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Smart Exploration:
New Ways to Explore the Subsurface

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EMinar (MTNet)
February 10-2021

Disclaimer:
A contribution by many!

MTNet

SMARTEXPLORATION
new ways to explore the subsurface

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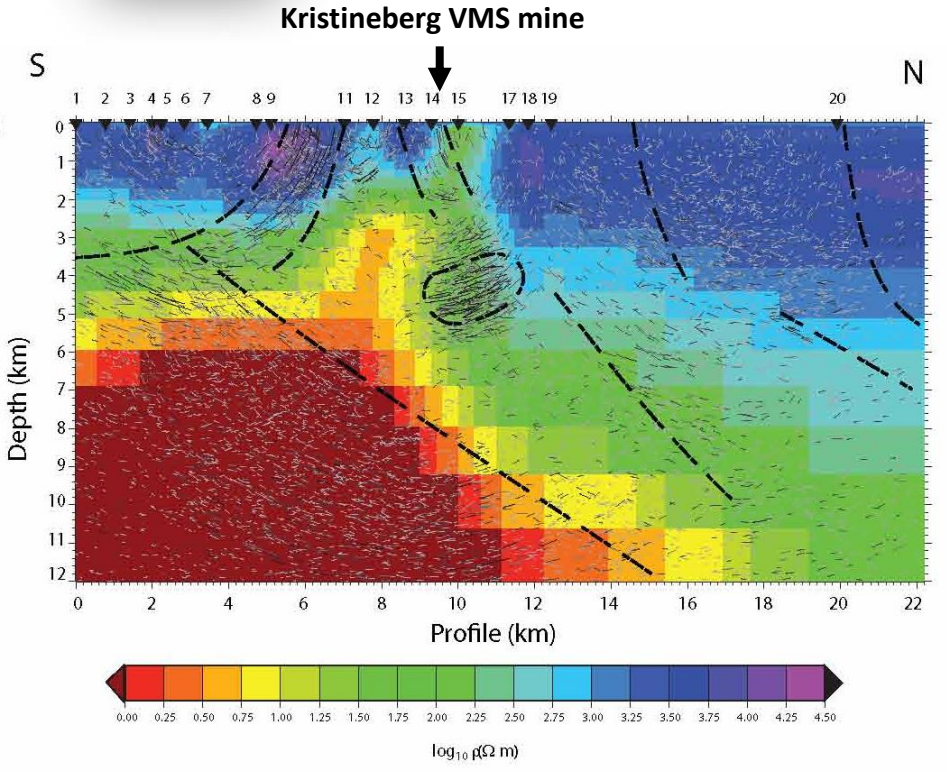
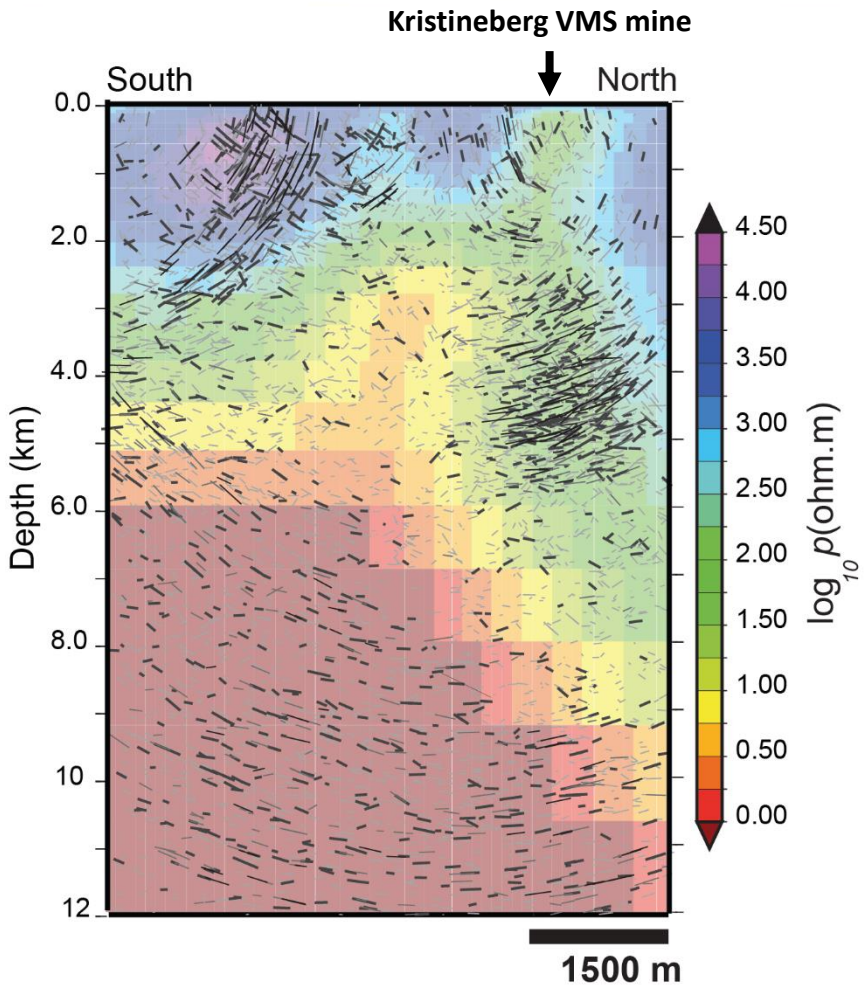
MT & Seismics





Malehmir et al. (2006, Precam. Res.)
Hübert et al. (2009-Tectonophysics)

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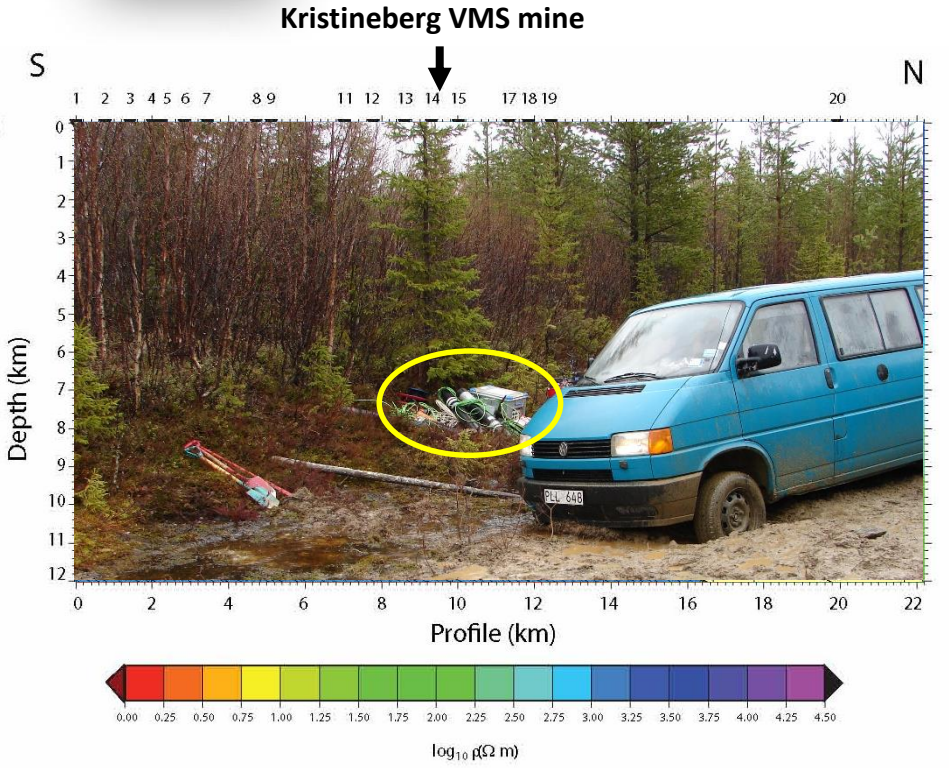
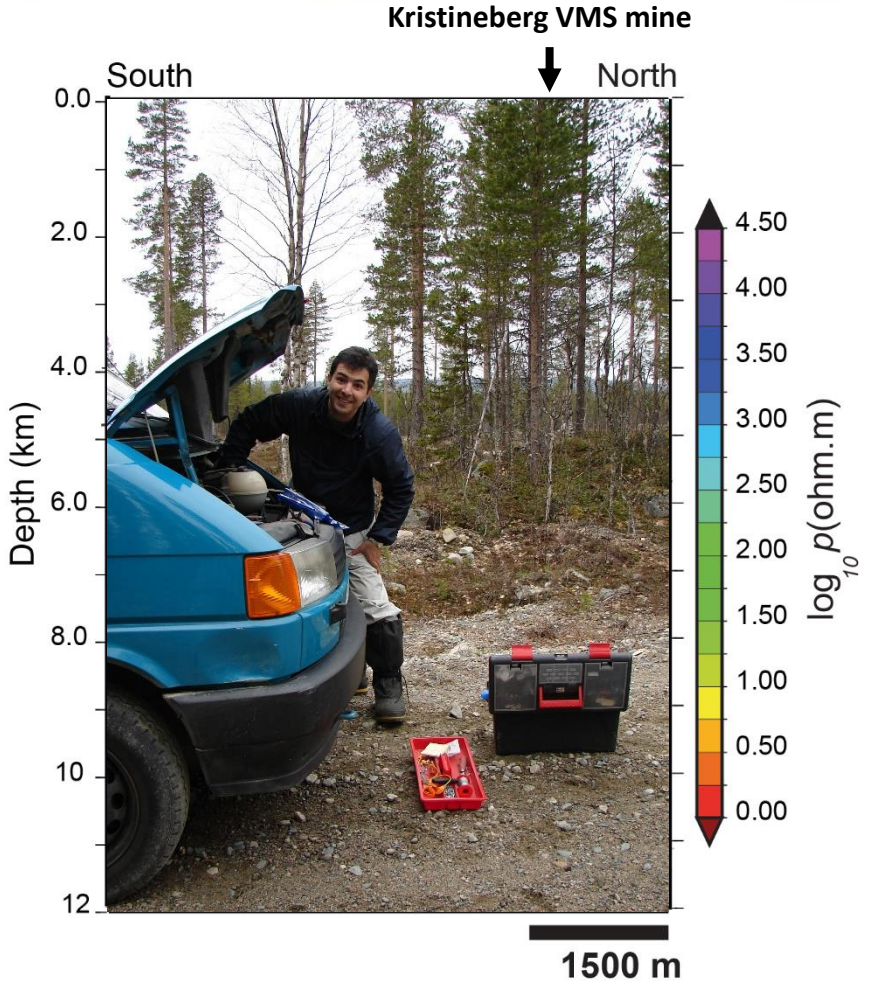
MT & Seismics





Malehmir et al. (2006, Precam. Res.)
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Outline

- **Problem statement (needs for energy and minerals)**
  - **Smart Exploration in a nutshell**
- **Smart Exploration**
  - **Legacy data (Ludvika & Gerolekas)**
  - **Prototypes and validation studies (Neves-Corvo/Ludvika)**
  - **Sparse data and their potential (Ludvika)**
  - **New EM modeling algorithms**

Summary!

Getty Images

Deloitte

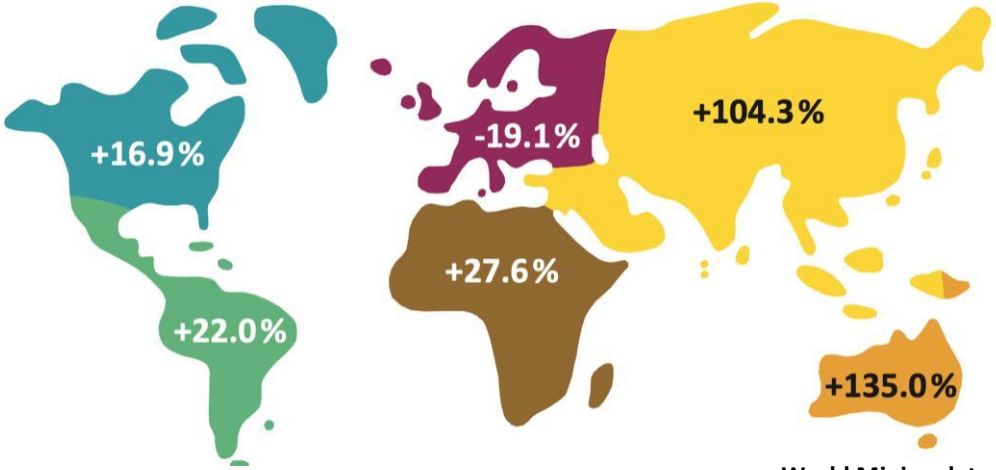
We need fresh raw materials!

We cannot afford just hammering ourselves on social and public acceptance with bad examples:

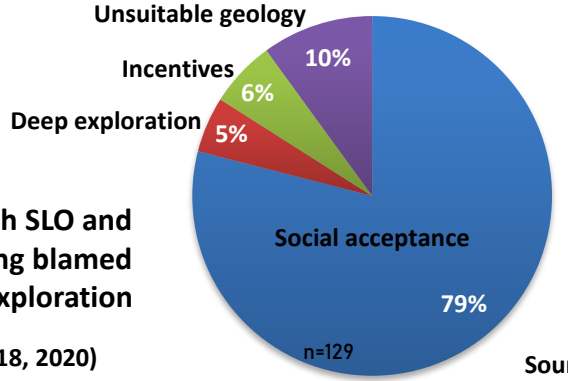
→ Better to learn, improve and showcase the way it should be, combining both technical-ethical disciplines (not "**wait-and-see**")!

→ Minerals for a smooth transition towards decarbonization and to support green techs

Declining production rates since 2000 only in Europe – Δ 2000 / 2018



World Mining data (2019)



Source: Smart Exploration

It is remarkable how much SLO and unsuitable geology are being blamed for unsuccessful exploration

Source: www.mining.com (August 18, 2020)

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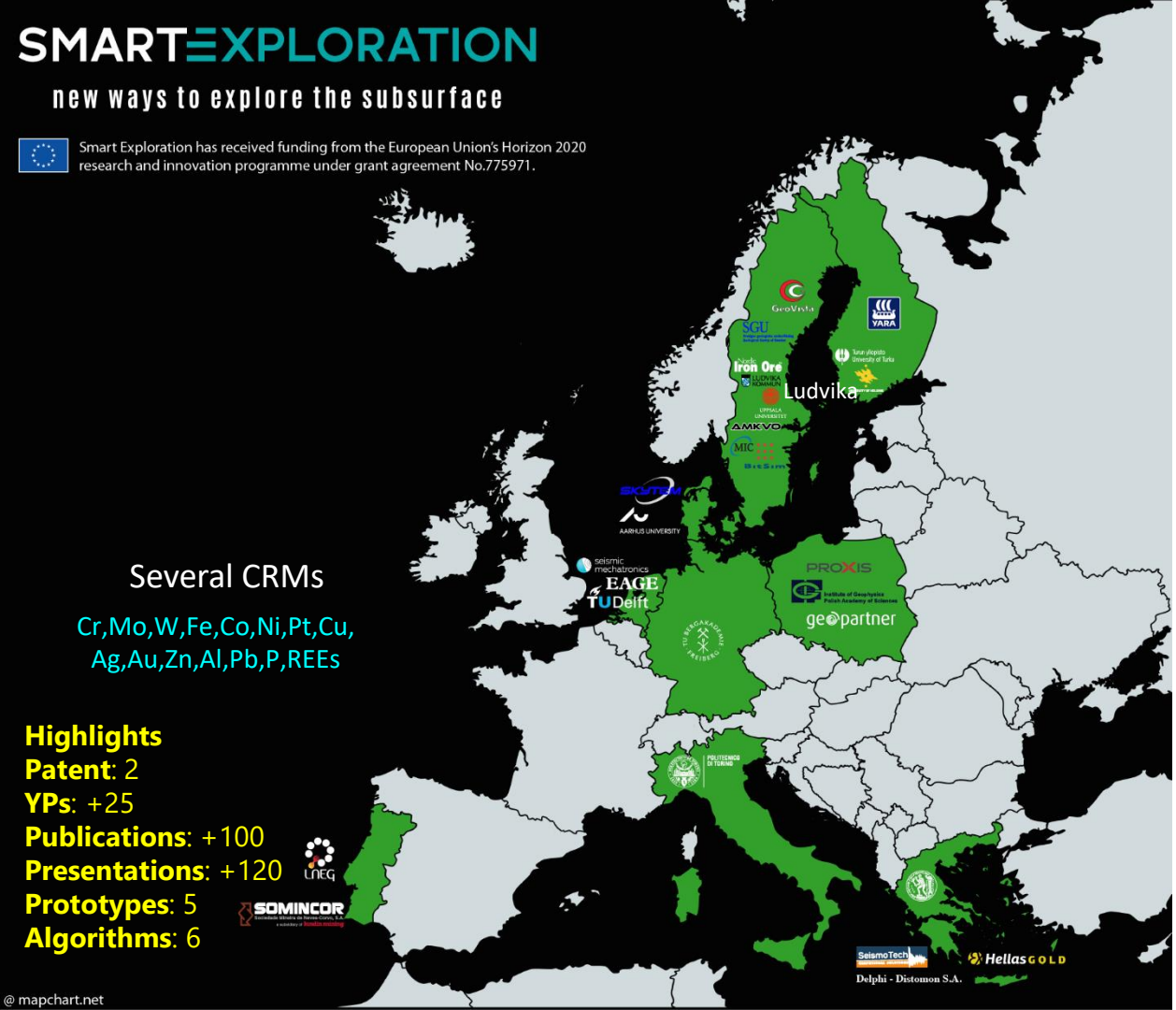
new ways to explore the subsurface

Smart Exploration has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.775971.



Several CRMs

Cr,Mo,W,Fe,Co,Ni,Pt,Cu, Ag,Au,Zn,Al,Pb,P,REEs

Highlights
Patent: 2
YPs: +25
Publications: +100
Presentations: +120
Prototypes: 5
Algorithms: 6

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new ways to explore the subsurface

Facts:

① 27 partners, 9 European countries (11 R&D, 11 SMEs and 5 stakeholders)

② 36 months project (Dec. 2017-Dec. 2020)

③ Six validation sites

④ Covering a wide range of commodities and exploration fields important for Europe

⑤ Research-Innovation action:

- **Primarily geophysical methods and instruments for deep targeting**
- **Focus on innovation, new markets and solutions addressing exploration issues (of CRMs) in Europe but also globally**

Target TRL: 5-6

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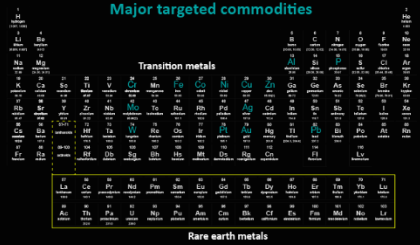

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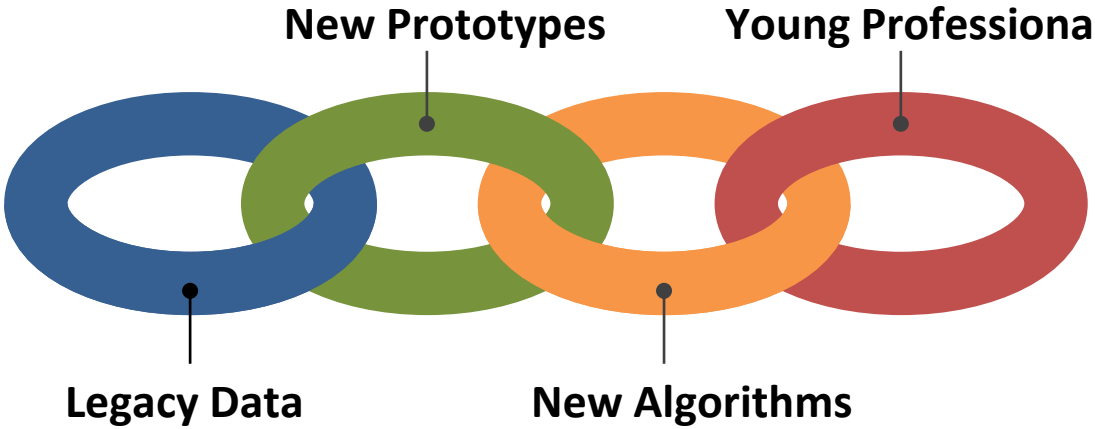
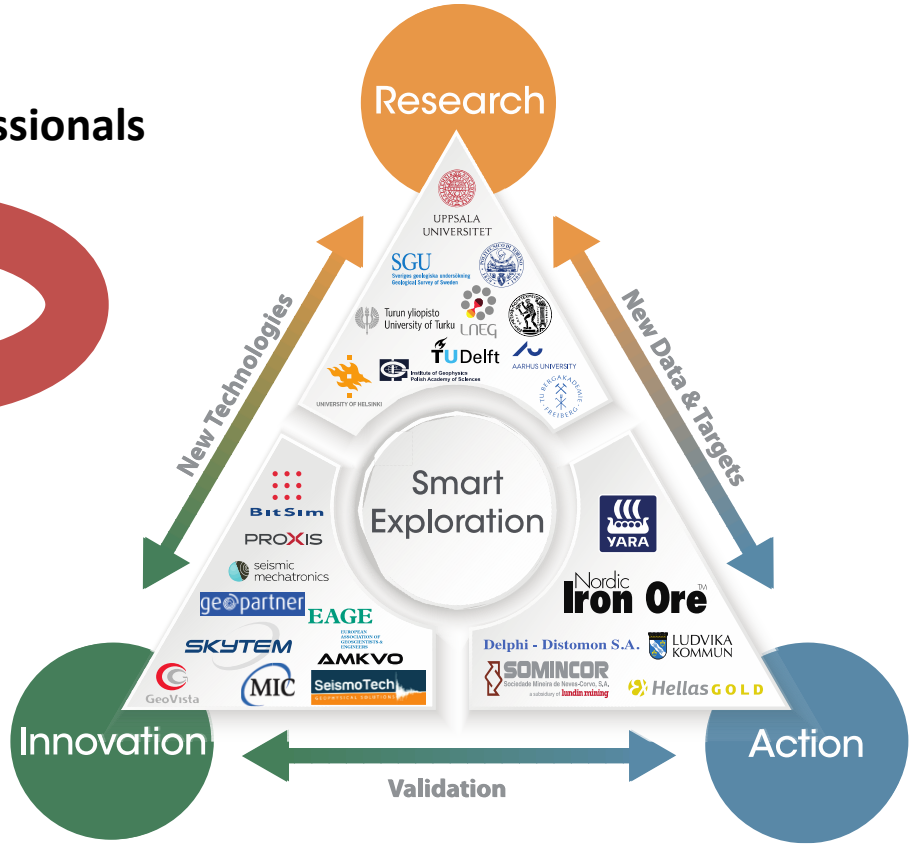
Smart Exploration Cornerstones





Connecting the dots …

Research-Innovation and Actions with a focus to also Young Professionals

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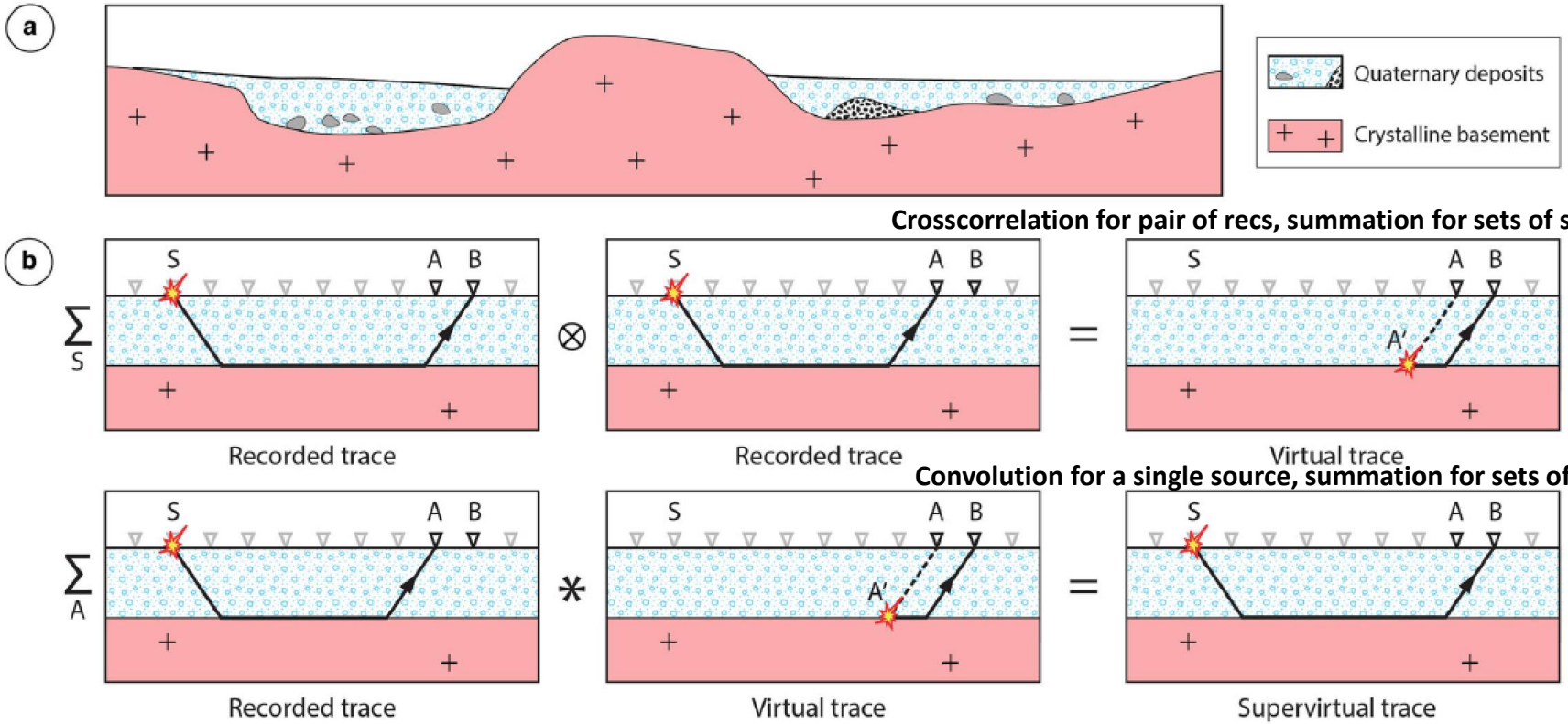
Noise and Seismic Interferometry



Place and Malehmir (2016, GJI)

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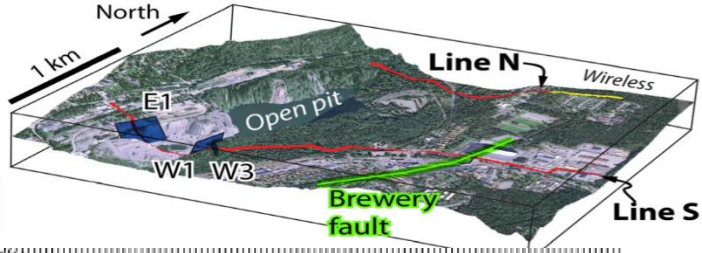
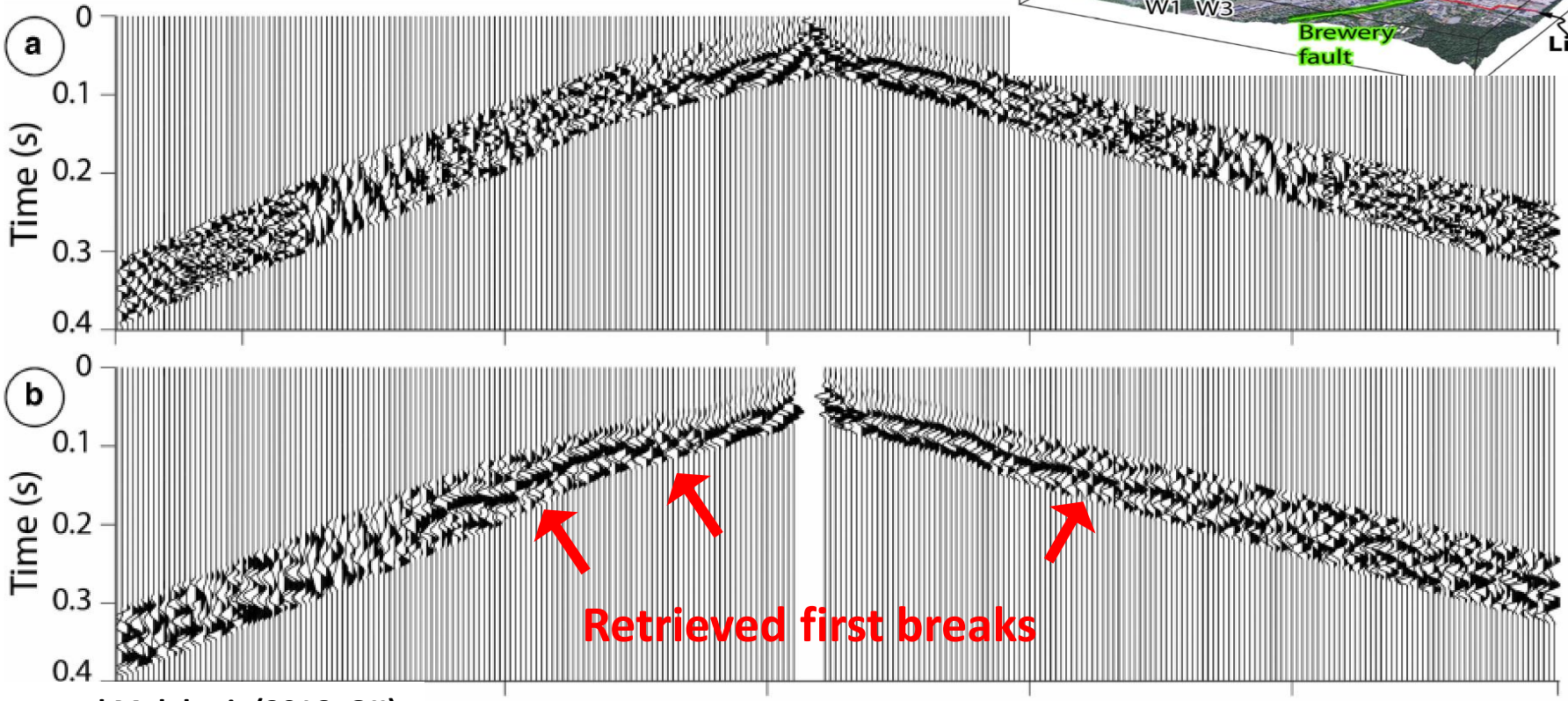
Data quality





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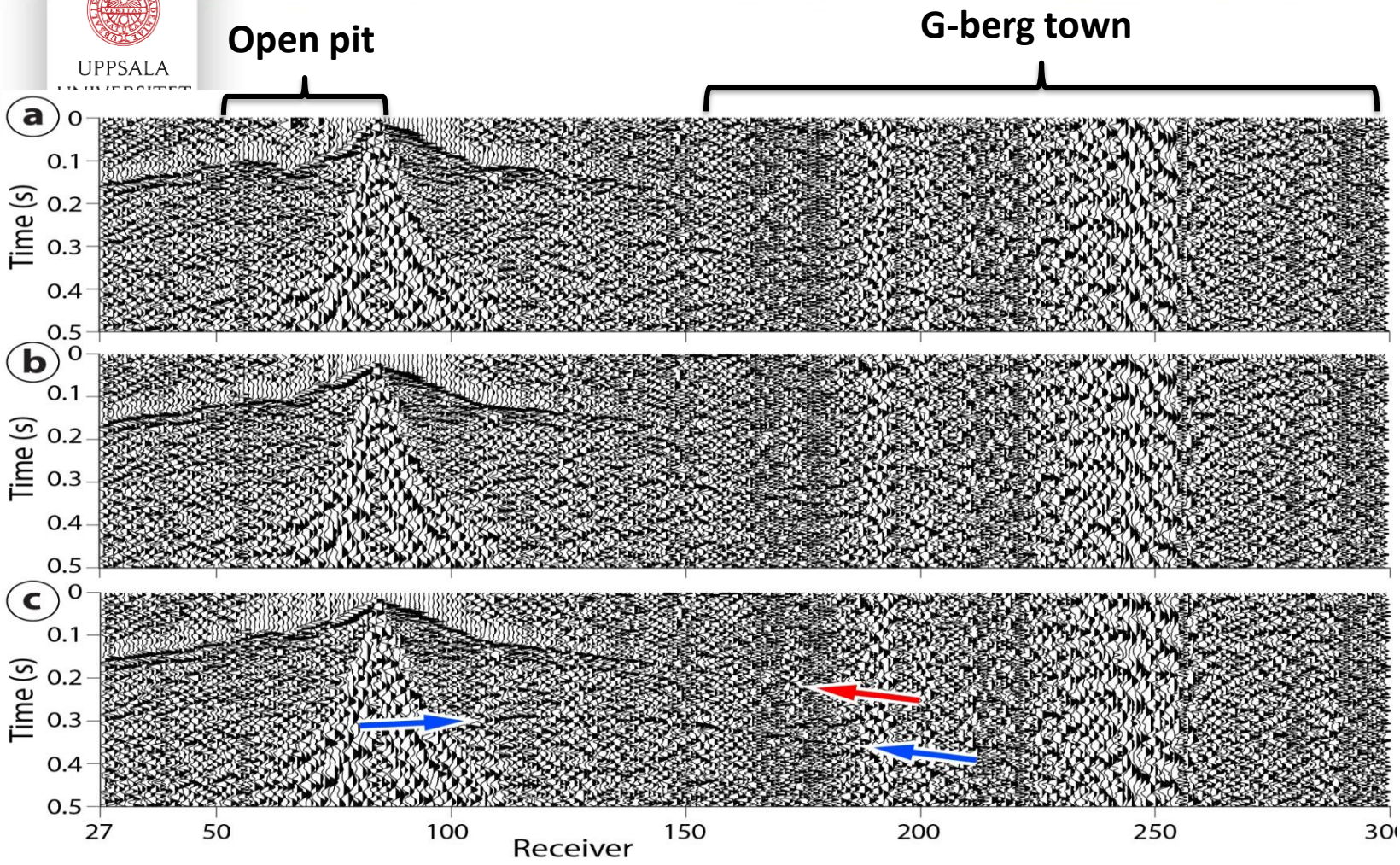
Open pit
G-berg town
a
b
c
Time (s)
0
0.1
0.2
0.3
0.4
0.5
27
50
100
150
200
250
Receiver
Raw shot
+ Refract. static
(FBs data)
+ Refract. static
(FBs virtual)

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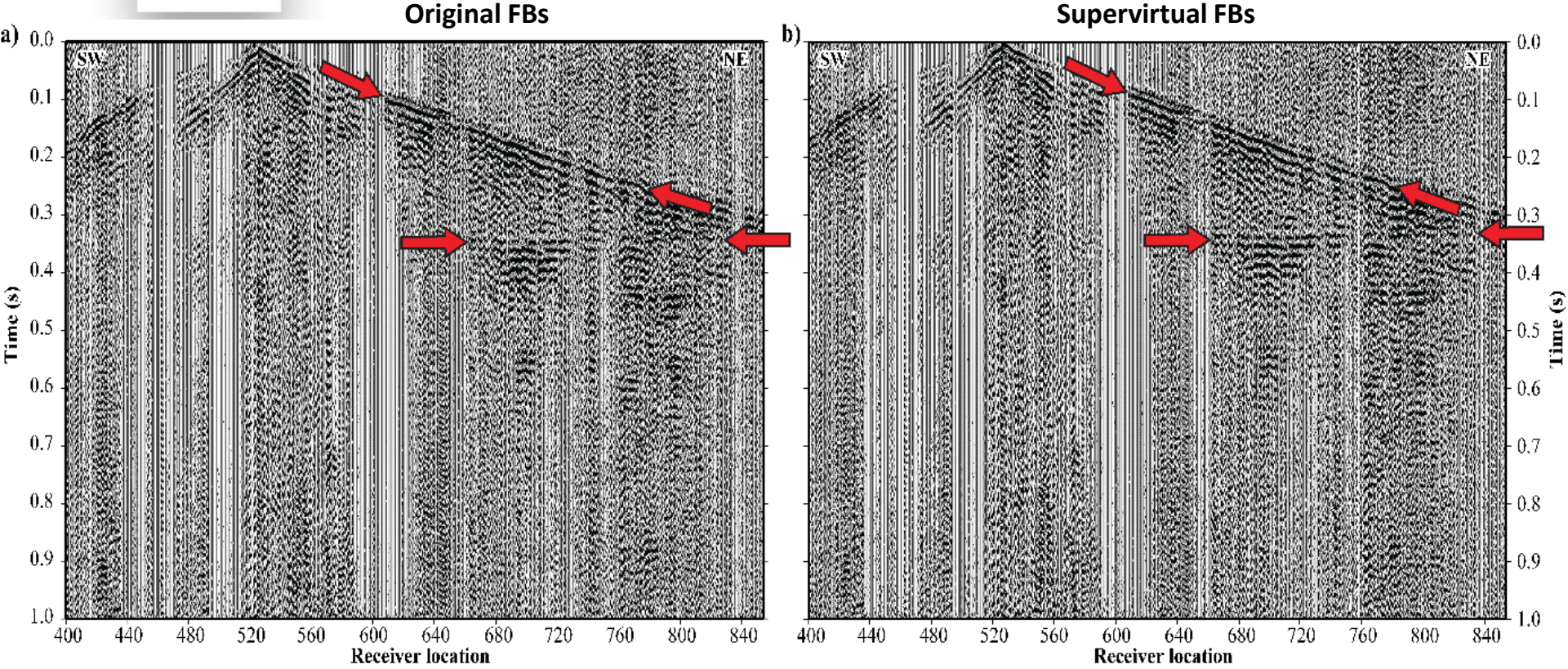
Static solution (via SVI)



Brodic et al. (2020)

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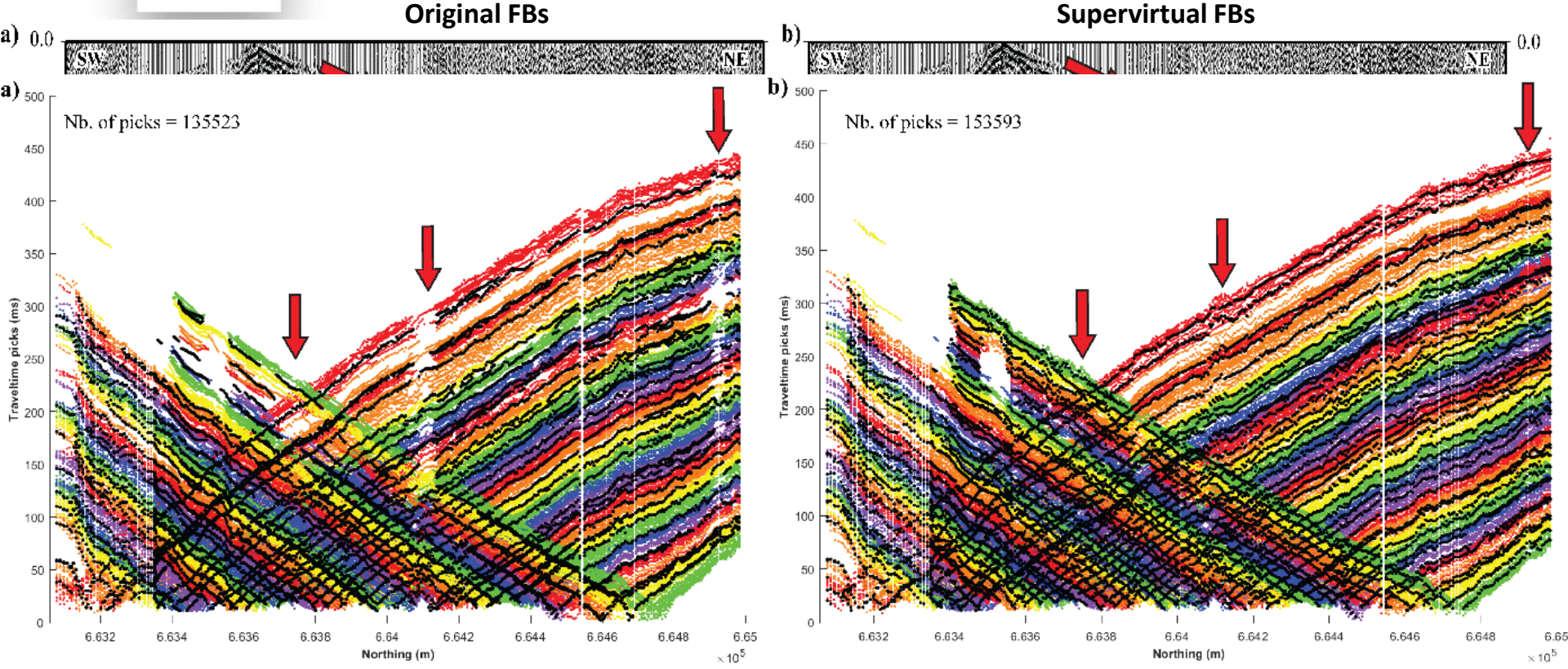
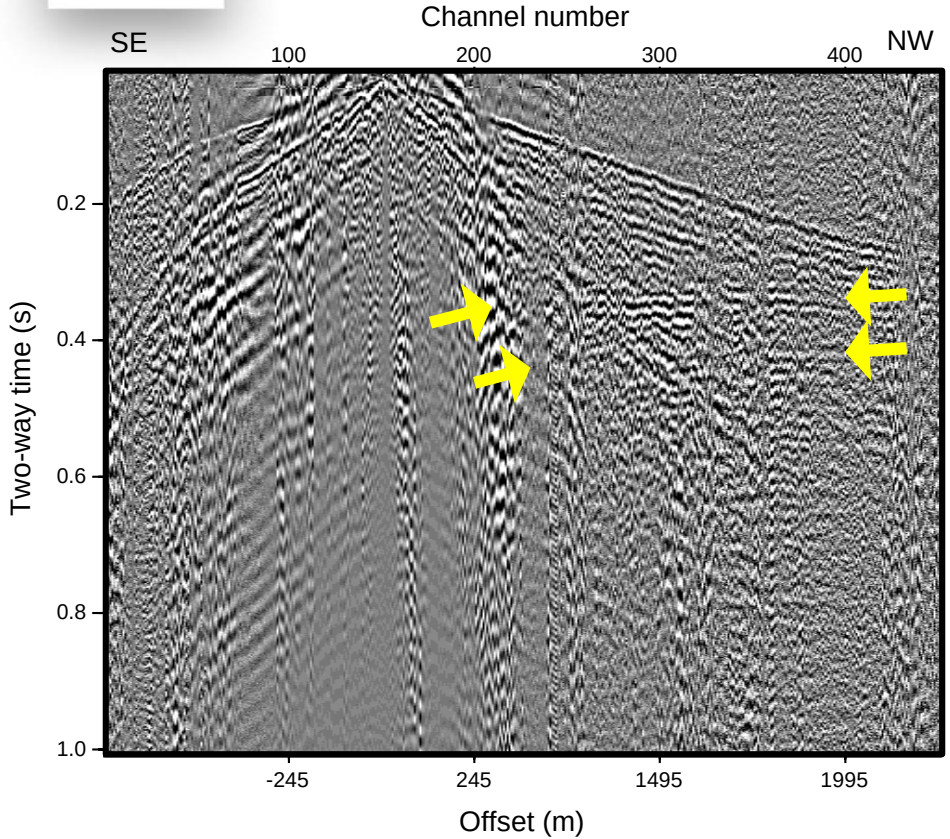
Static solution (via SVI)



Brodic et al. (2020)

Tackling surface-waves

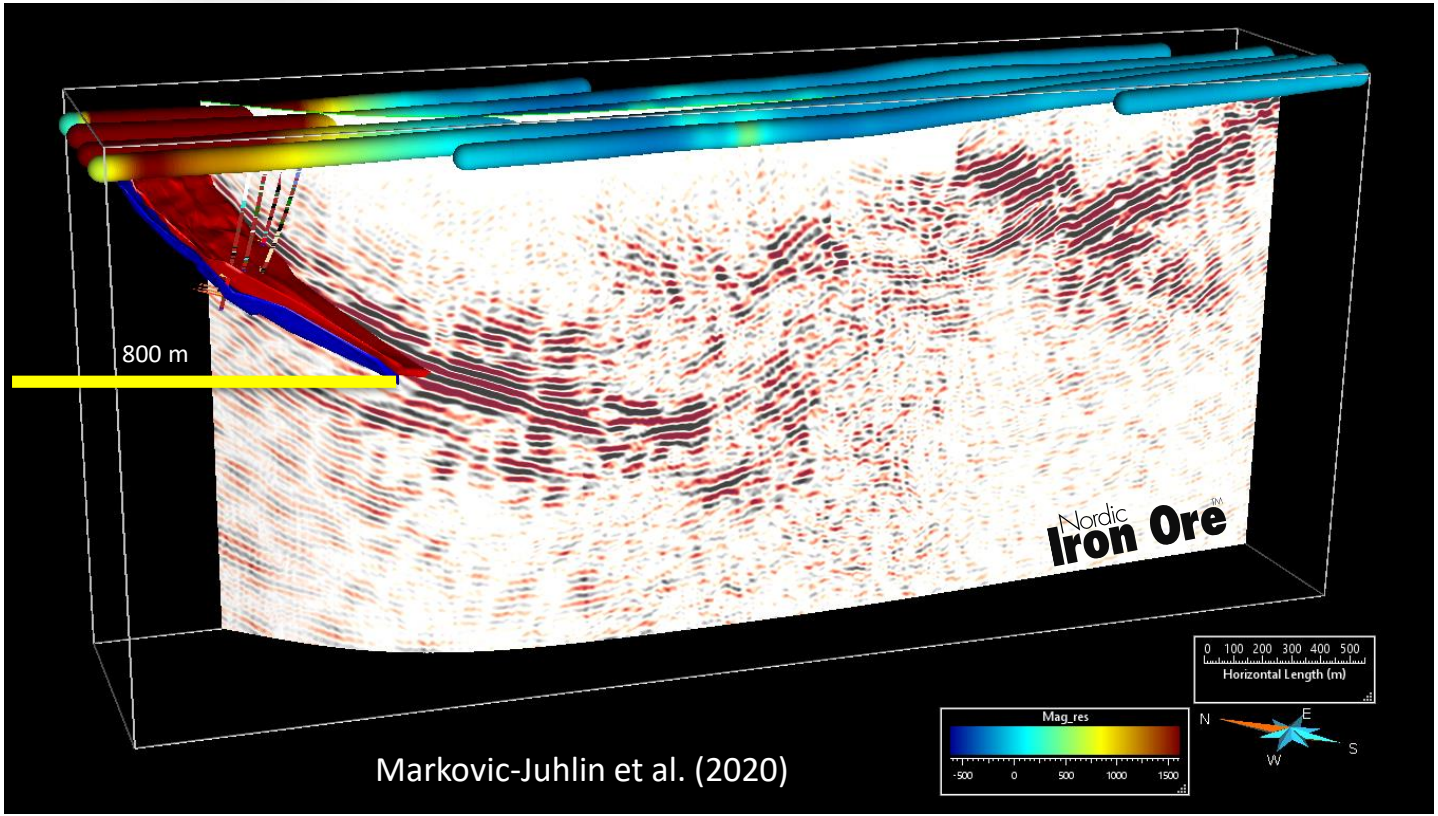


Seismic interferometry for:

- for extracting surface-waves and their attenuation
- retrieving First-Breaks (refraction statics)
- retrieving missing shots

Balestrini et al. (2020)

Potential resources-Ludvika (Sweden)



Markovic-Juhlin et al. (2020)

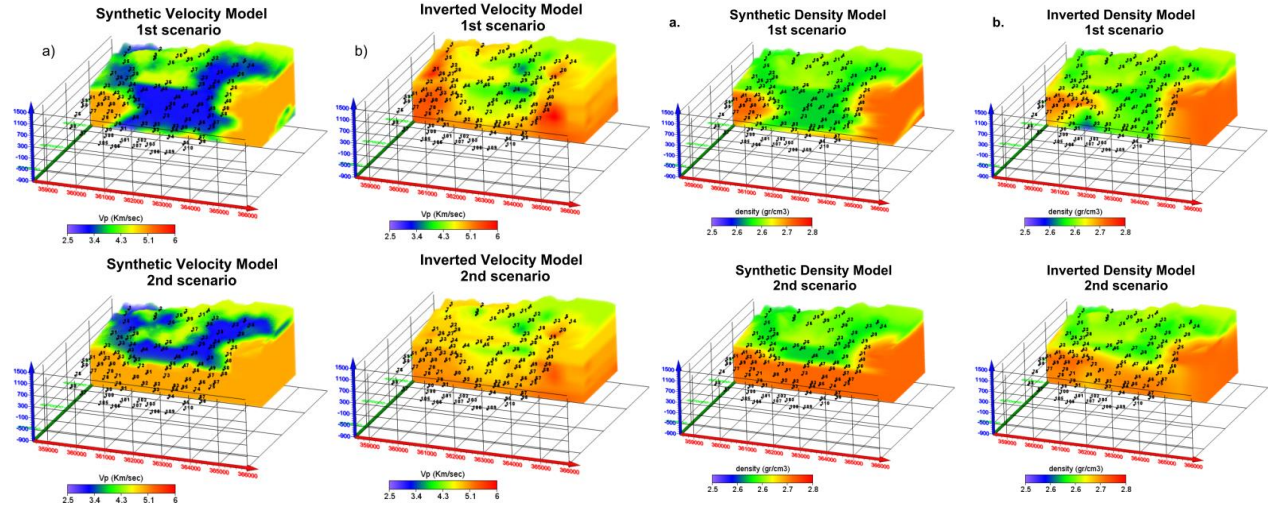
Potential resources:
- 300 m down-dip?
- Footwall exploration targets?
- Key geological features

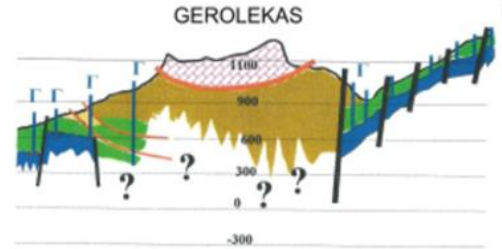
3D effects?

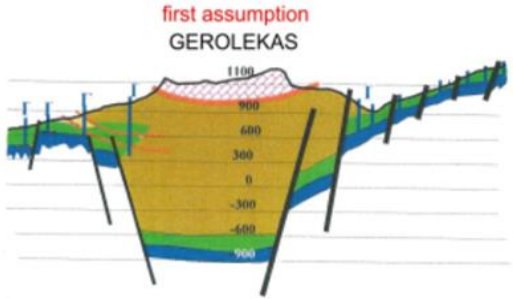
Scenario testing

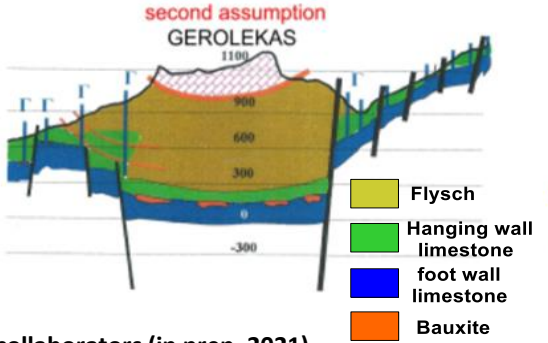
Where are the bauxite deposits?

- **Scenario1**: Down-faulted (even thrusted) and sit far below sea-level or eroded away
- **Scenario2**: Down-faulted and sit not far from sea-level



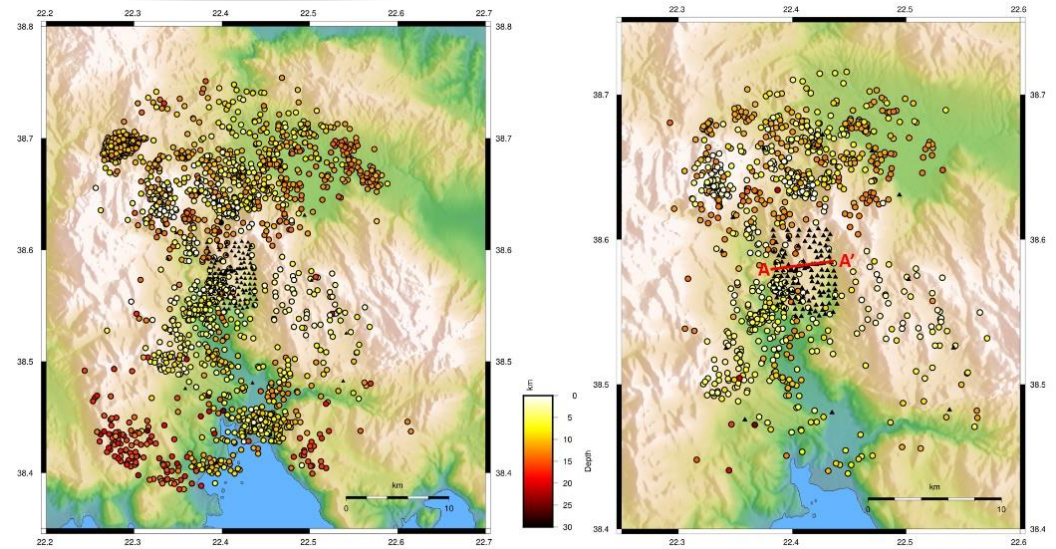


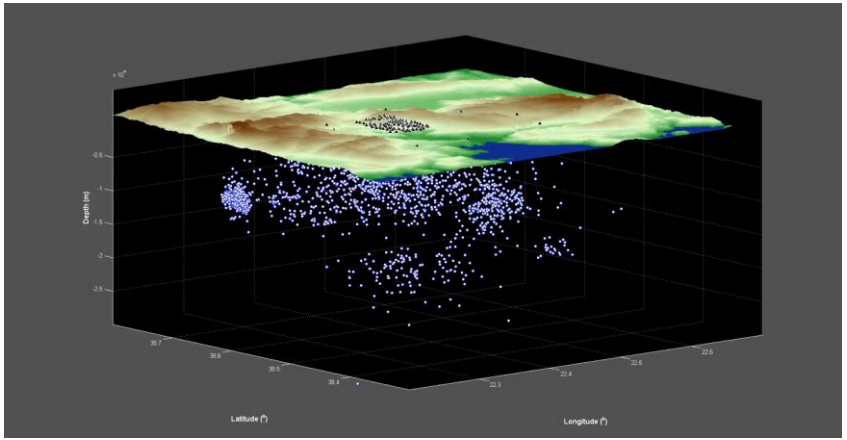




NTUA team and collaborators (in prep. 2021)

Micro-earthquakes



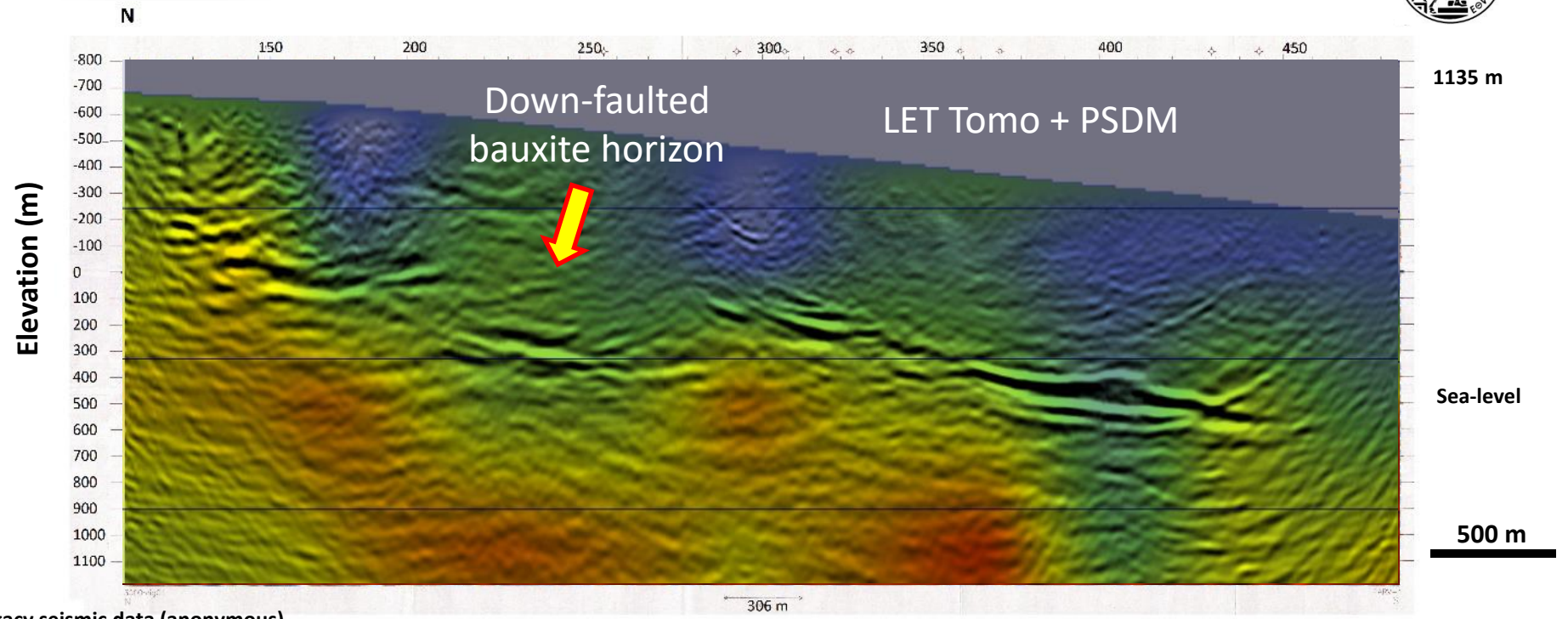


Polychronopoulou et al. (2020)

~3000 local events fulfilled the criteria to be used for Local Earthquake Tomography (**LET**)
Mmin: -1.5R, Mmax:3.0 R
954 local events fulfilled the criteria to be used for Body-Wave Seismic Interferometry

Gerolekas bauxites-Greece

Legacy data: revealing the wining scenario!



Legacy seismic data (anonymous)

Reprocessed work by the Gerolekas task partners (IGPAS et al. (in prep.))

Institute of Geophysics
Polish Academy of Sciences

Delphi - Distomon S.A.

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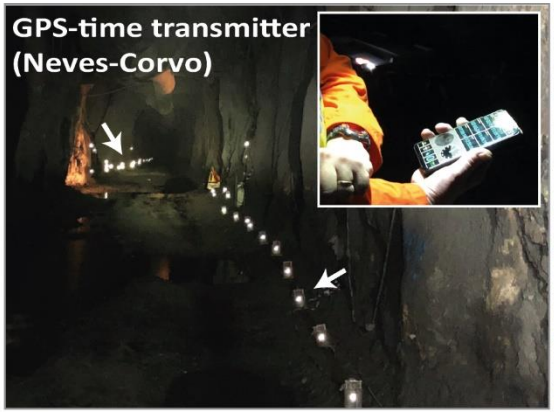
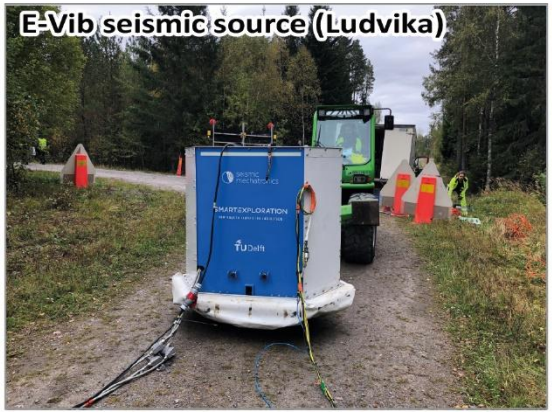
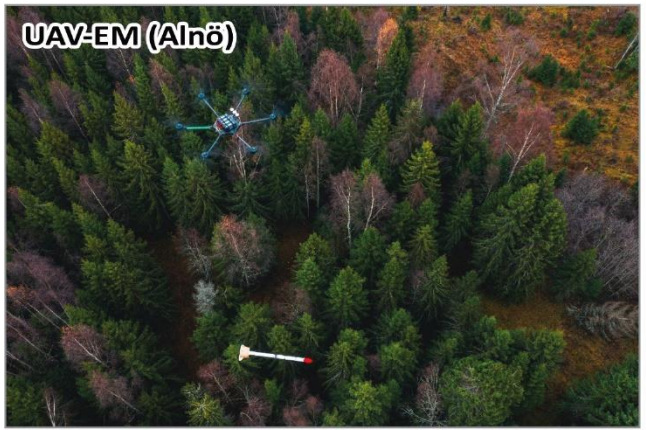
Prototypes

Five **Smart Prototypes** have been developed for various exploration challenges!







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seismic mechatronics

SGU
Sveriges geologiska undersökning
Geological Survey of Sweden

BitSim

SKYTEM

AMKVO

MIC

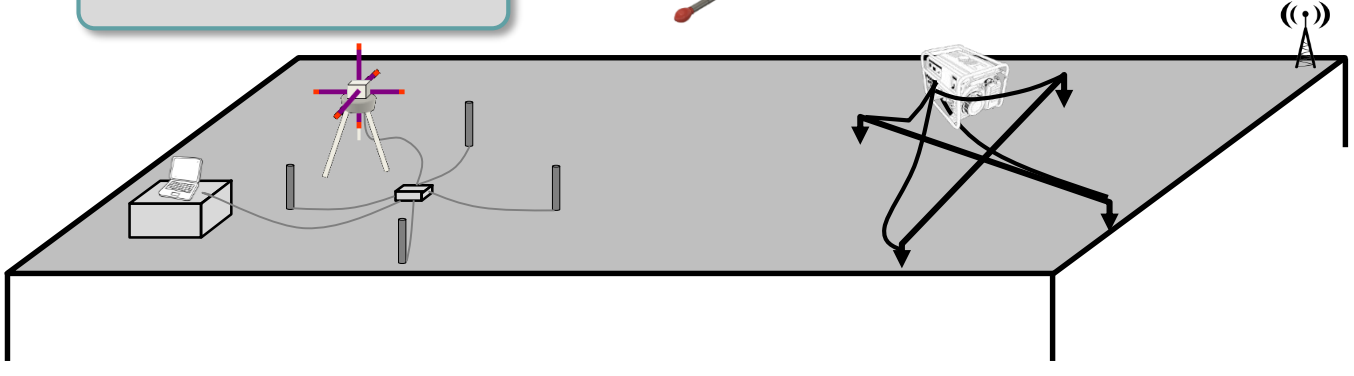
UAV-Ground system: 2 in 1!

- UAV platform for magnetic (total field), and broadband electromagnetic (EM) (1 – 350 kHz) for both Radio MagnetoTelluric (RMT) and Controlled-Source MagnetoTelluric (CSMT) surveys
- Ground-based broadband EM (10 Hz – 350 kHz) system for both RMT and CSMT surveys
- Rapid on-site data visualization and simple modeling to guide detailed ground surveys

2 airborne systems:
- Magnetic (MAG)
- Electromagnetic (EM)

1 ground-based system:
- EM

Extended VLF band (1-350 kHz)



SGU
Sveriges geologiska undersökning
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AMKVO

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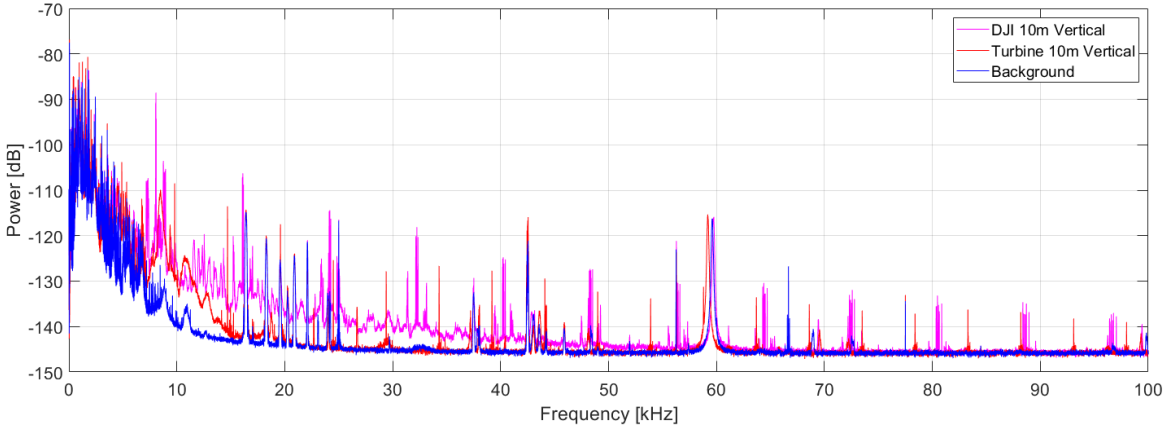
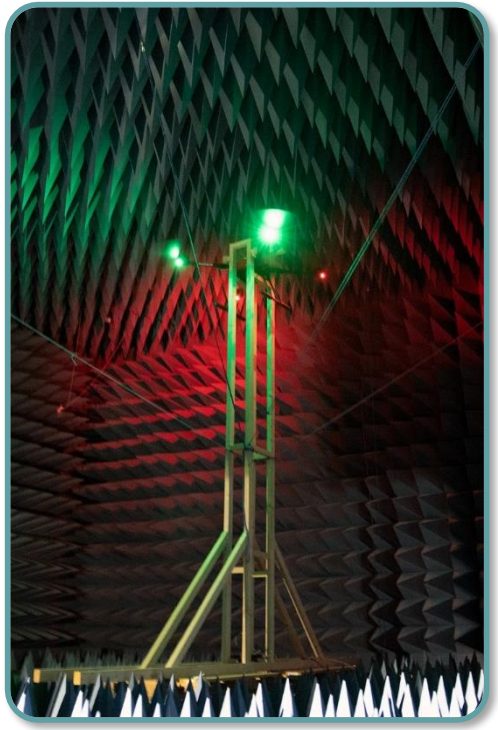
Noise tests



Verification in EM Shielded Room



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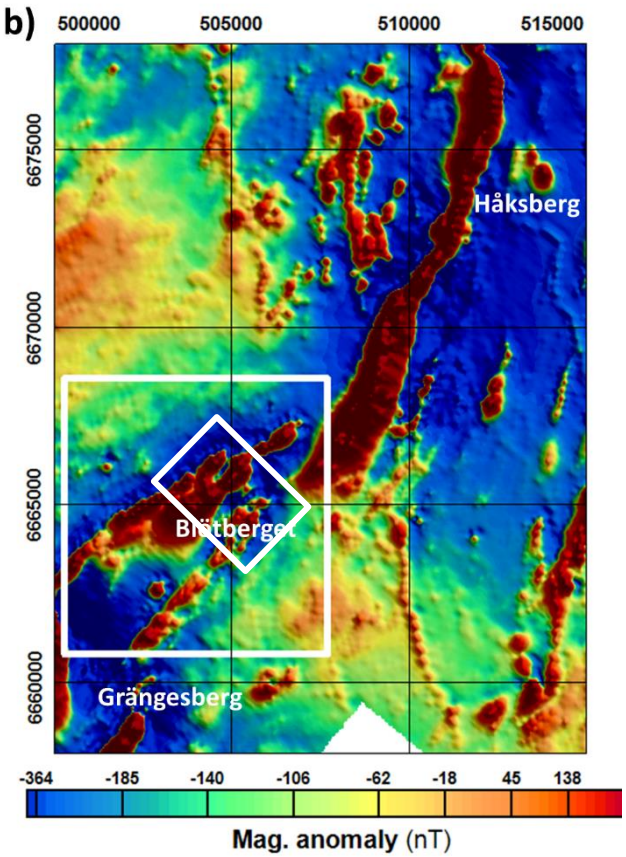
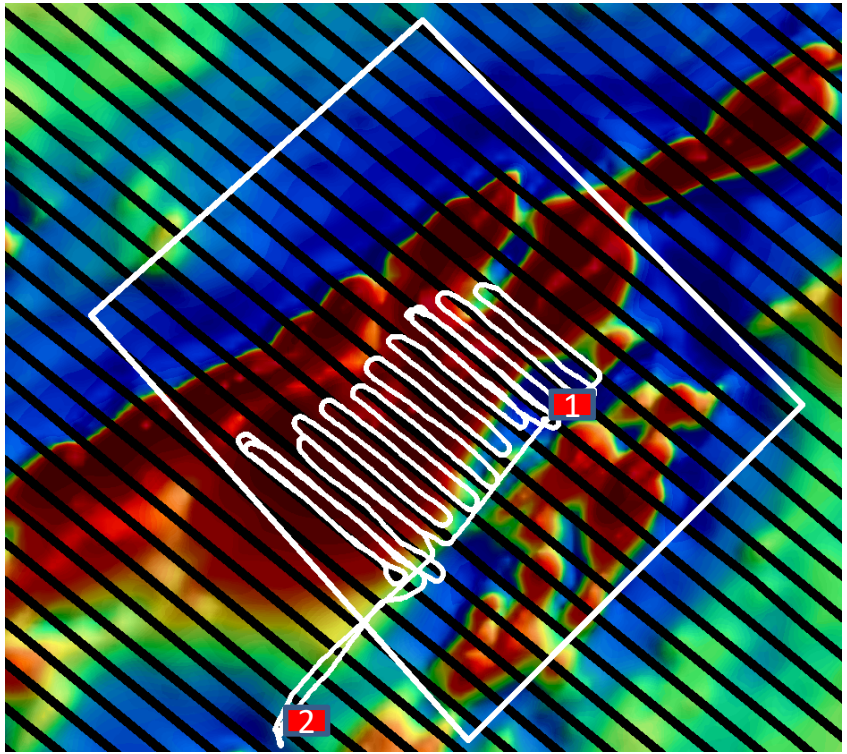
Validation surveys

Day 1 (UAV measurements: Two landing locations)





Bastani et al. (2020, First Break)

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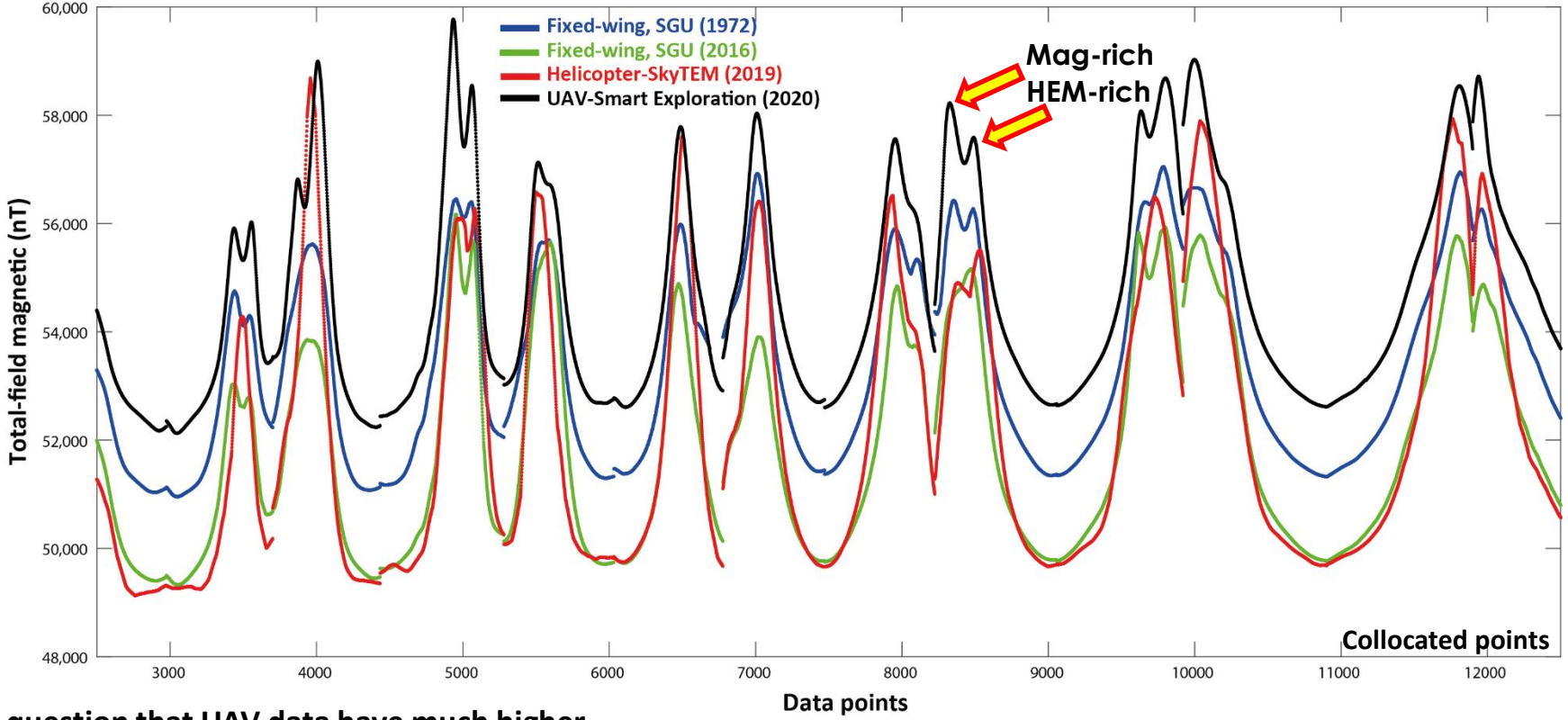
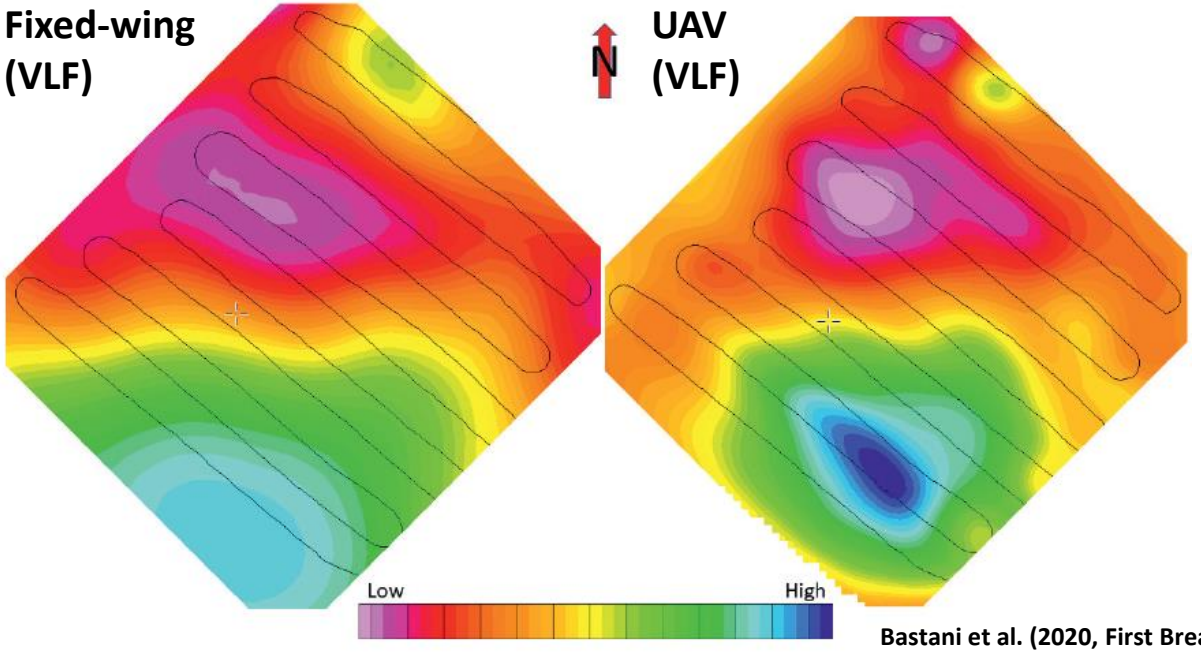
UAV-MAG comparisons

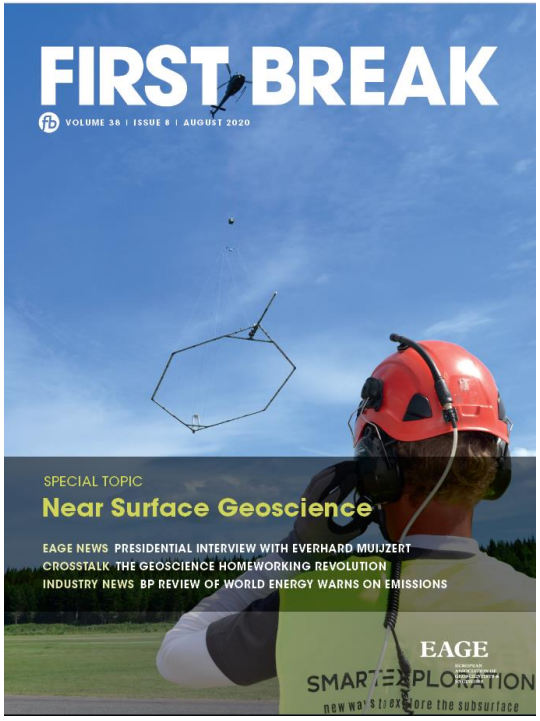


No question that UAV data have much higher sampling/spatial resolution

UAV-EM survey (Ludvika)



Bastani et al. (2020, First Break)

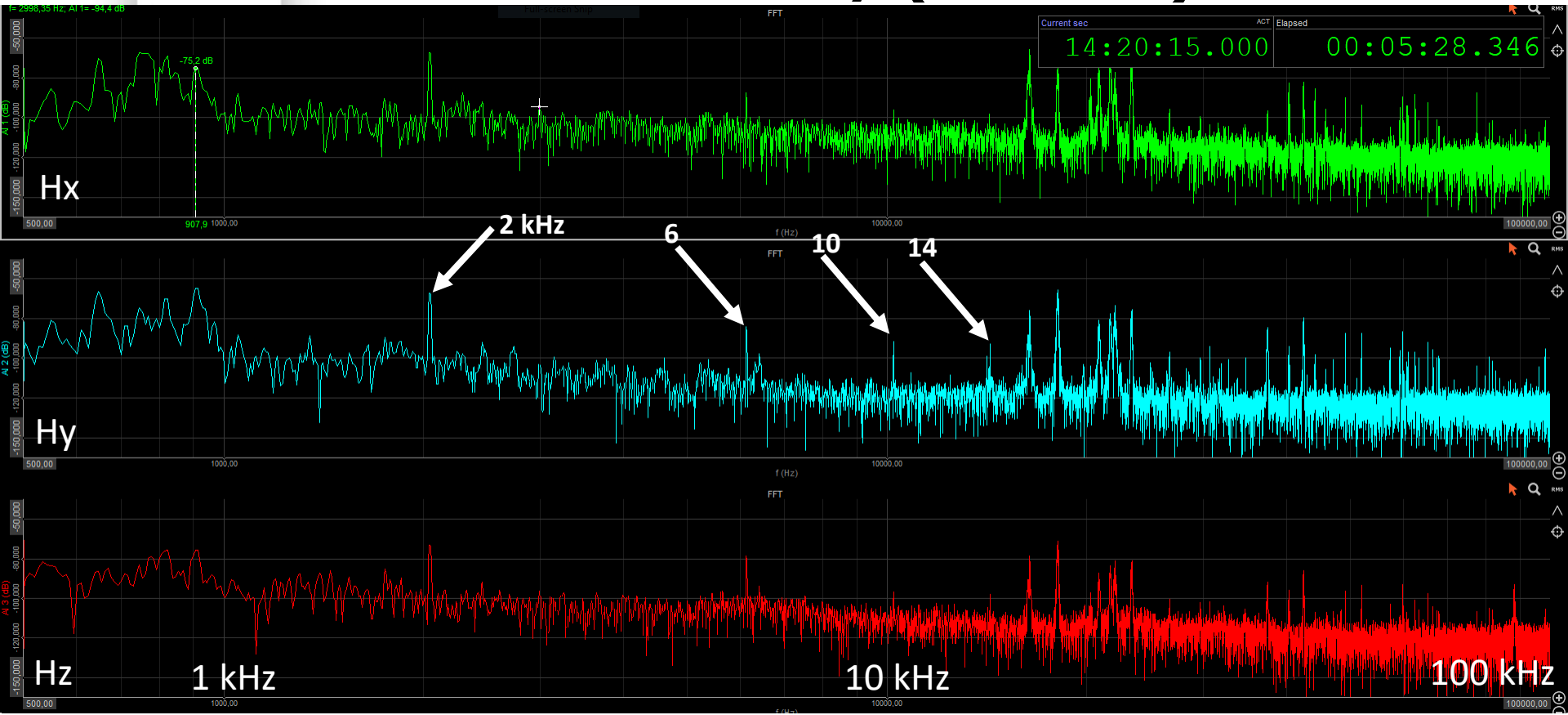


Preliminary results. **Apparent resistivity** map from SGU's fixed-wing VLF measurements carried out in 2016 with a flight-line separation of 200 m (left). Apparent resistivity map from the UAV measurements with a flight-line separation of 100 m (right). UAV flight-lines are shown in both figures for reference.

Unmanned Aerial Vehicles (UAV) and ground-based electromagnetic (EM) systems

Mehrdad Bastani (Geological Survey of Sweden), Henrik Johansson (Geological Survey of Sweden), Alex Paulusson (AMKVO AB), Kent Paulusson (AMKVO AB), Lars Dynesius (Uppsala University)

UAV-CSMT survey (Ludvika)



Bastani et al. (2021, in prep.)

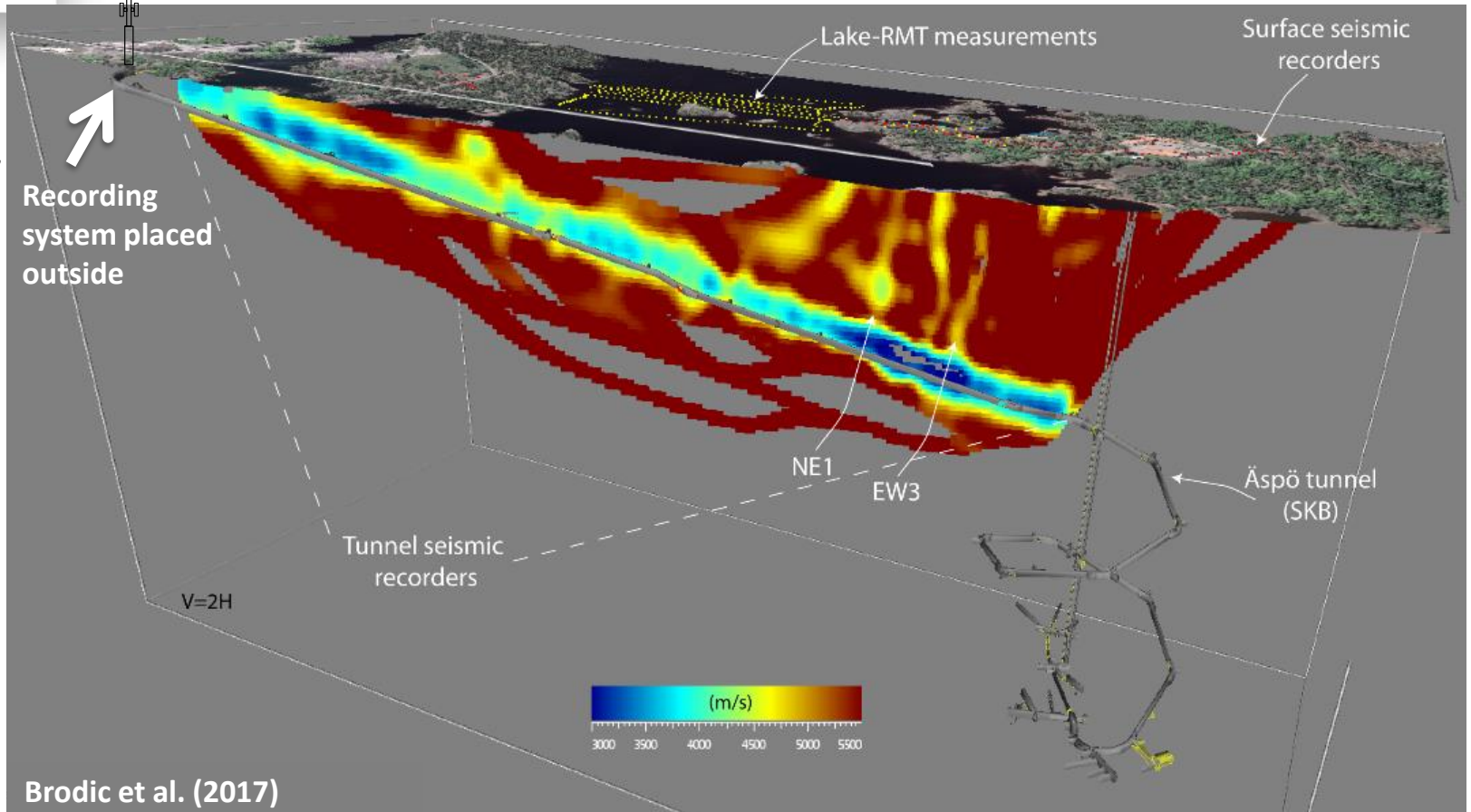
The base frequencies and their odd harmonices could be clearly detected as a distance of 3-4 km

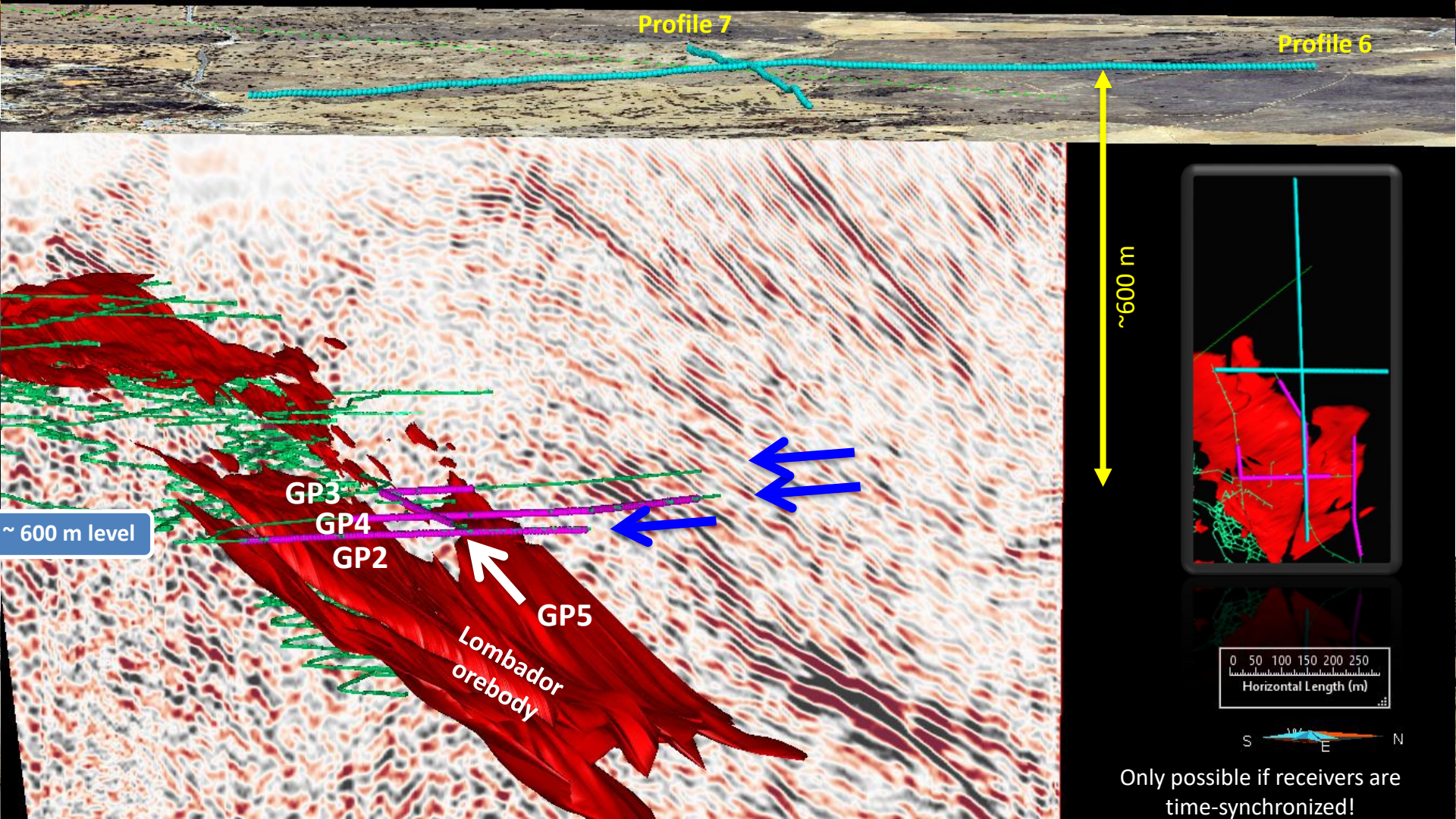
Tunnel seismics: Äspö (Sweden)

Realized that if we could perform synchronized survey, we would overcome several challenges and introduce new opportunities!

We needed a GPS-time transmitter for array sensors to make it practical!

Malehmir et al. (Swedish Patent 2020, SE 1851332)




Profile 7
Profile 6
~600 m
~ 600 m level
GP3
GP4
GP2
GP5
Lombador orebody
0 50 100 150 200 250
Horizontal Length (m)
S
E
N
Only possible if receivers are time-synchronized!

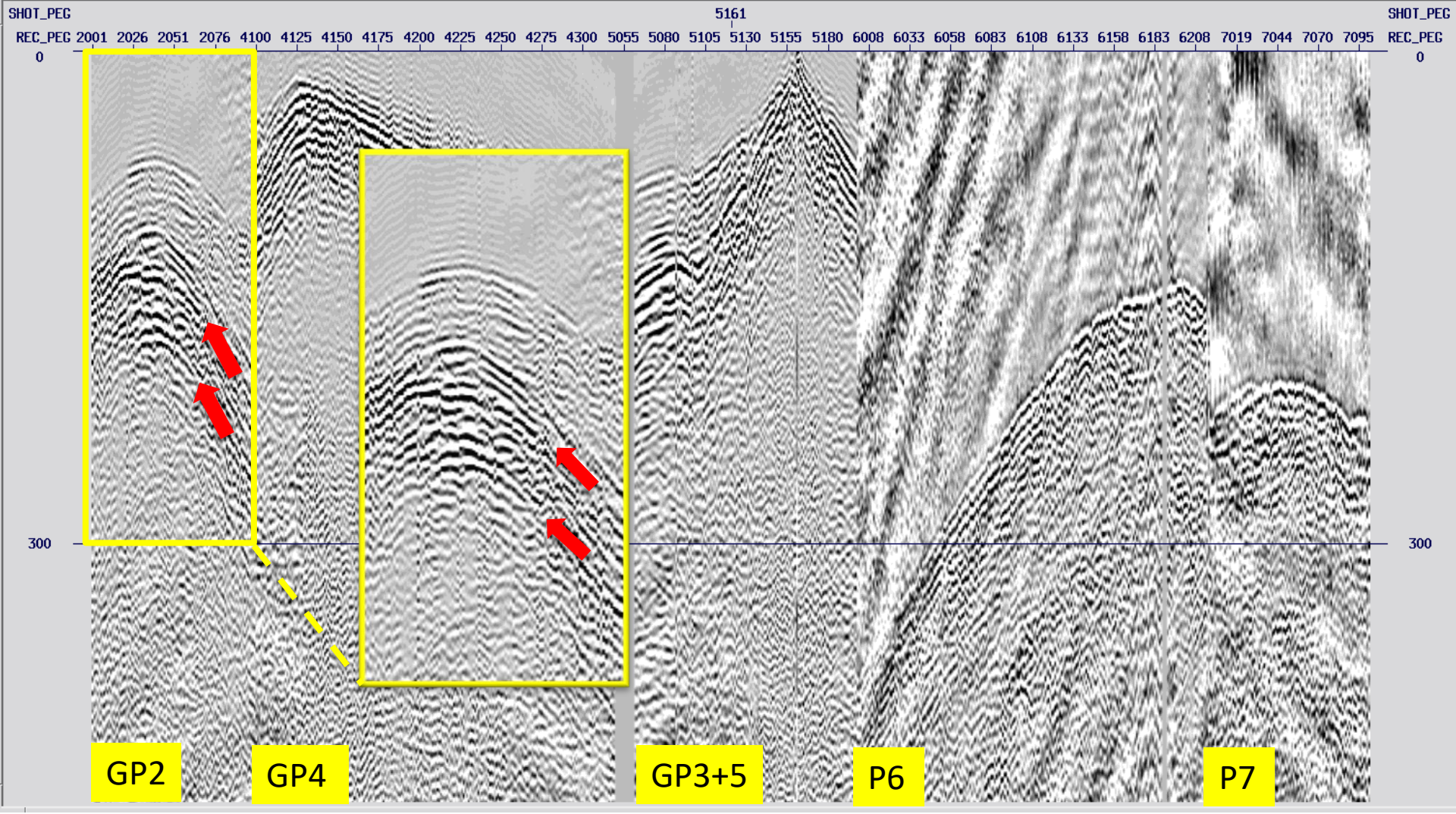
Exploration of Deep Targets: Tunnel-surface seismic, Neves-Corvo

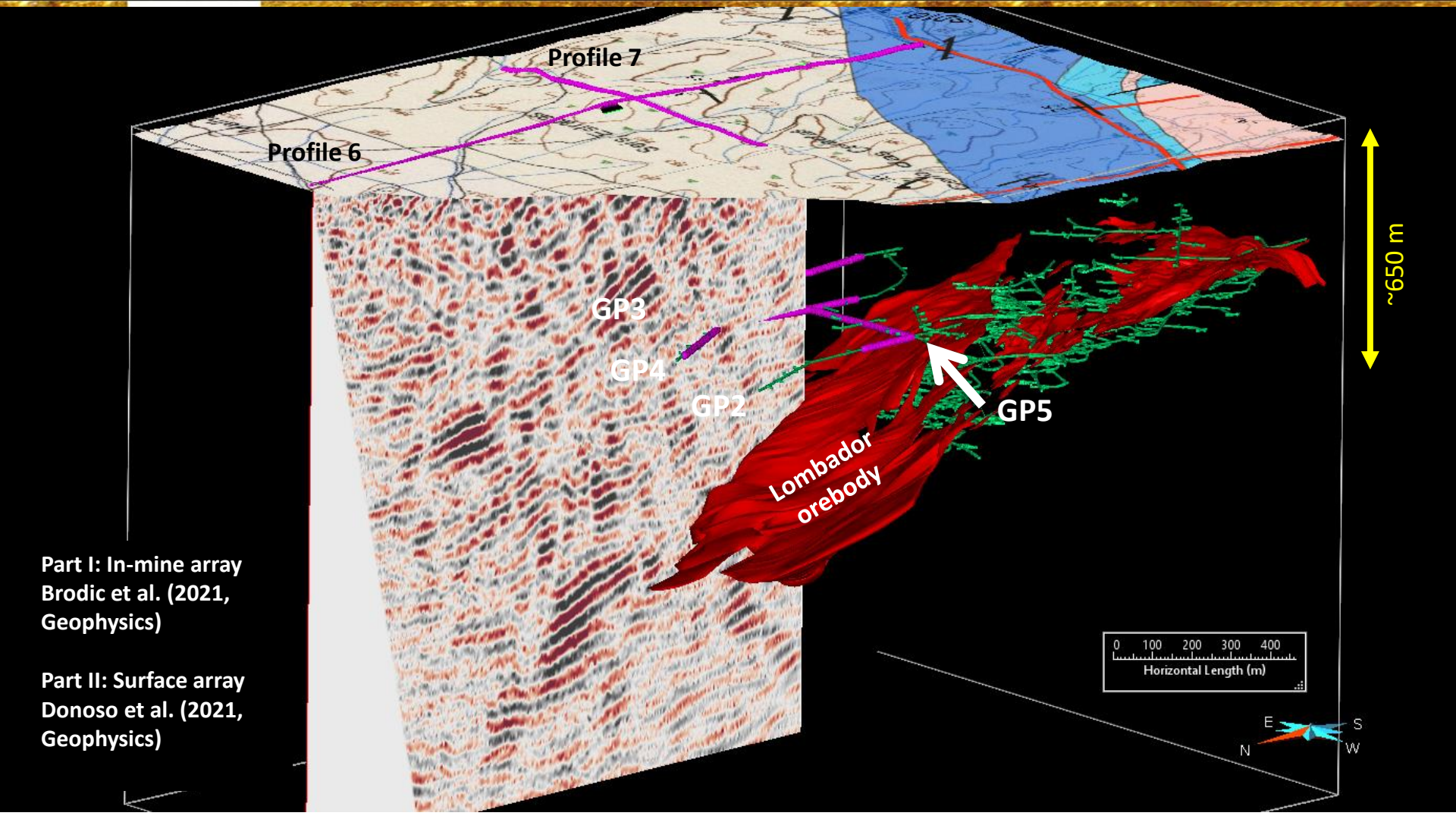
Synchronized nodal seismic recorder

E-vib (seismic source)

Synchronized cabled seismic recorder

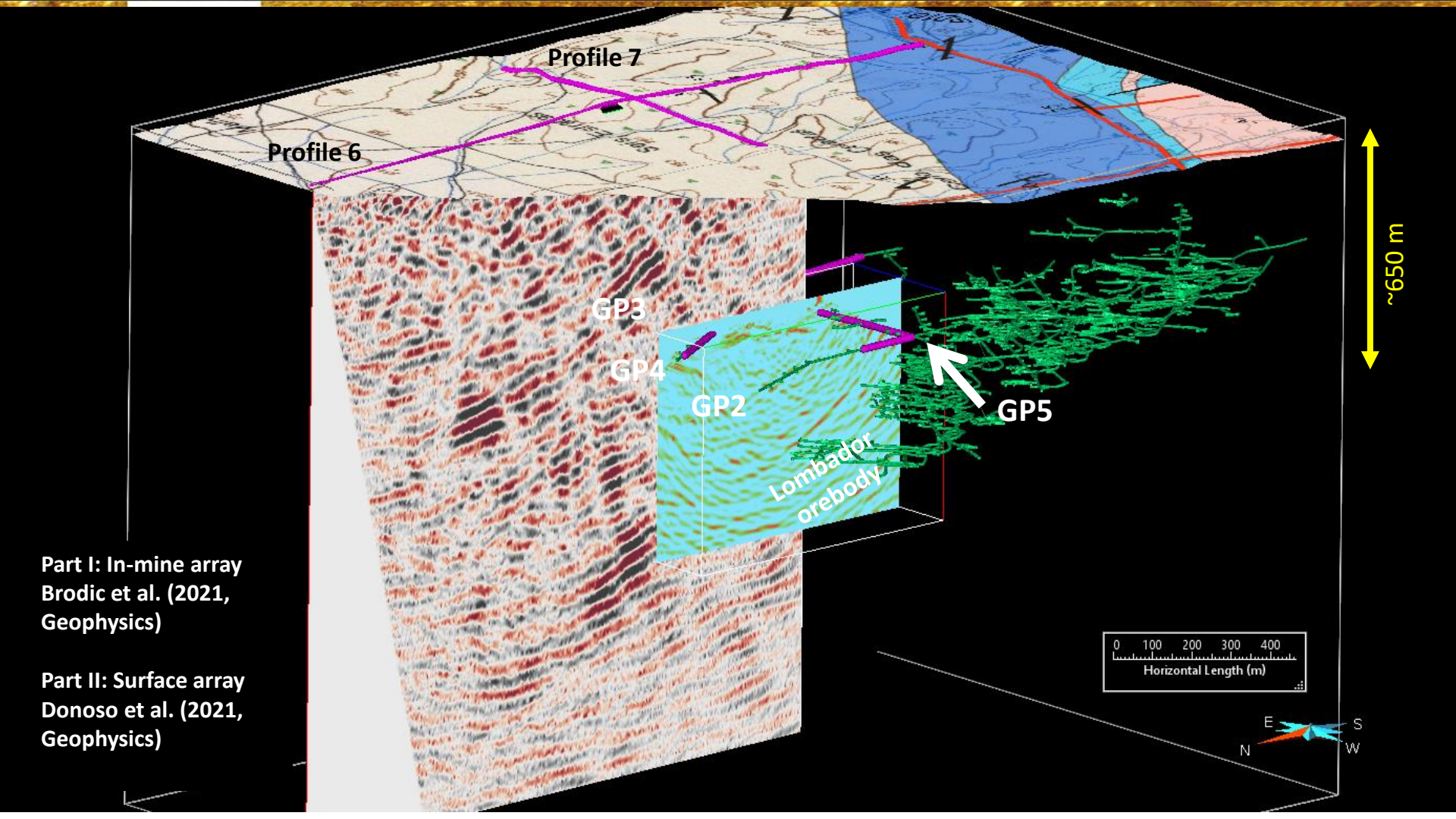
GP4: Exploration tunnel (Lombador deposit)


SHOT_PEG
5161
SHOT_PEG
REC_PEG 2001 2026 2051 2076 4100 4125 4150 4175 4200 4225 4250 4275 4300 5055 5080 5105 5130 5155 5180 6008 6033 6058 6083 6108 6133 6158 6183 6208 7019 7044 7070 7095
REC_PEG
0
0
300
300
GP2
GP4
GP3+5
P6
P7



Part I: In-mine array
Brodic et al. (2021, Geophysics)

Part II: Surface array
Donoso et al. (2021, Geophysics)



Part I: In-mine array
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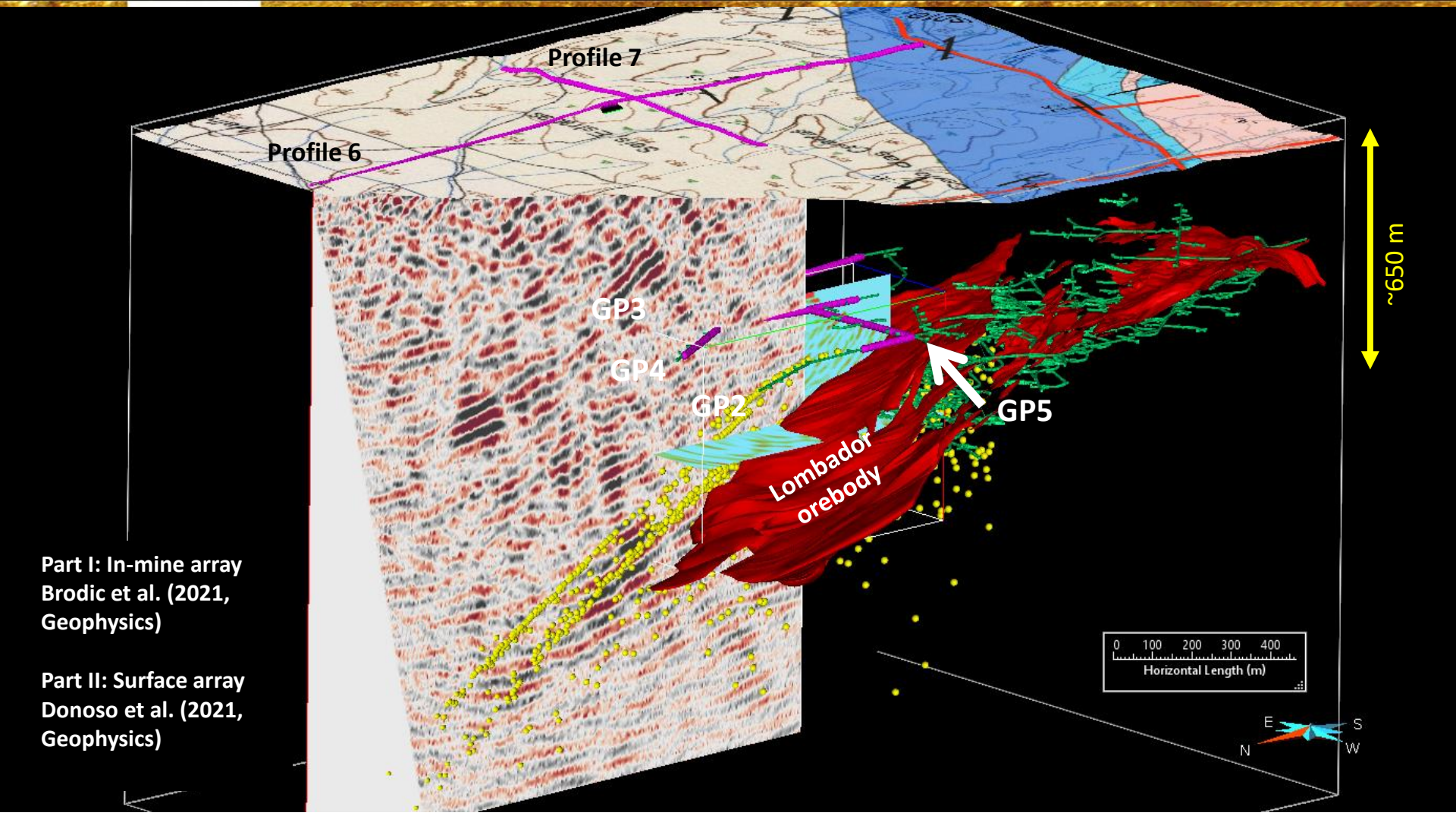
Part II: Surface array
Donoso et al. (2021, Geophysics)



Part I: In-mine array
Brodic et al. (2021, Geophysics)

Part II: Surface array
Donoso et al. (2021, Geophysics)

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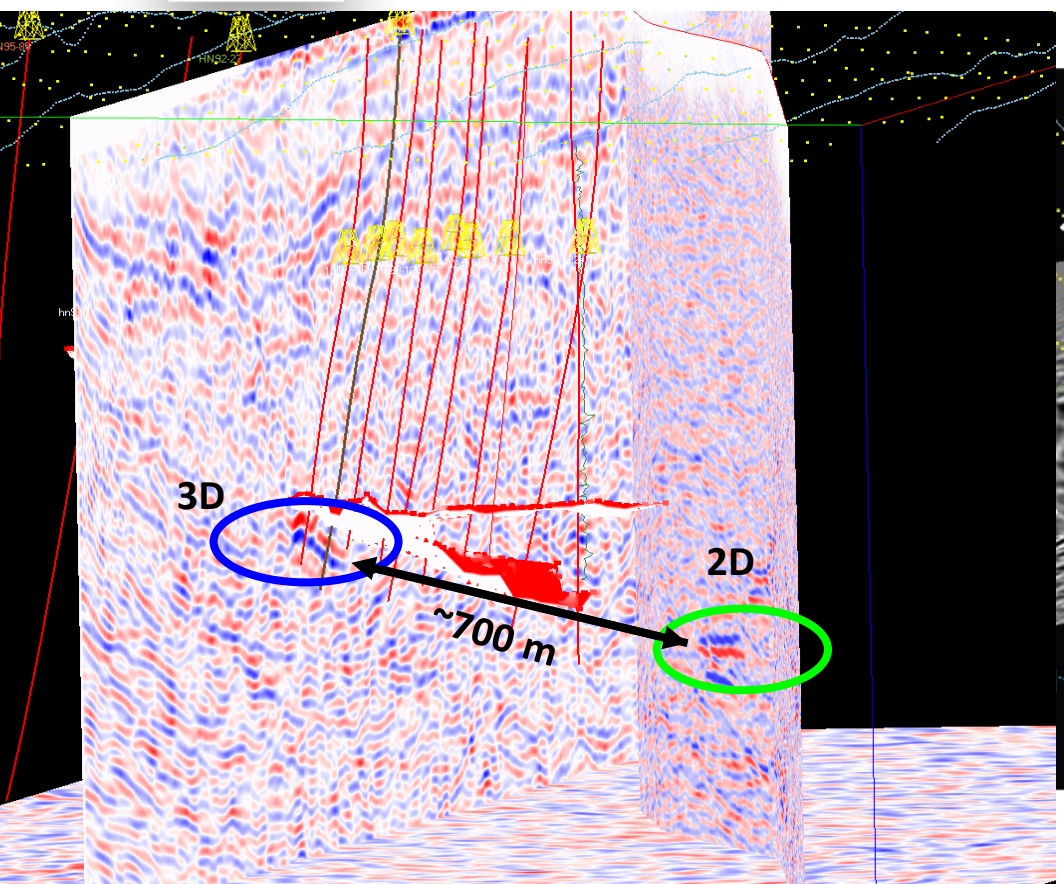
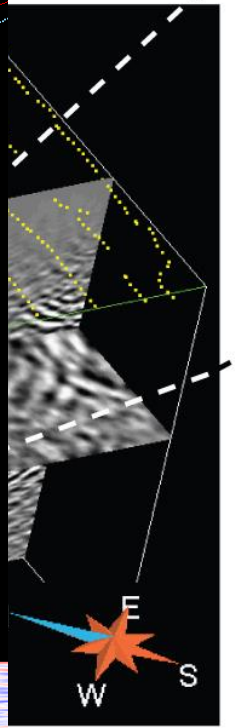
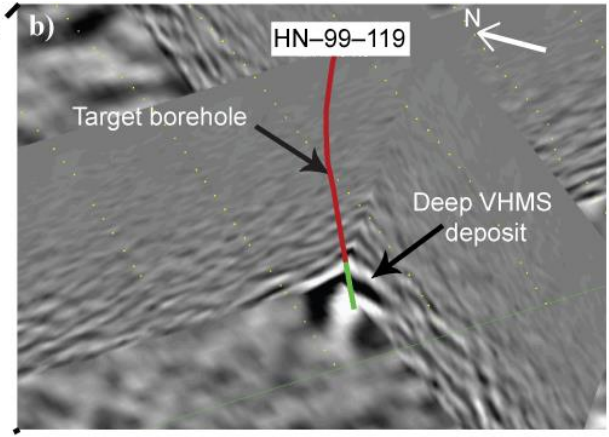
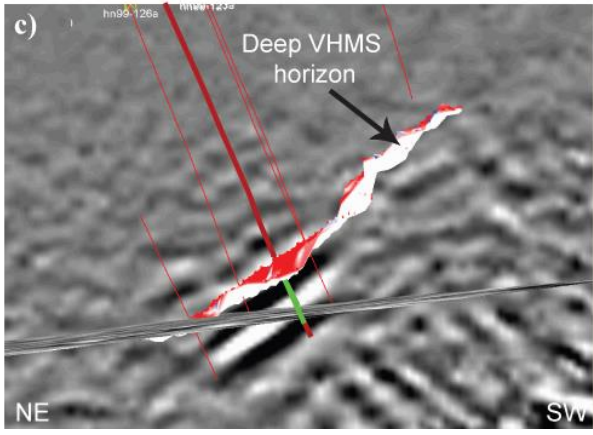
2D vs. 3D issues!









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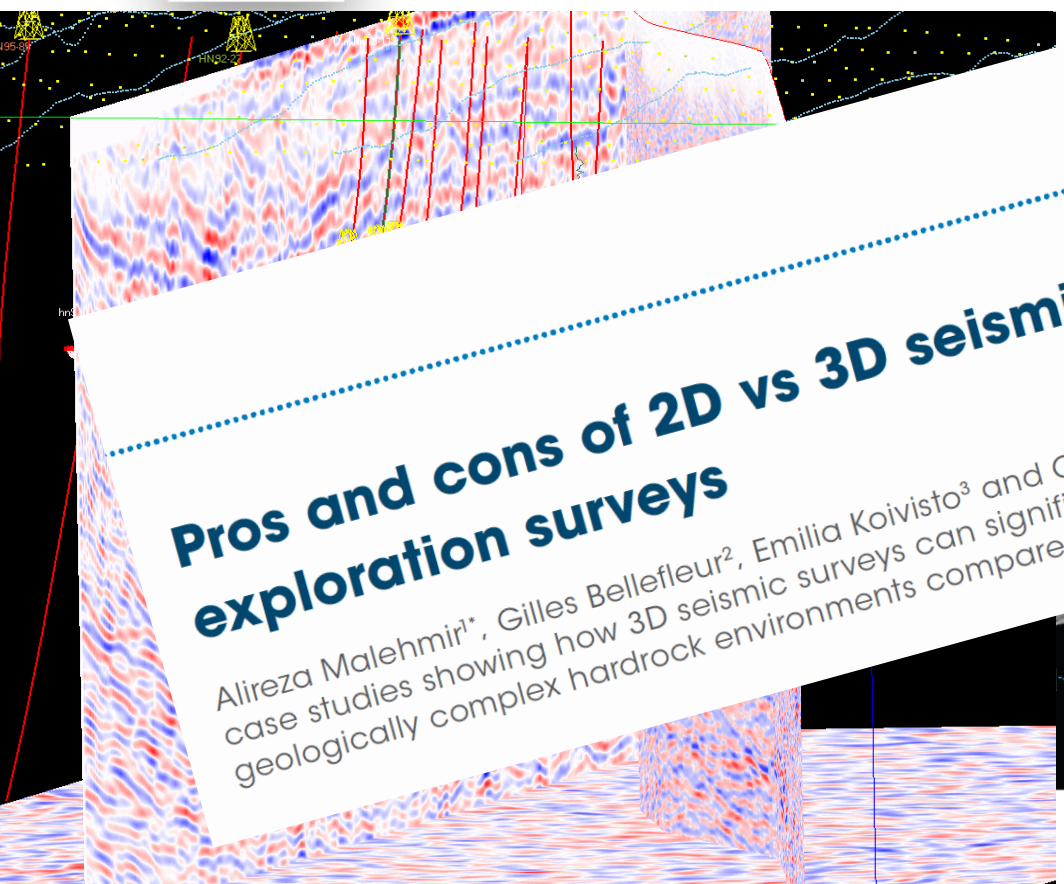
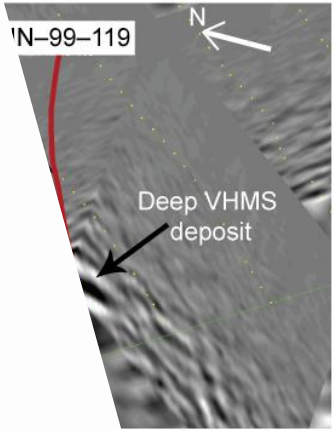
2D vs. 3D issues!

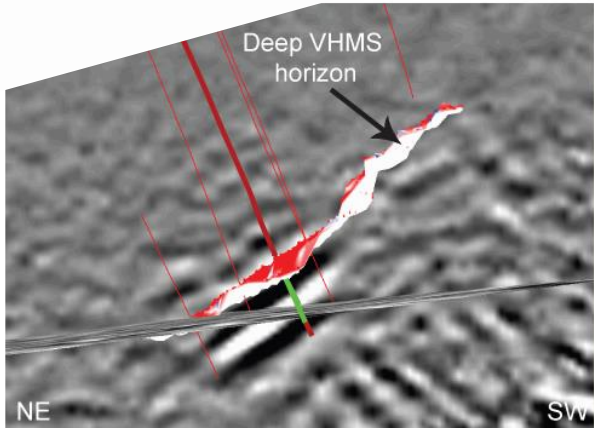


SPECIAL TOPIC: NEAR SURFACE GEOSCIENCE

Pros and cons of 2D vs 3D seismic mineral exploration surveys

Alireza Malehmir[1]*, Gilles Bellefleur[2], Emilia Koivisto[3] and Christopher Juhlin[1] present three case studies showing how 3D seismic surveys can significantly improve interpretations in geologically complex hardrock environments compared to 2D data.





Nordic Iron Ore™

geopartner

TU BERGAKADEMIE FREIBERG

N

Blötberget mine

A collaborative work!
First 3D (sparse) seismic dataset from Sweden

P1

Vibrator source

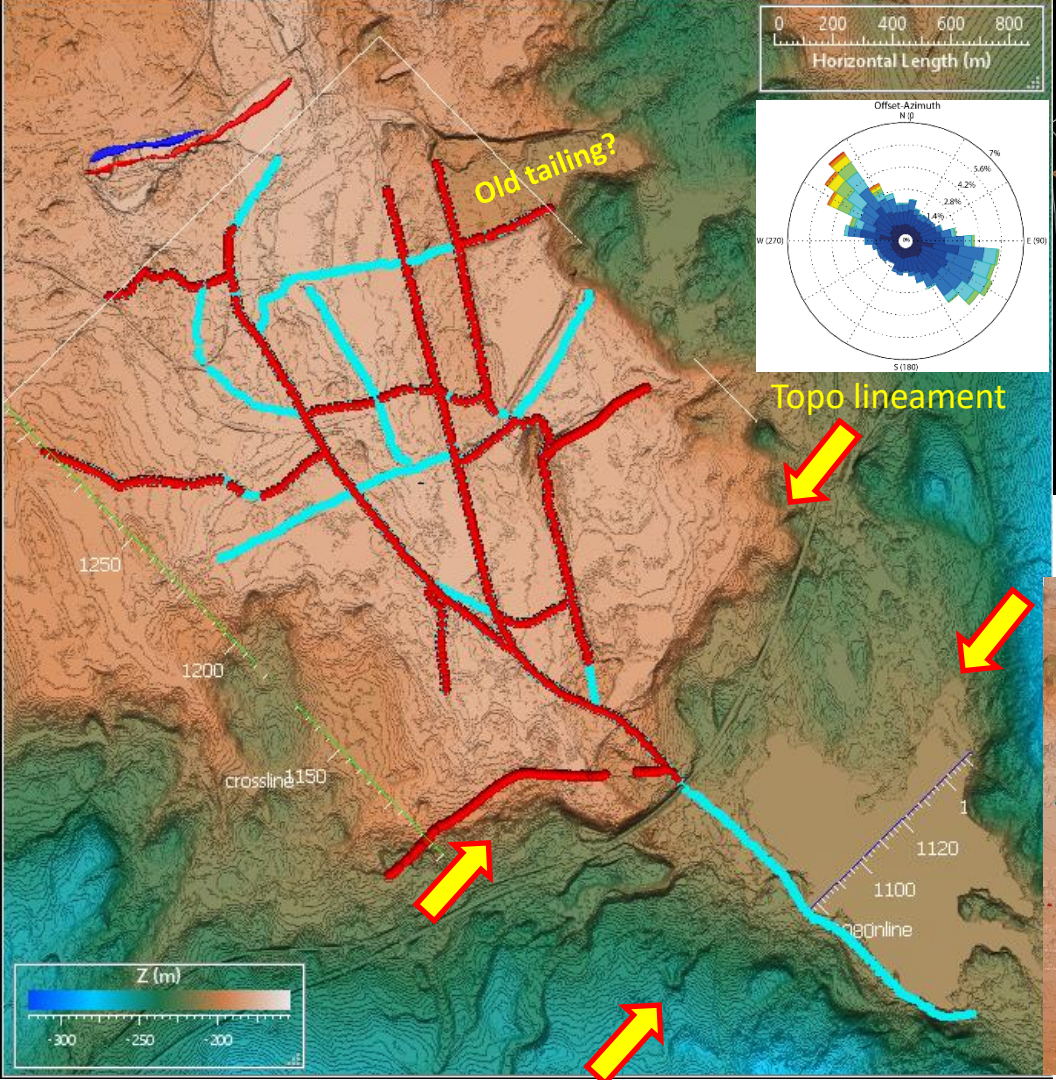
P6

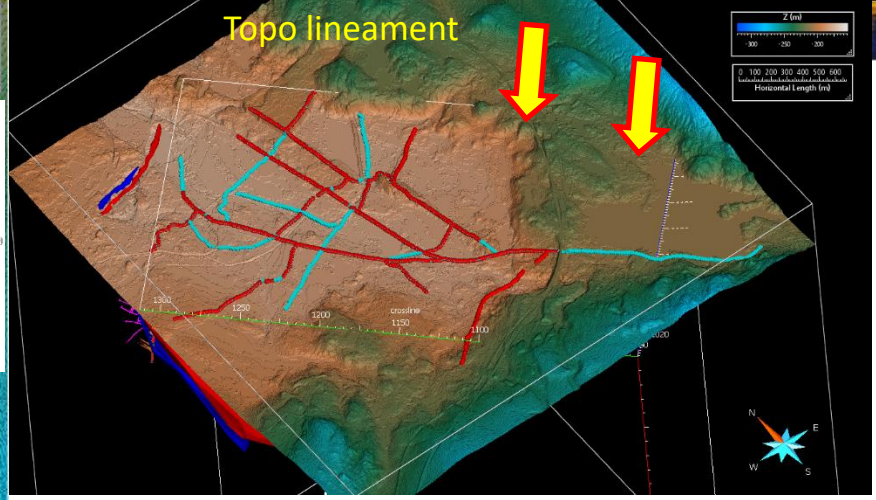
Recording truck

P6

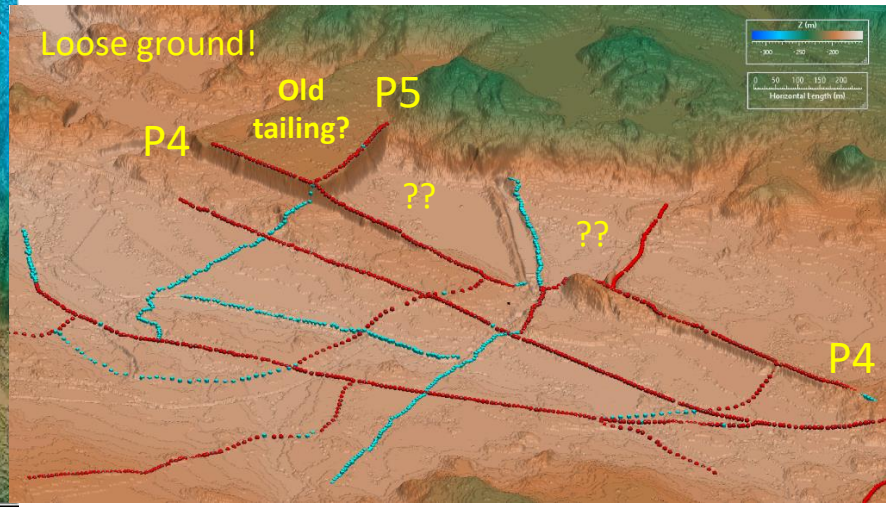
P1

April-May 2019

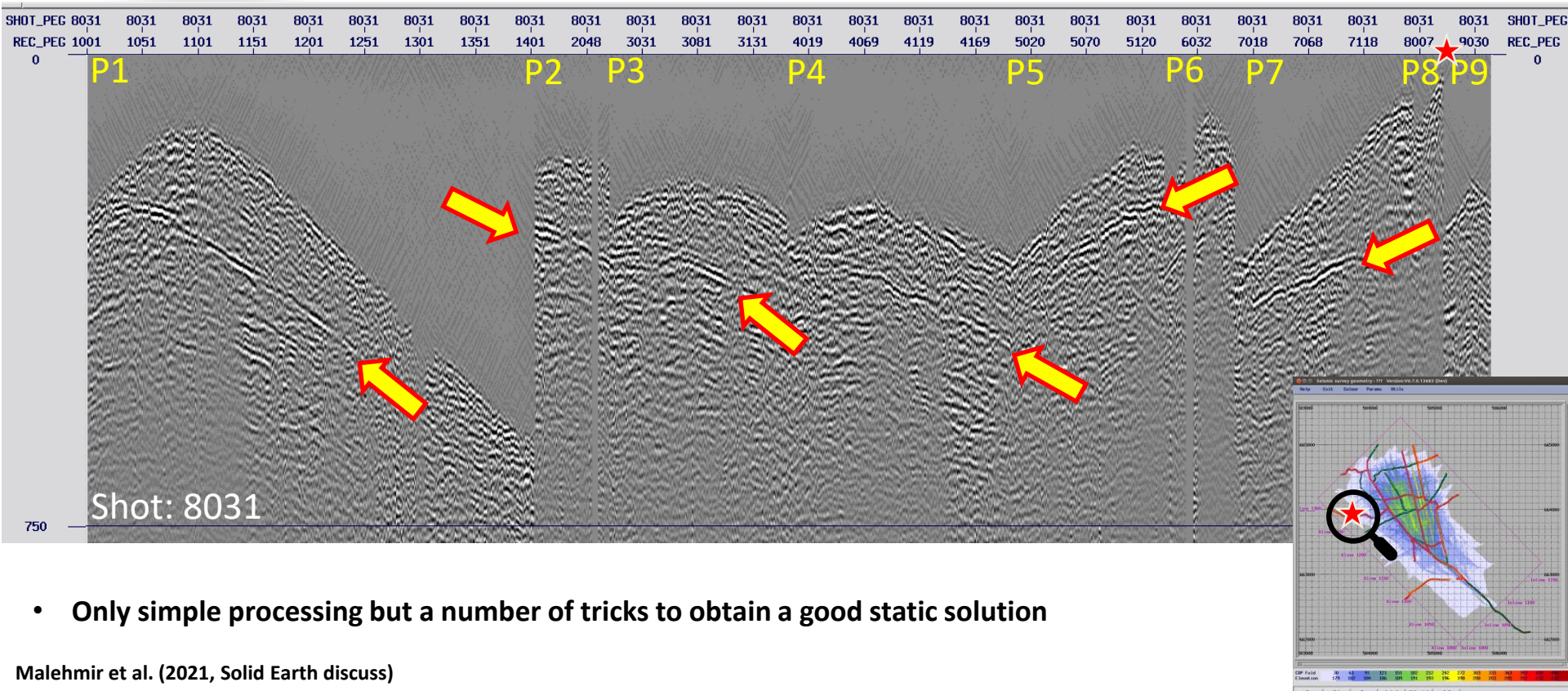




Complex surface morphology

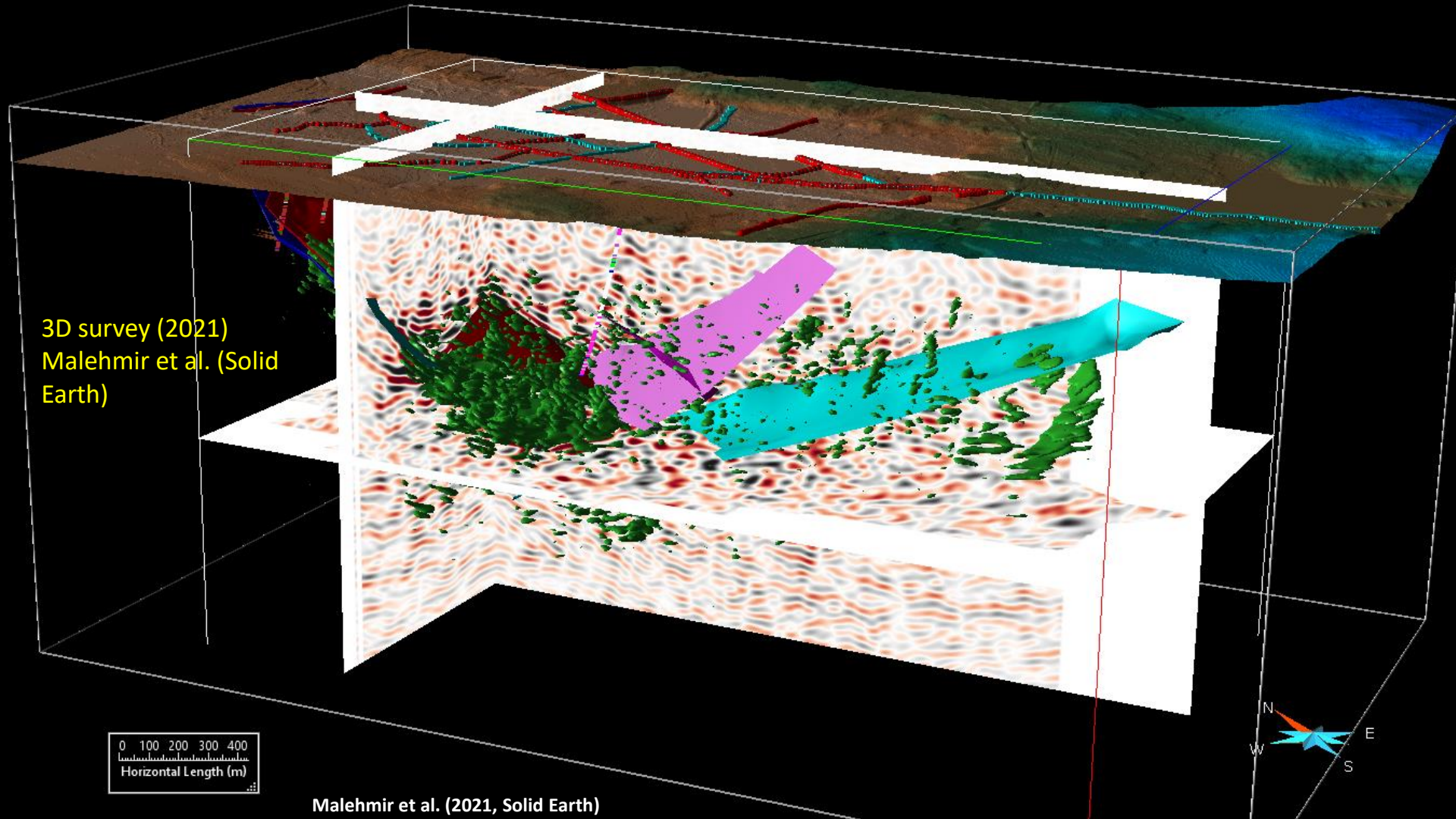


Data quality



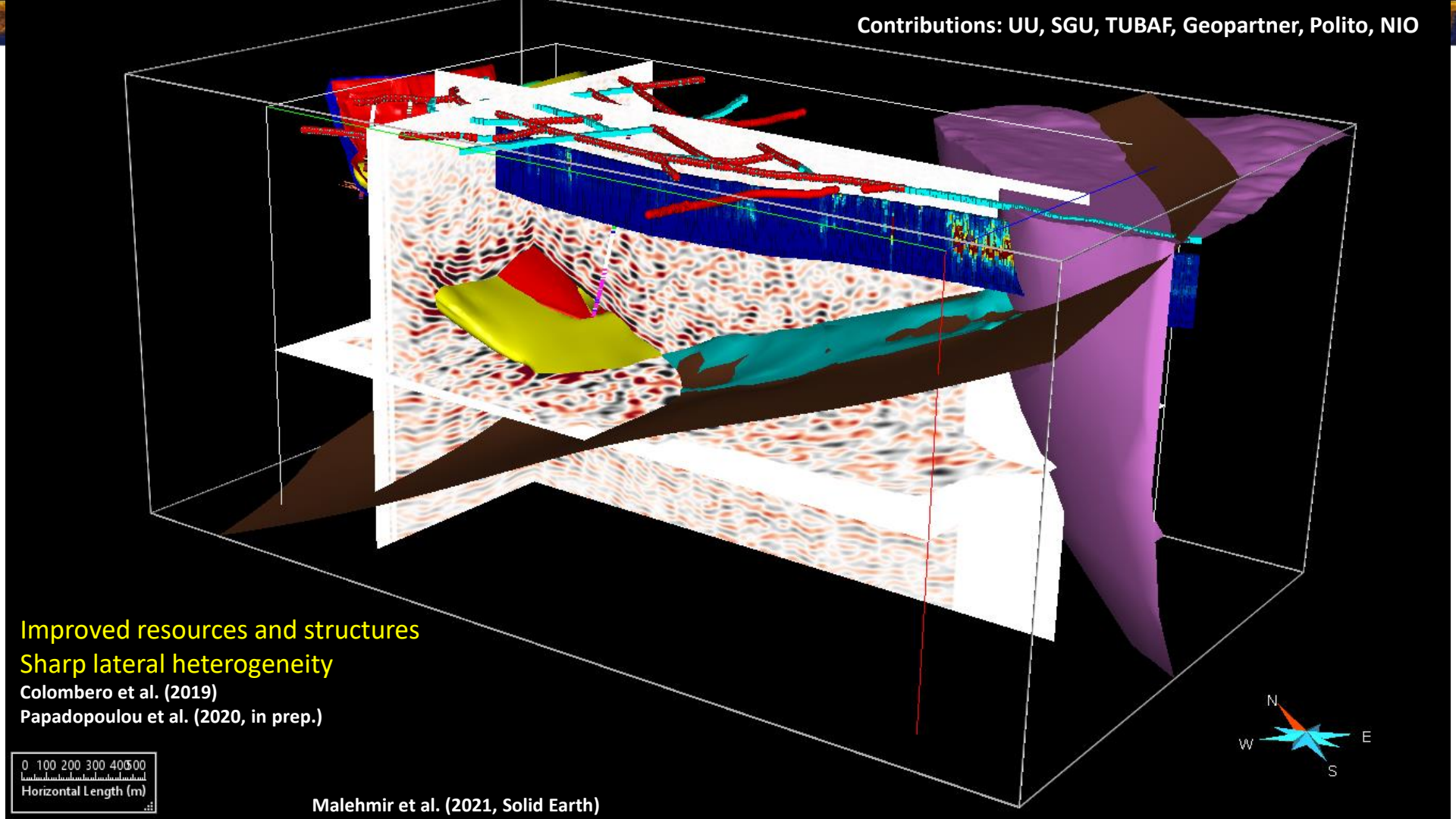
- **Only simple processing but a number of tricks to obtain a good static solution**

Malehmir et al. (2021, Solid Earth discuss)



Malehmir et al. (2021, Solid Earth)

Contributions: UU, SGU, TUBAF, Geopartner, Polito, NIO



Improved resources and structures

Sharp lateral heterogeneity

Colombero et al. (2019)

Papadopoulou et al. (2020, in prep.)

Malehmir et al. (2021, Solid Earth)

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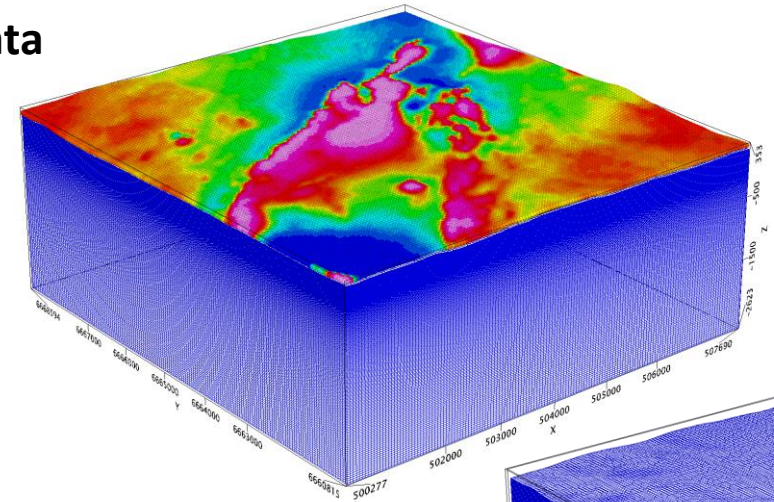
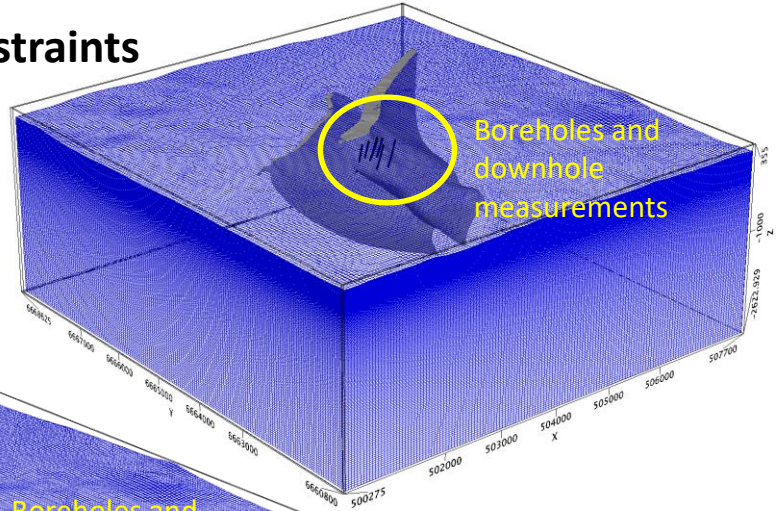
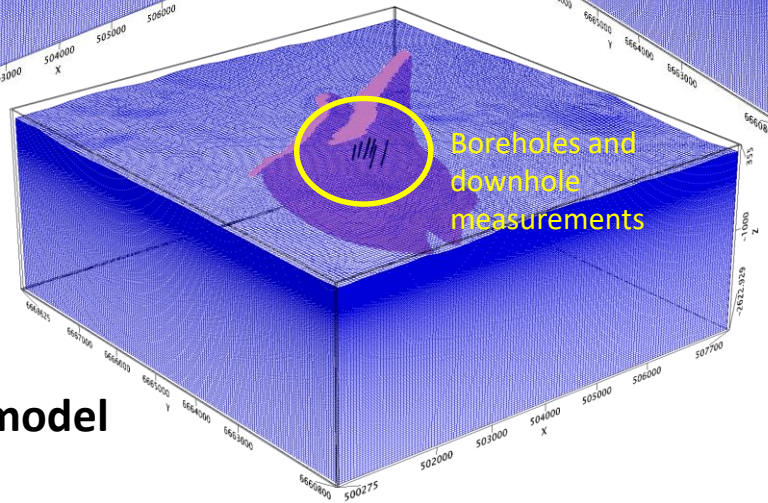
3D constrained magnetic inversion

Data



Constraints





Reference model

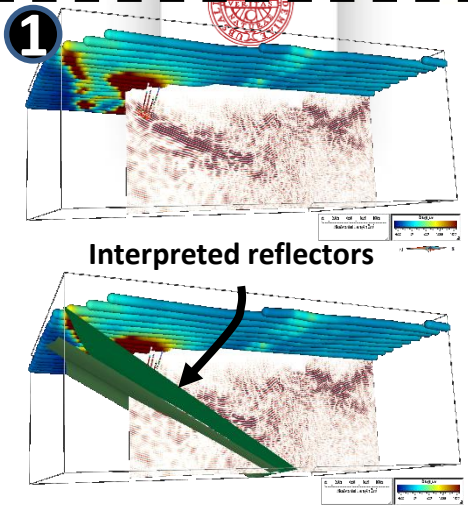
Can the seismic interpretations be verified using other geophysical methods?

⬇

Potential field data are great for this purpose!

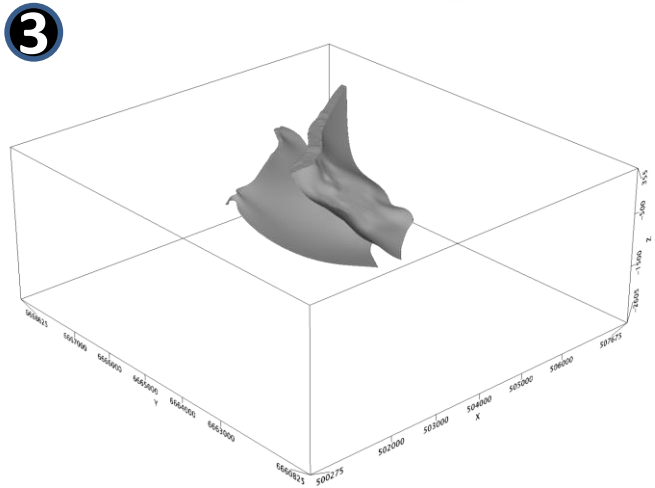
Bastani et al. (2021, in prep.)

1



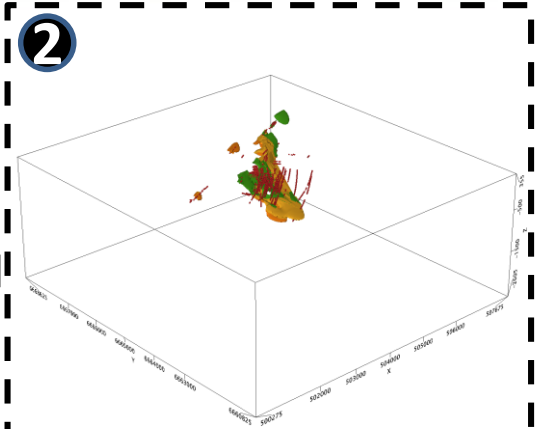
Interpreted reflectors

3



Final expert interpretation & a-priori model building

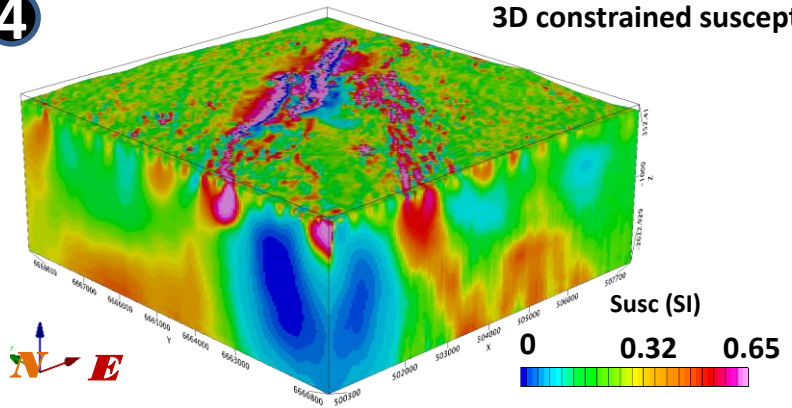
2



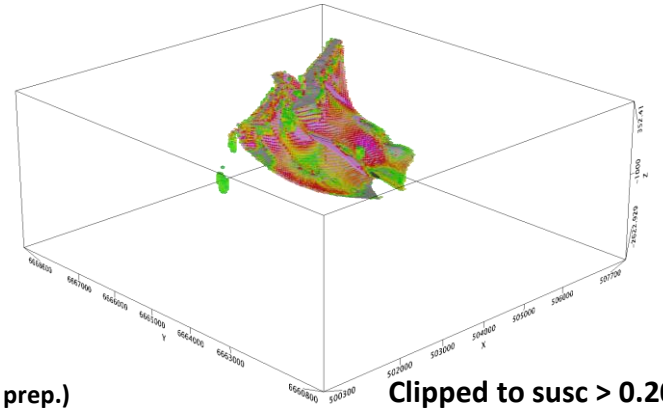
Surfaces from assay data & resource model

4

3D constrained susceptibility model



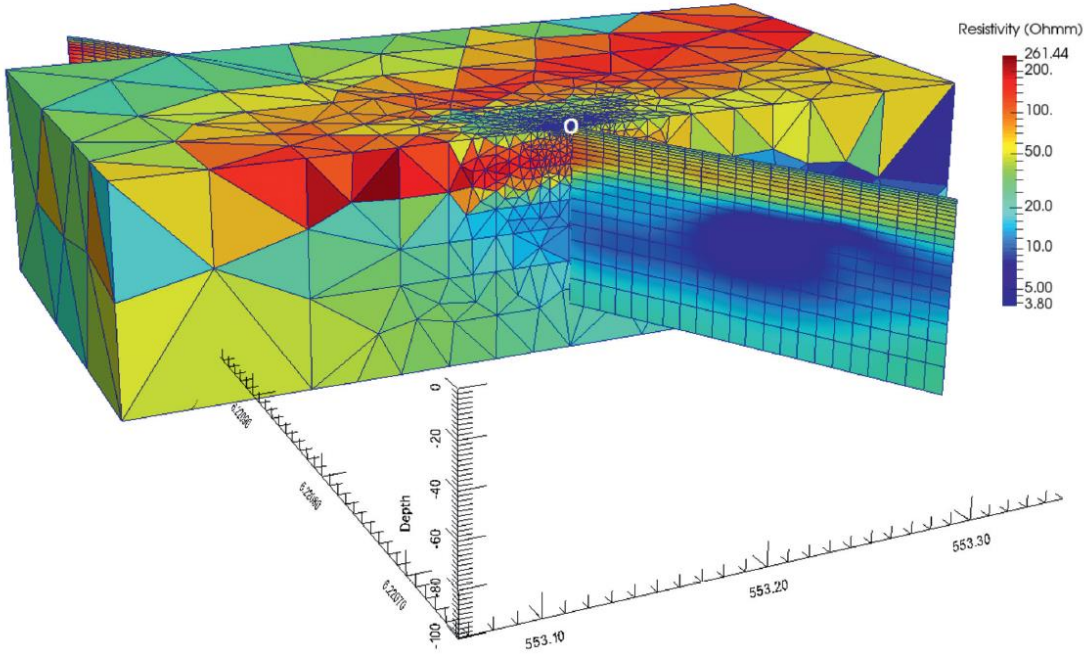
Bastani et al. (2021, in prep.)



Clipped to susc > 0.20

3D/2D TEM-FEM modeling

- **3D inversion code** capable of modelling the full airborne system
- **faster 2D-mode**, where the forward models are calculated in 3D, but the resistivity model is mapped in 2D
- relevant when covering large areas with a sparse line sampling
- **optimized** to increase speed and decrease memory usage



3D finite-element forward modelling mesh superimposed on the 2D model mesh (Engebretsen et al., First Break, **39**, 2021)

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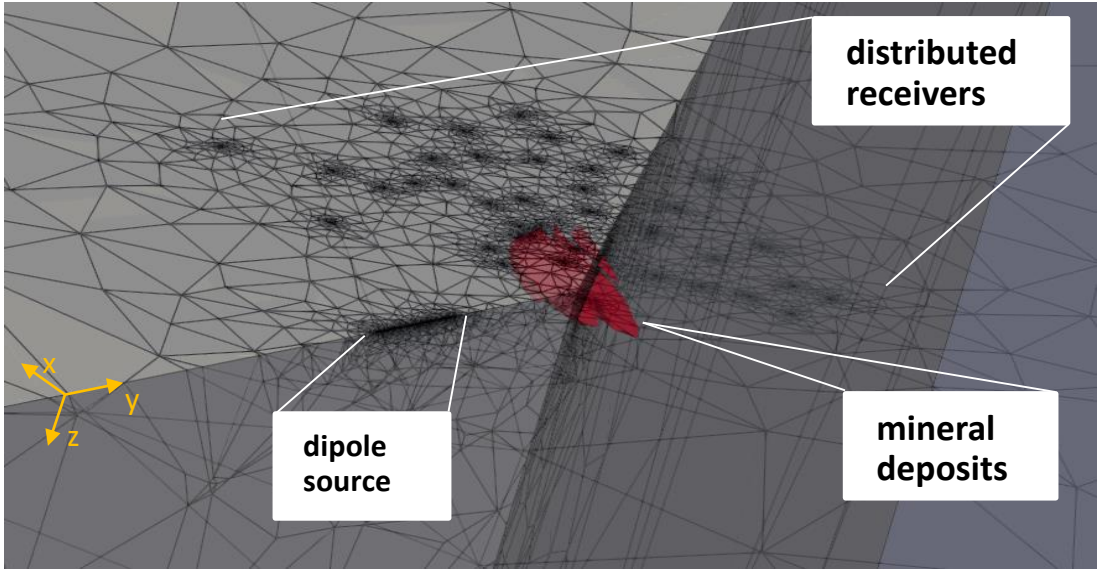
3D CSEM-FEM modeling

- **3D forward modelling code** for ground-based and borehole **CSEM** setups
- verified with 1D, 3D and realistic mineral exploration examples
- finite-element approach on tetrahedral meshes
- including goal-oriented adaptive **refinement**
- implemented in inversion framework
- **3D NLCG inversion**



3D finite-element mesh for a 3D forward modelling study with mineral deposits (results in: Rulff et al., 2021, in revision)

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Summary!

Smart Exploration has demonstrated that sustainable mineral exploration is possible through good practices, innovation, reviving legacy data, how-to solutions and contributions from both Senior and Young Professionals!

For Alan:
We made the first step: spelling "**Exploration Geophysics**" in Europe ...

Let's now do even "**Smarter Exploration**" and lots of Maxwell equations incl. MT!

SMARTEXPLORATION
new ways to explore the subsurface

SMARTEXPLORATION

new ways to explore the subsurface

THANK YOU

Smart Exploration has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.775971.