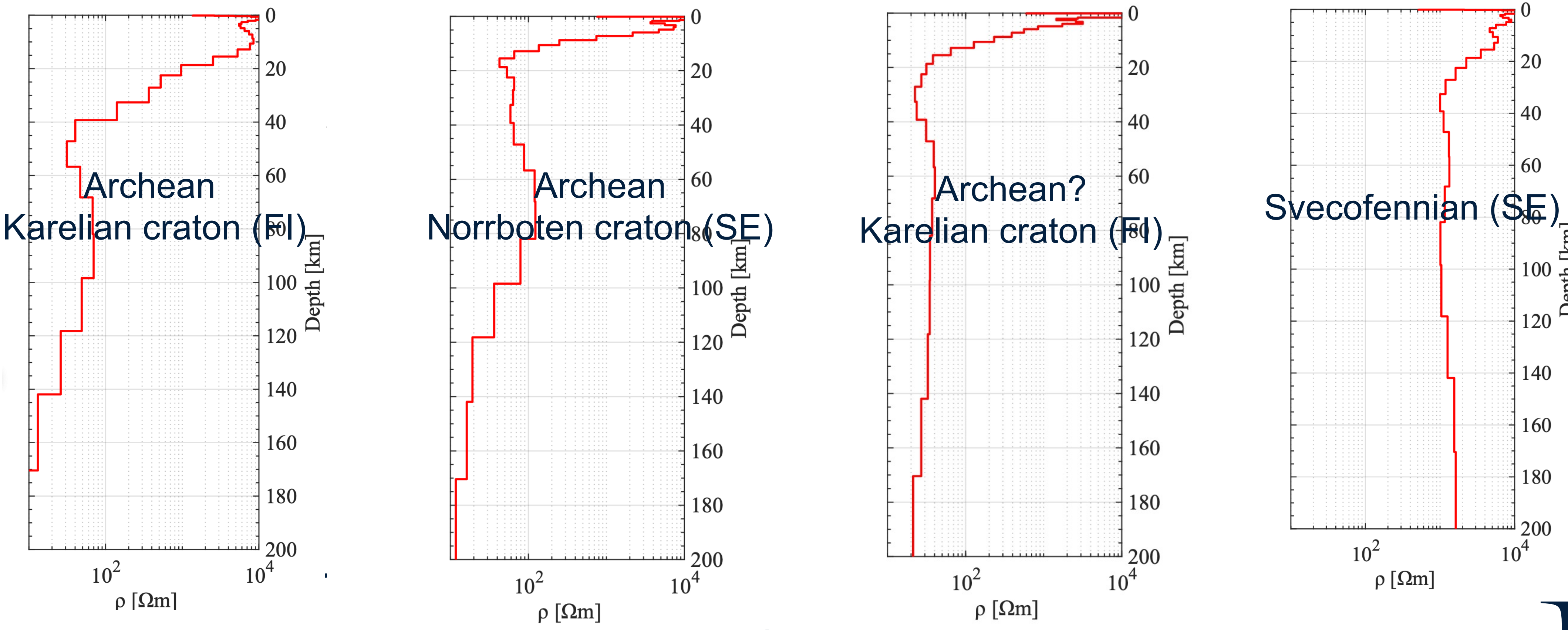



*Lantinen et al. 2005*



# From Archean to Proterozoic lithosphere

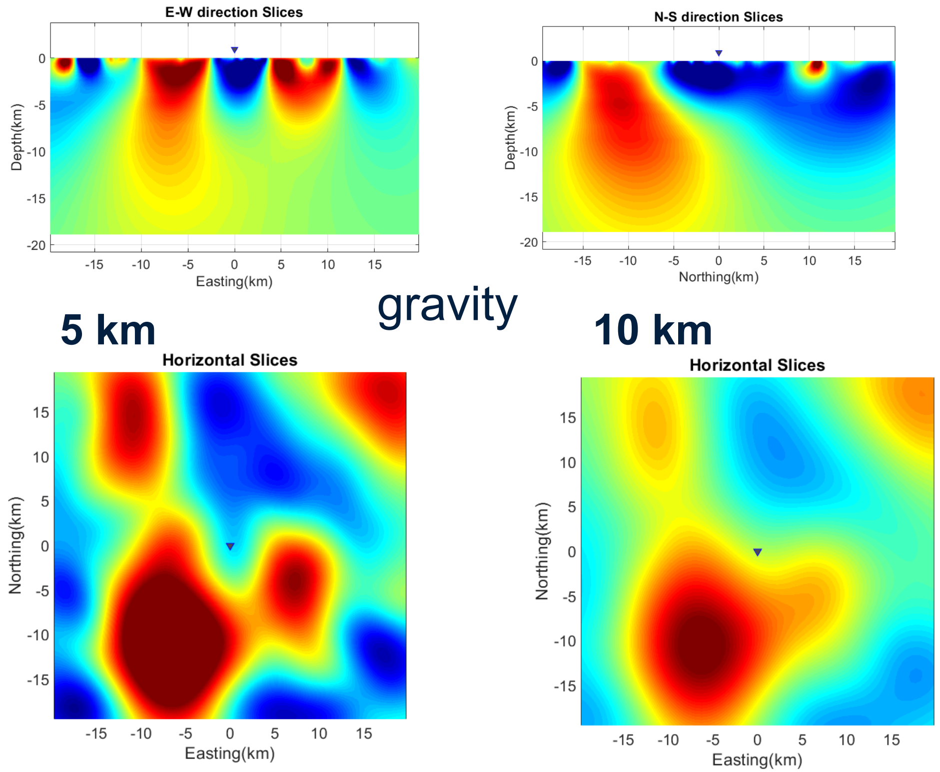
Proterozoic – Archean boundary

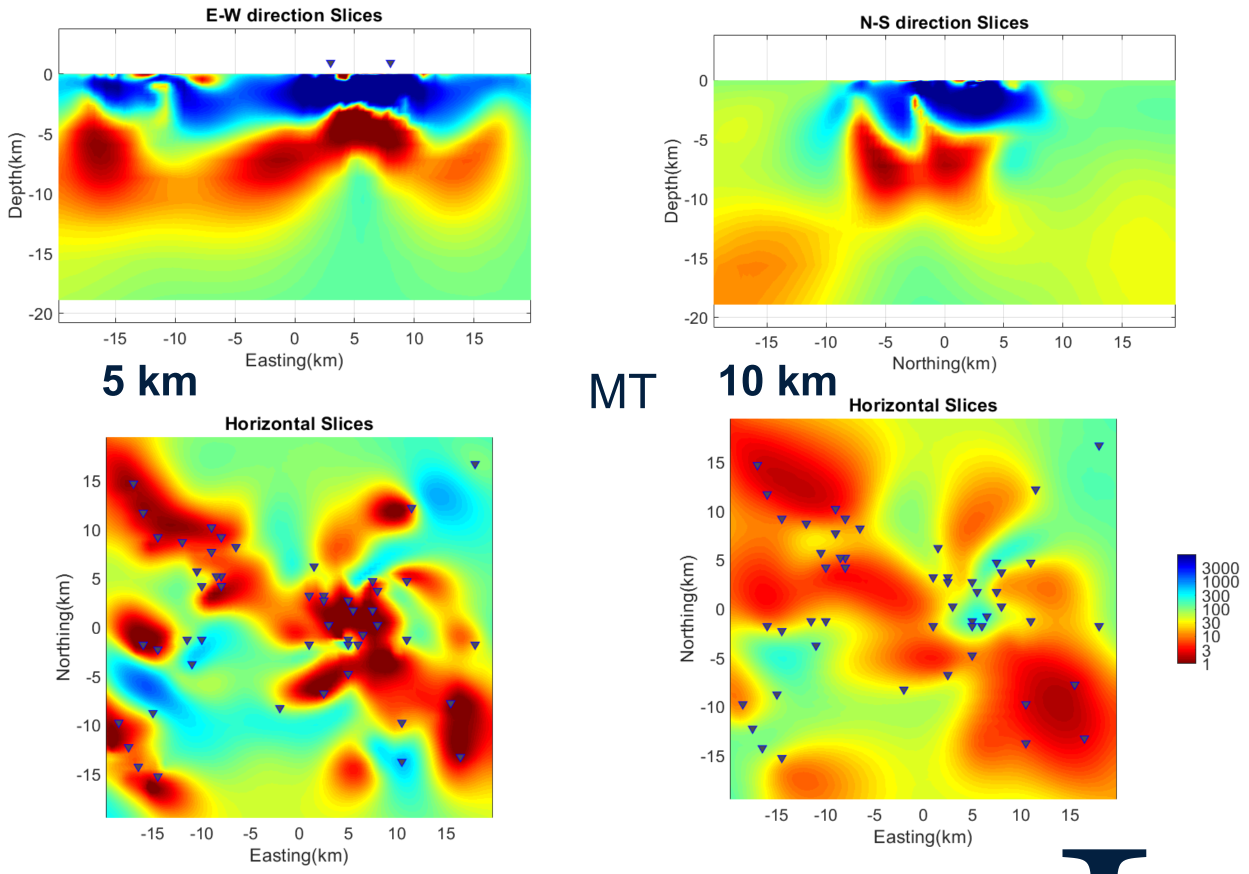



LULEÅ UNIVERSITY OF TECHNOLOGY

# Joint inversions jif3D – gravity + MT - MI

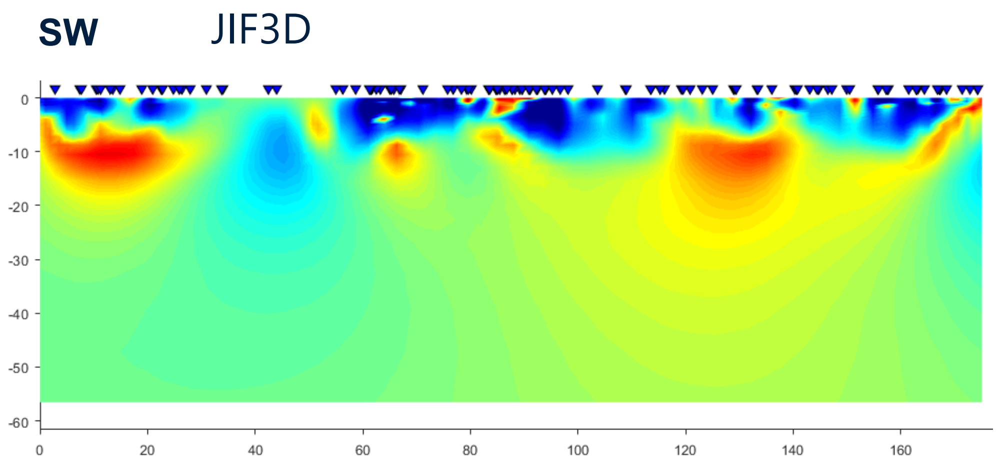
Very preliminary, first results



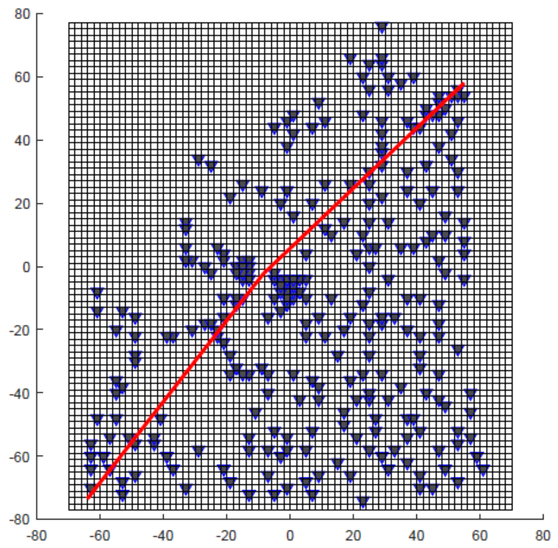



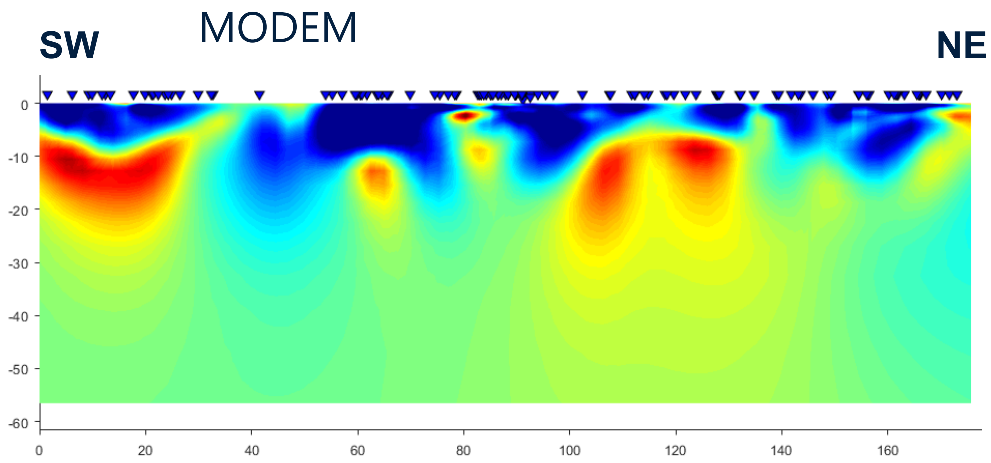

LULEÅ UNIVERSITY OF TECHNOLOGY

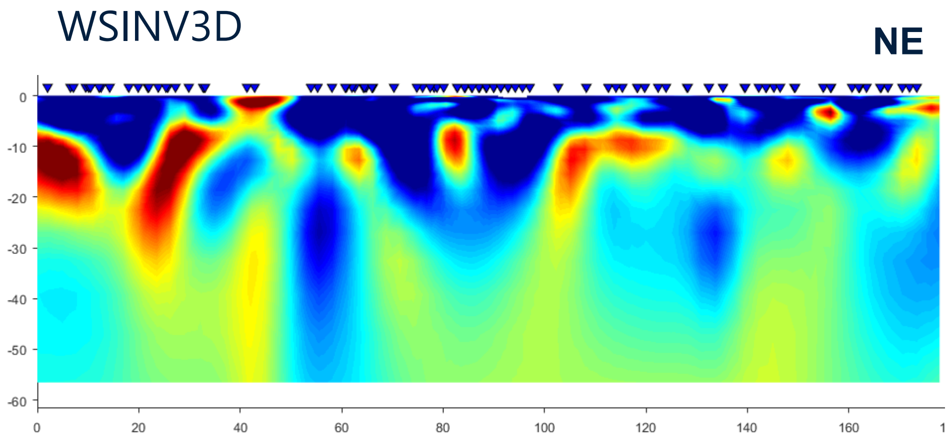
# Comparison on 3D inversion codes – vertical slices




Comparison of horizontal distribution along same section through 3D geoelectrical models from different codes



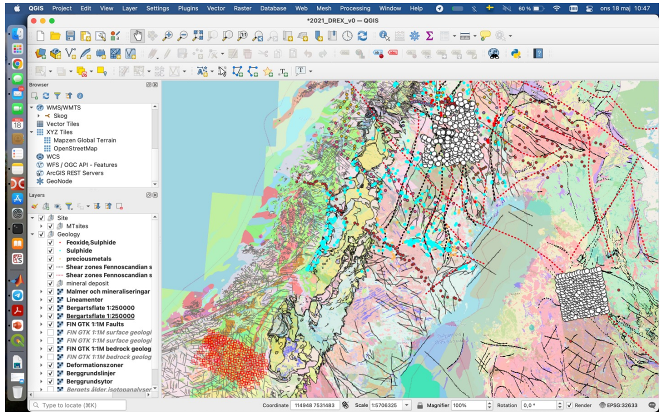




D-REX

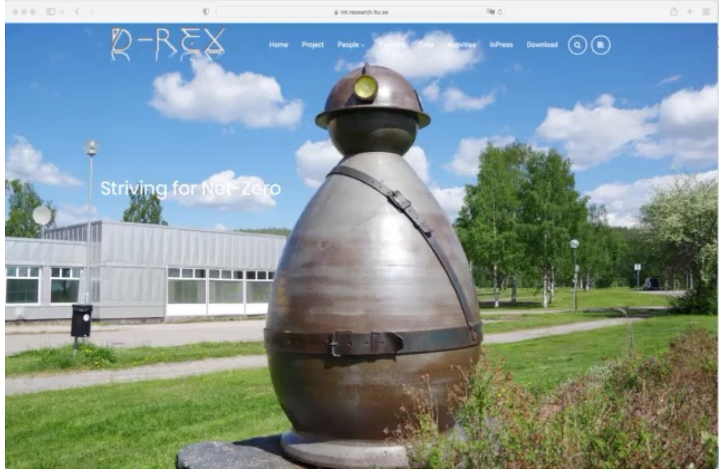
LULEÅ UNIVERSITY OF TECHNOLOGY

# Data and models exchange

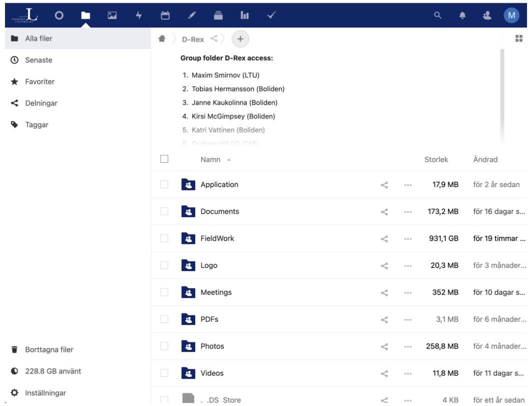
## QGIS integrated project



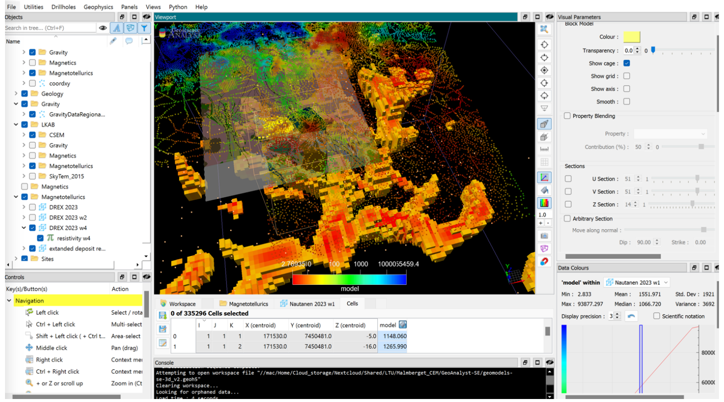
## DREX Website: https://mt.research.ltu.se/web/




## Data repository in nextcloud




## Projects for each area in Geoscince Analyst



D-REX

LULEÅ
UNIVERSITY
OF TECHNOLOGY

# EMTDAMO

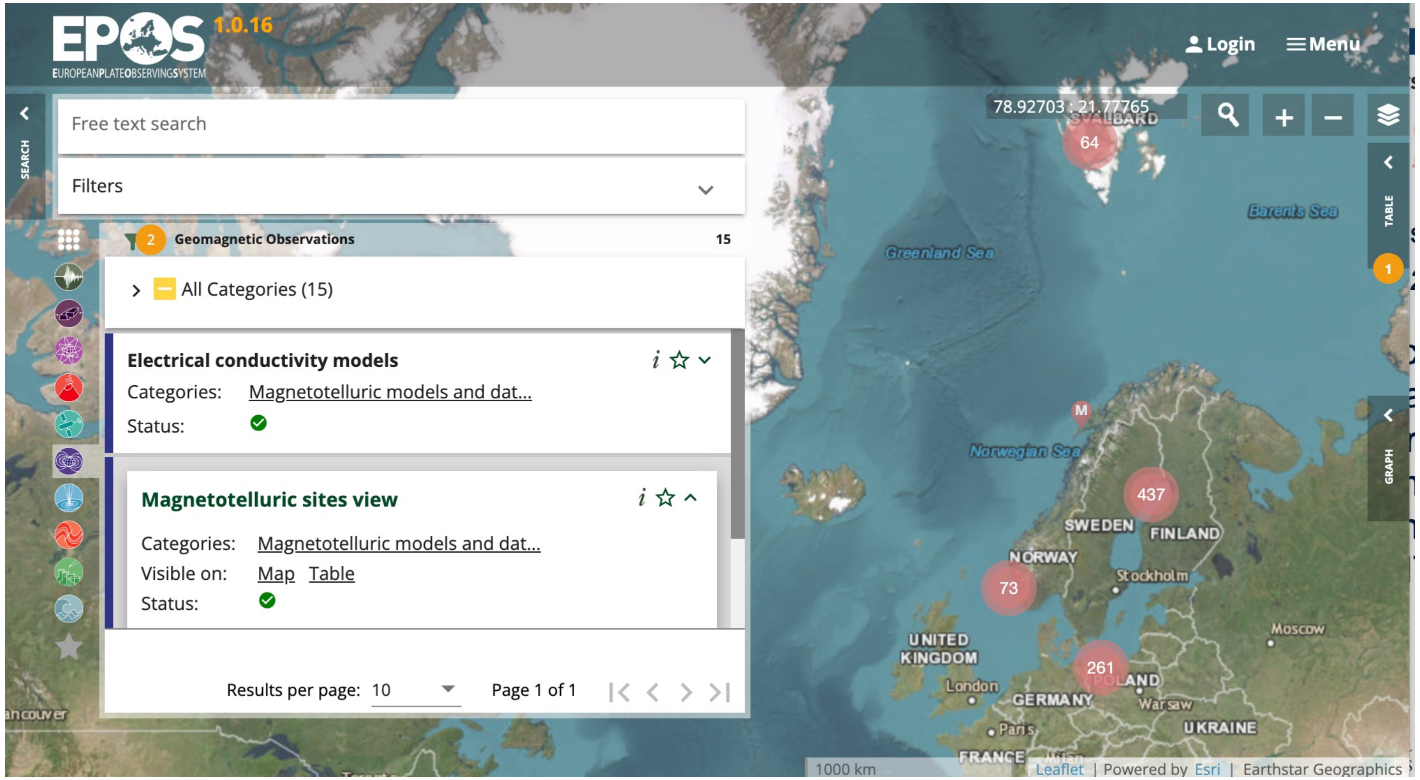
EUROPEAN PLATE OBSERVING SYSTEM

SEISMOLOGY | NEAR-FAULT OBSERVATORIES | GNSS DATA AND PRODUCTS | VOLCANO OBSERVATIONS | SATELLITE DATA | GEOMAGNETIC OBSERVATIONS | ANTHROPOGENIC HAZARDS | GEOLOGICAL INFORMATION AND MODELING | MULTI-SCALE LABORATORIES | GEO-ENERGY TEST BEDS FOR LOW CARBON ENERGY

https://www.epos-eu.org/

https://www.ics-c.epos-eu.org/

*Released at EGU 2023*




Find and access magnetotelluric (MT) data including transfer functions (TFs) , time series (TSs) and conductivity models

*In progress*

LULEÅ UNIVERSITY OF TECHNOLOGY

# Conclusions

- 3D magnetotelluric arrays are important to identify key components of mineral systems and the tectonic context
- Some conductors closely correlate with deposits. Alteration zones?
- On the crustal scale, MT provides an important structural information
- 3D data acquisition and interpretation is necessary in complex Precambrian environments
- Joint inversions are on the way…. as well as integration with 3D geological models at deposit scale

D-REX

LULEÅ UNIVERSITY OF TECHNOLOGY


D-REX