From the mantle into space:
Unique synergy of the **Swarm** and **USArray** for 3-D mantle imaging & Space Weather hazard

Federico Munch & Alexander Grayver

Swiss National Science Foundation

Deutsche Forschungsgemeinschaft
Heisenberg Grant

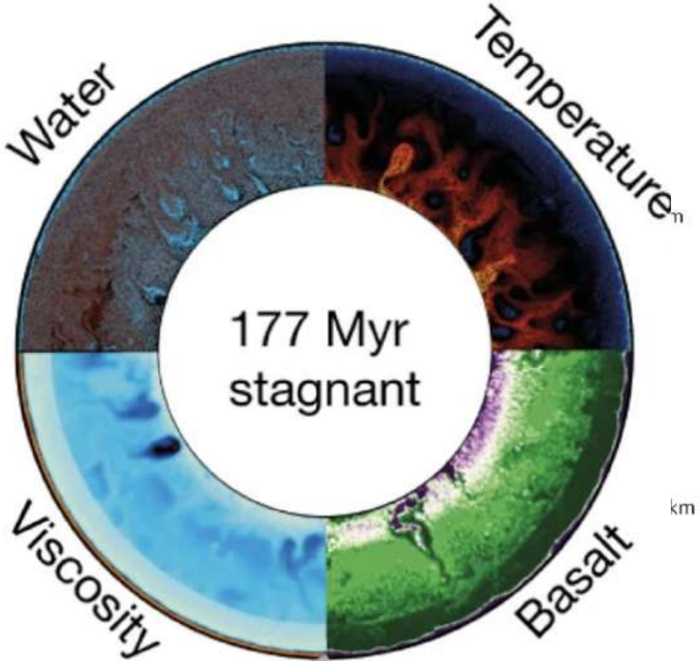
esa eo

SWARM DISC

Motivation

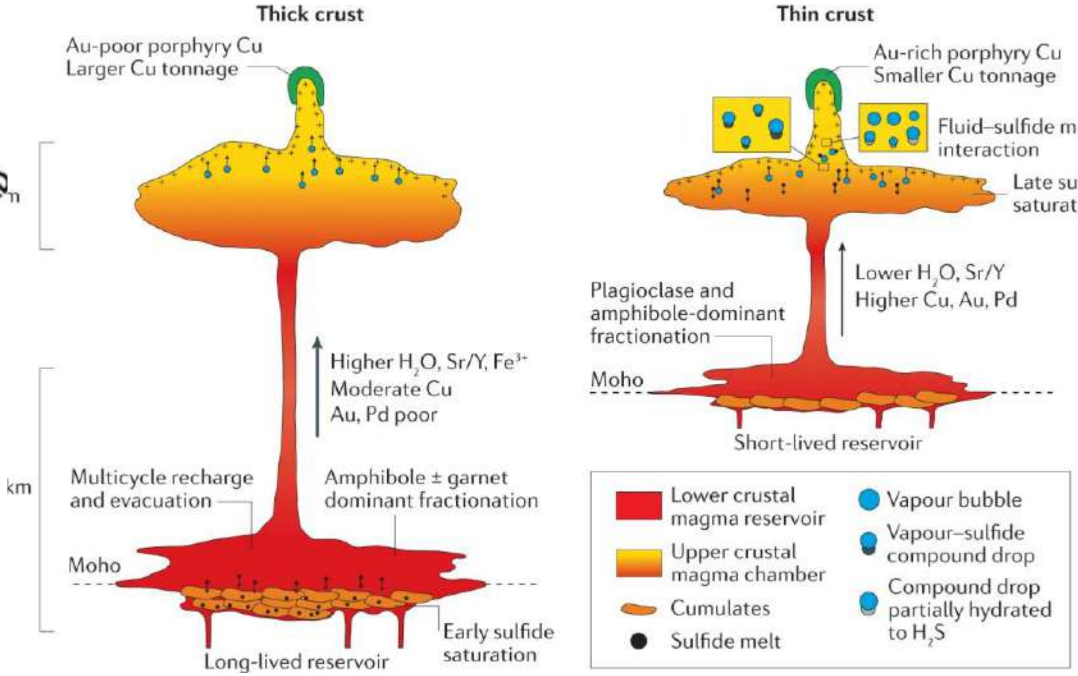
Natural EM field variations measured by SWARM & ground stations

Subsurface electrical conductivity



Rozel et al, 2017

Mantle **temperature** & **water** content exert a fundamental control on mantle dynamics



Park et al, 2021

Crustal fluids play a key role in the formation and evolution of mineral systems

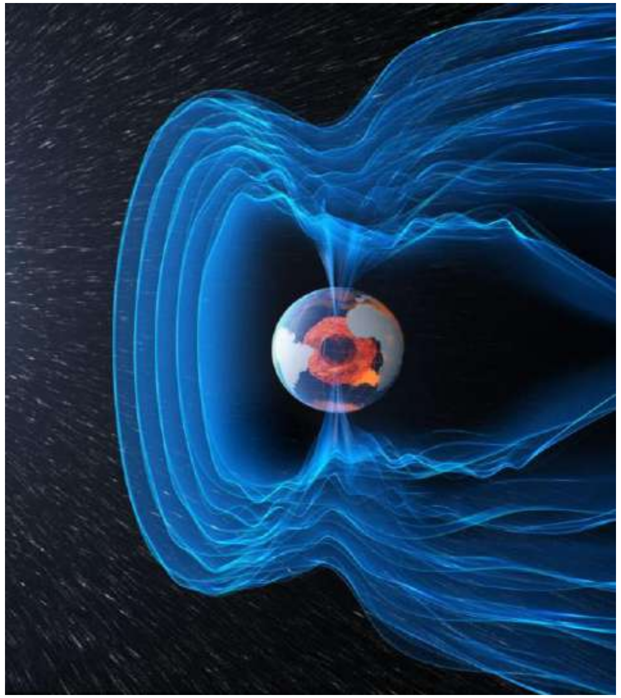


Image Credit: Telescope Live

Space weather hazard evaluation (Geomagnetically Induced Currents)

Motivation

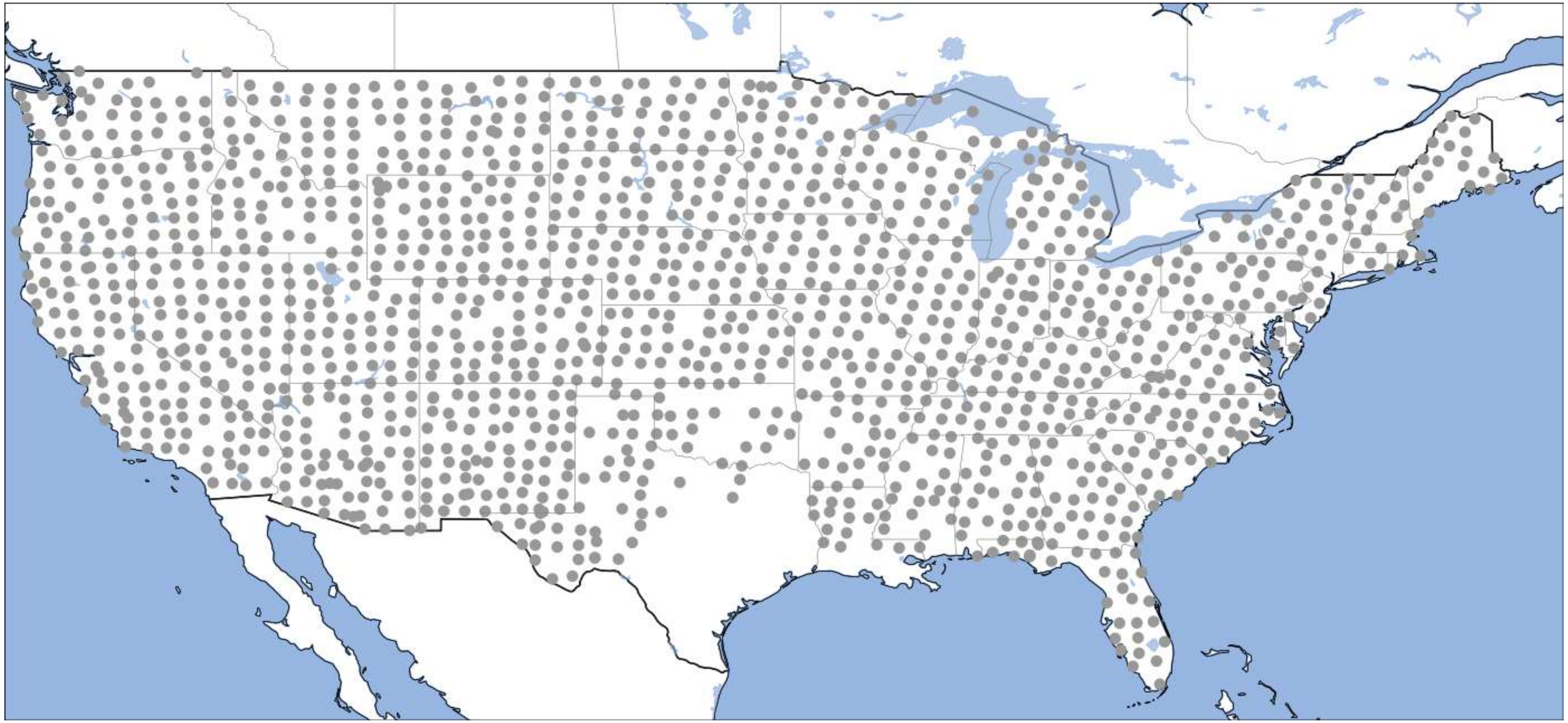
There is only “one” electrical conductivity of the Earth.

Both **ground** and **satellite magnetic field observations** are governed by the same physics*.

How to **exploit synergies** between these measurements?

*At frequencies relevant for EM induction

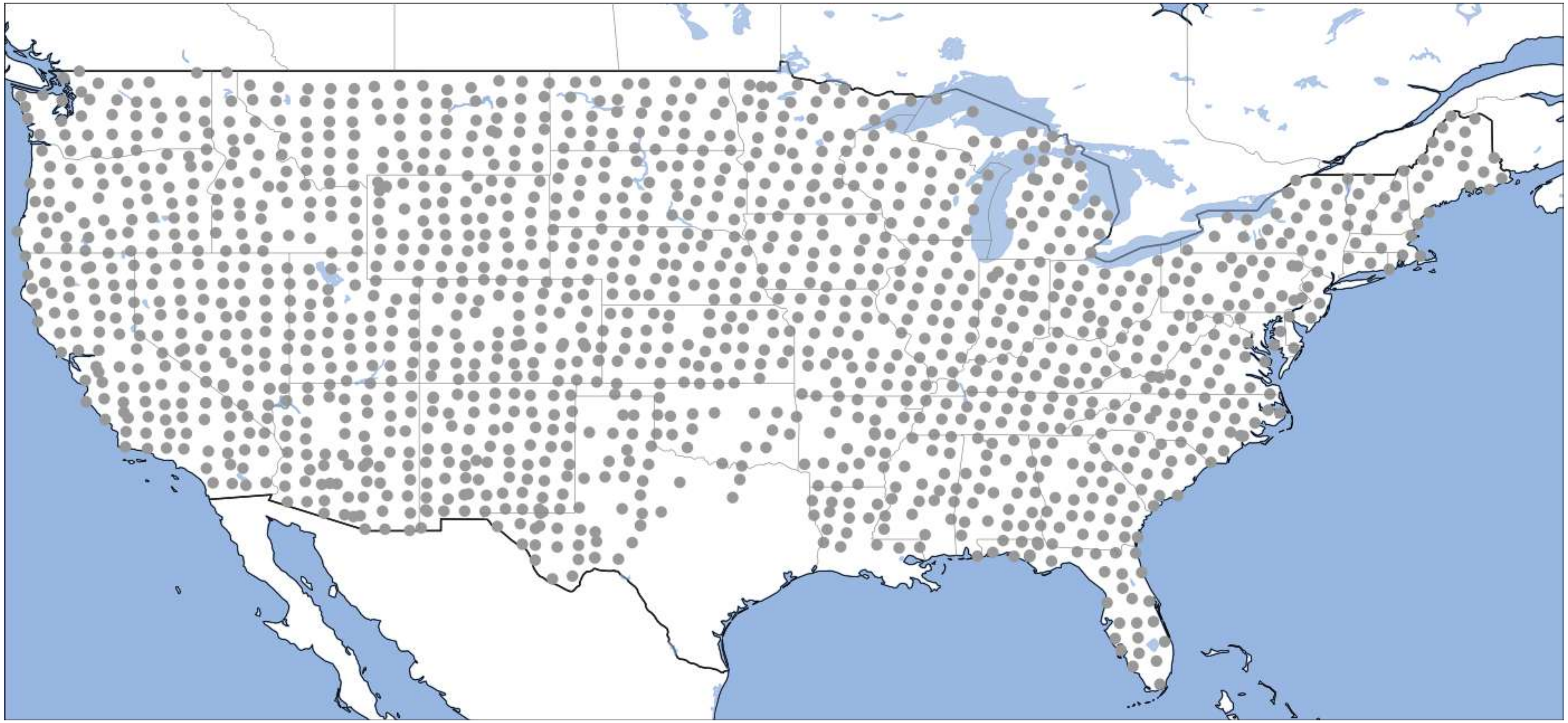
Towards continental-scale conductivity models



USArray is the first (available) continental magnetotelluric (MT) survey

We acknowledge all involved parties and institutions (NSF, USGS, OSU, among others) for making the USArray data set available.

Towards continental-scale conductivity models

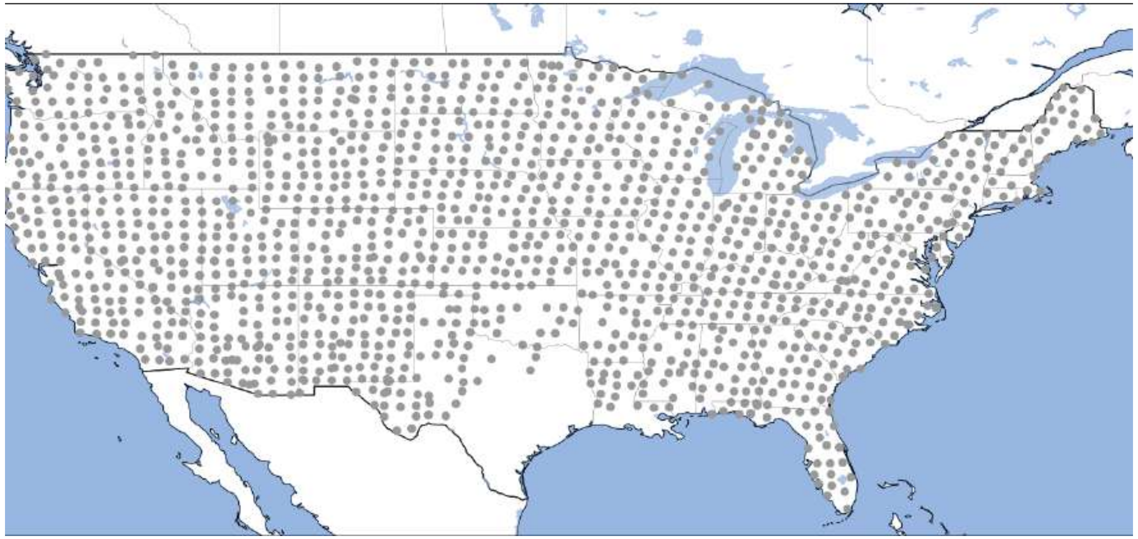


We constructed the first 3D Multi-scale Electrical Conductivity Model of the United States (MECMUS-2022) from the inversion of the USArray MT dataset in a spherical frame

Munch and Grayver (2023, EPSL).
Multi-scale imaging of 3-D electrical conductivity structure under the contiguous US constrains lateral variations in the upper mantle water content

Model Construction

- Data: ~1450 MT stations; full MT impedance at periods 15 - 29,000 s.
  (~1300 stations in MECMUS2022)



- Finite-element solver (GoFEM) combined with high-order locally refined meshes (Grayver & Kolev, 2015).

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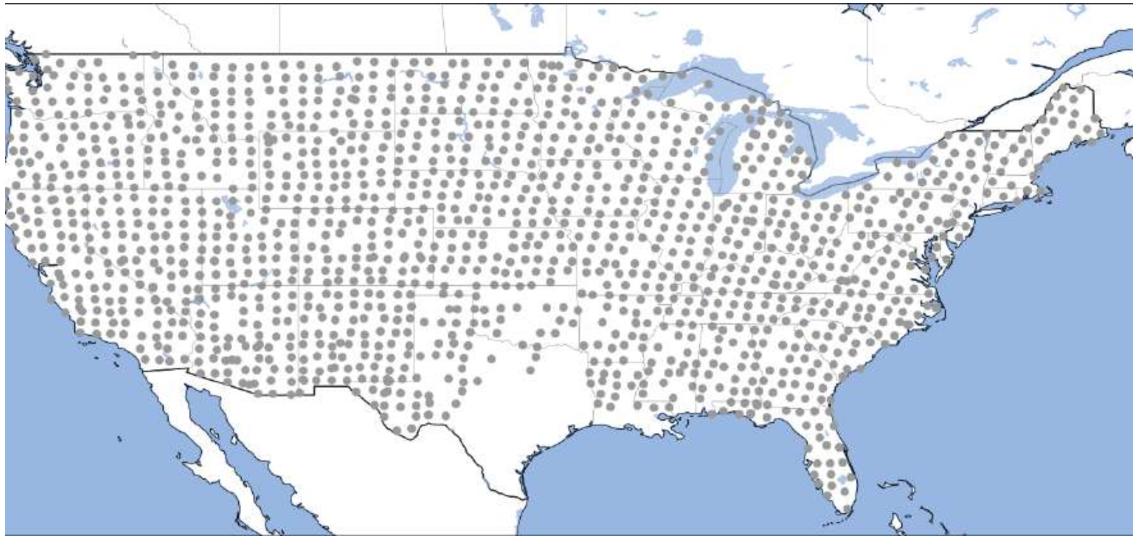

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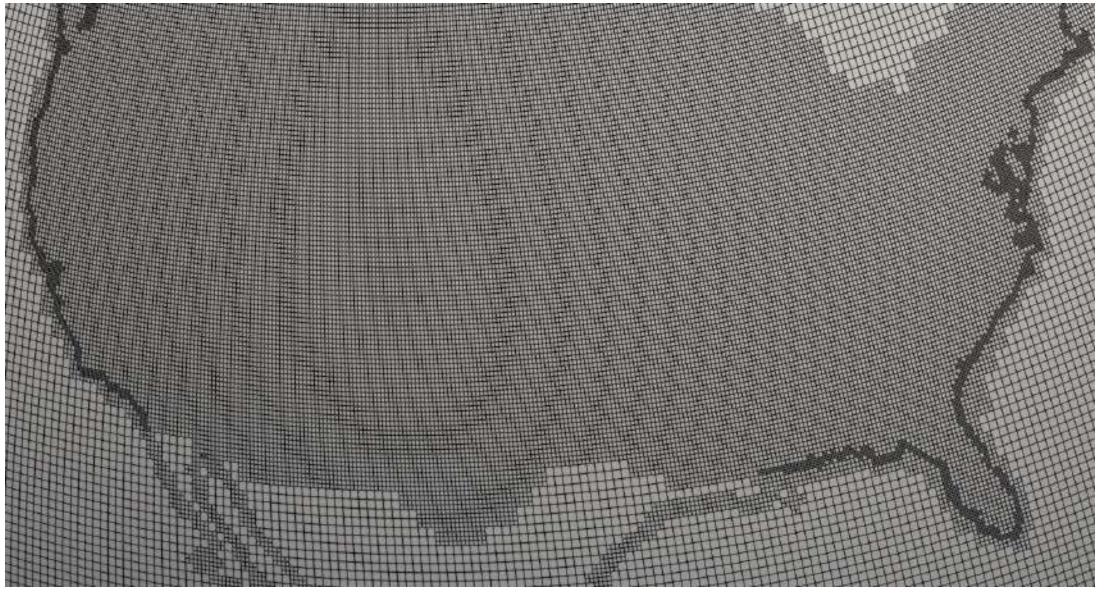
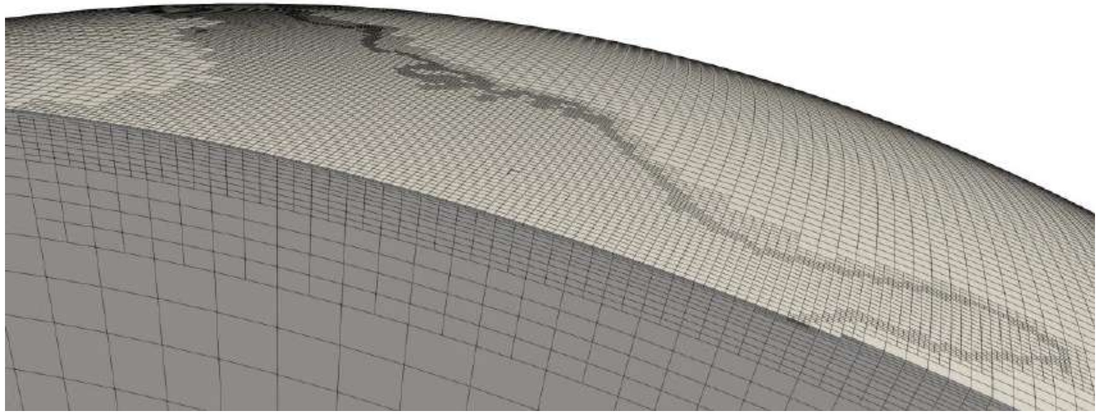
Spherical mesh used to invert USArray data



Model domain 6000 x 8000 x 4000 km
Smallest cell diameter 1.5 km



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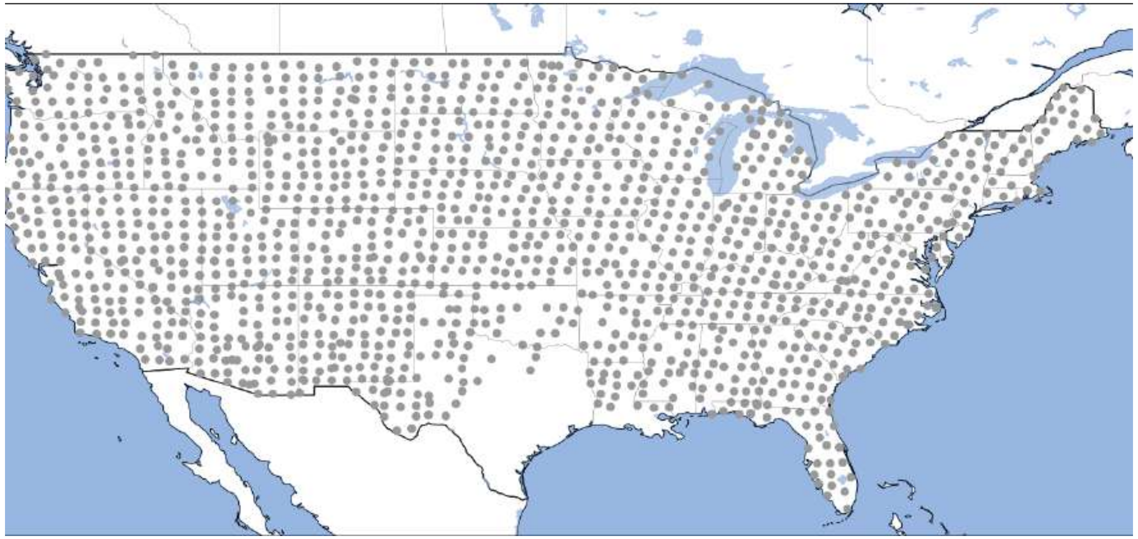
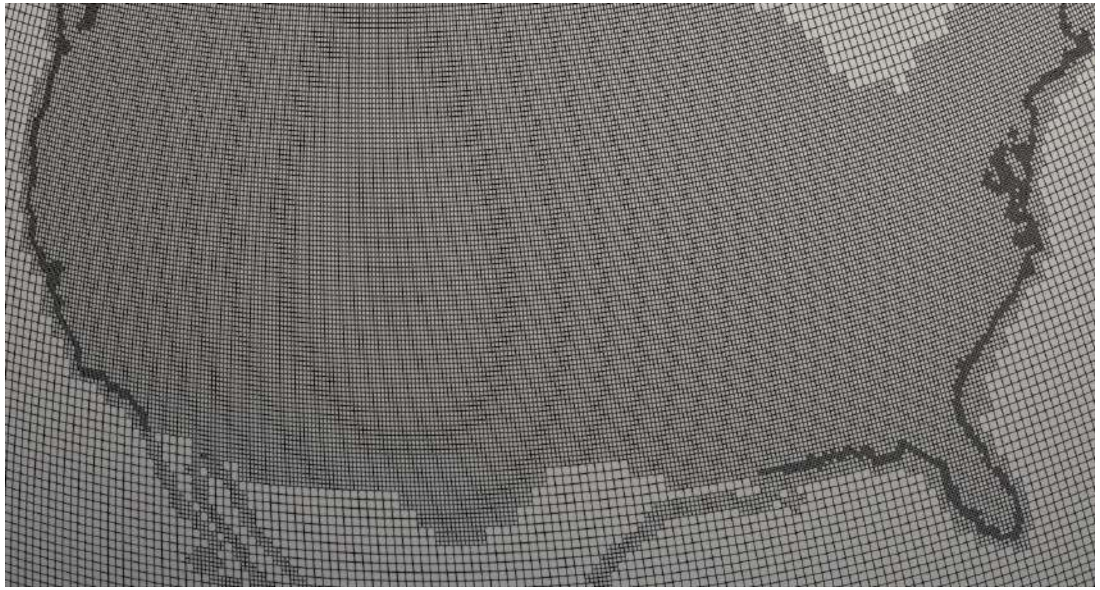


- Finite-element solver (GoFEM) combined with high-order locally refined meshes (Munch and Grayver, 2023).
- Incorporated 3-D conductivity of the ocean and marine sediments (Grayver, 2021).

Spherical mesh used to invert USArray data



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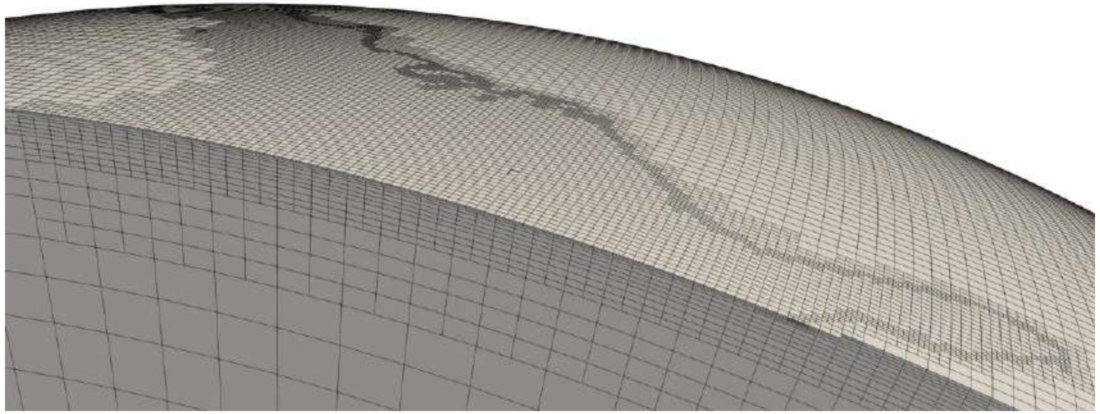
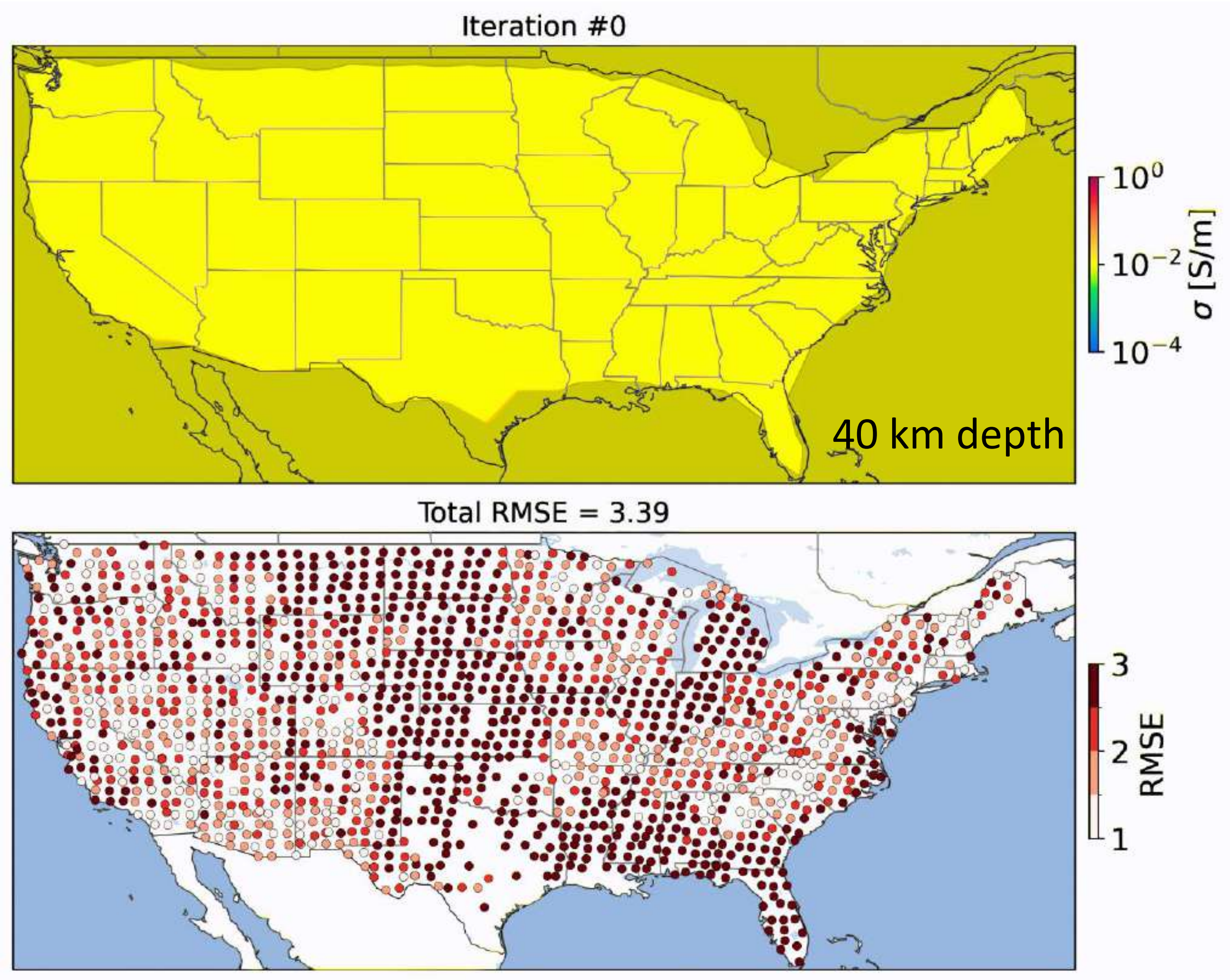


Unraveling 3-D conductivity variations

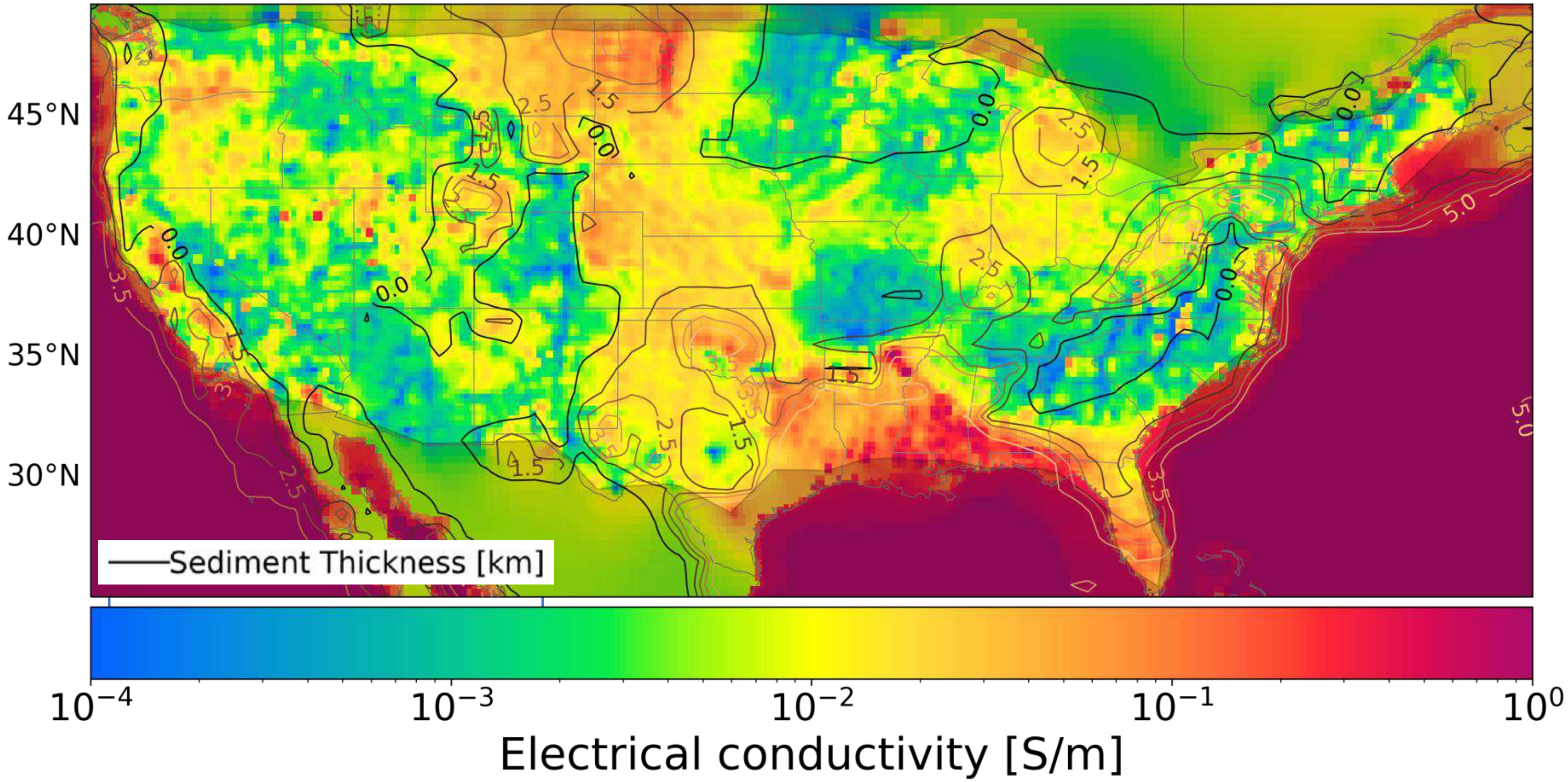

Iteration #0

Total RMSE = 3.39

Starting model
1-D global conductivity model
derived from Swarm satellite data
(See Poster 49 by Grayver et al.)

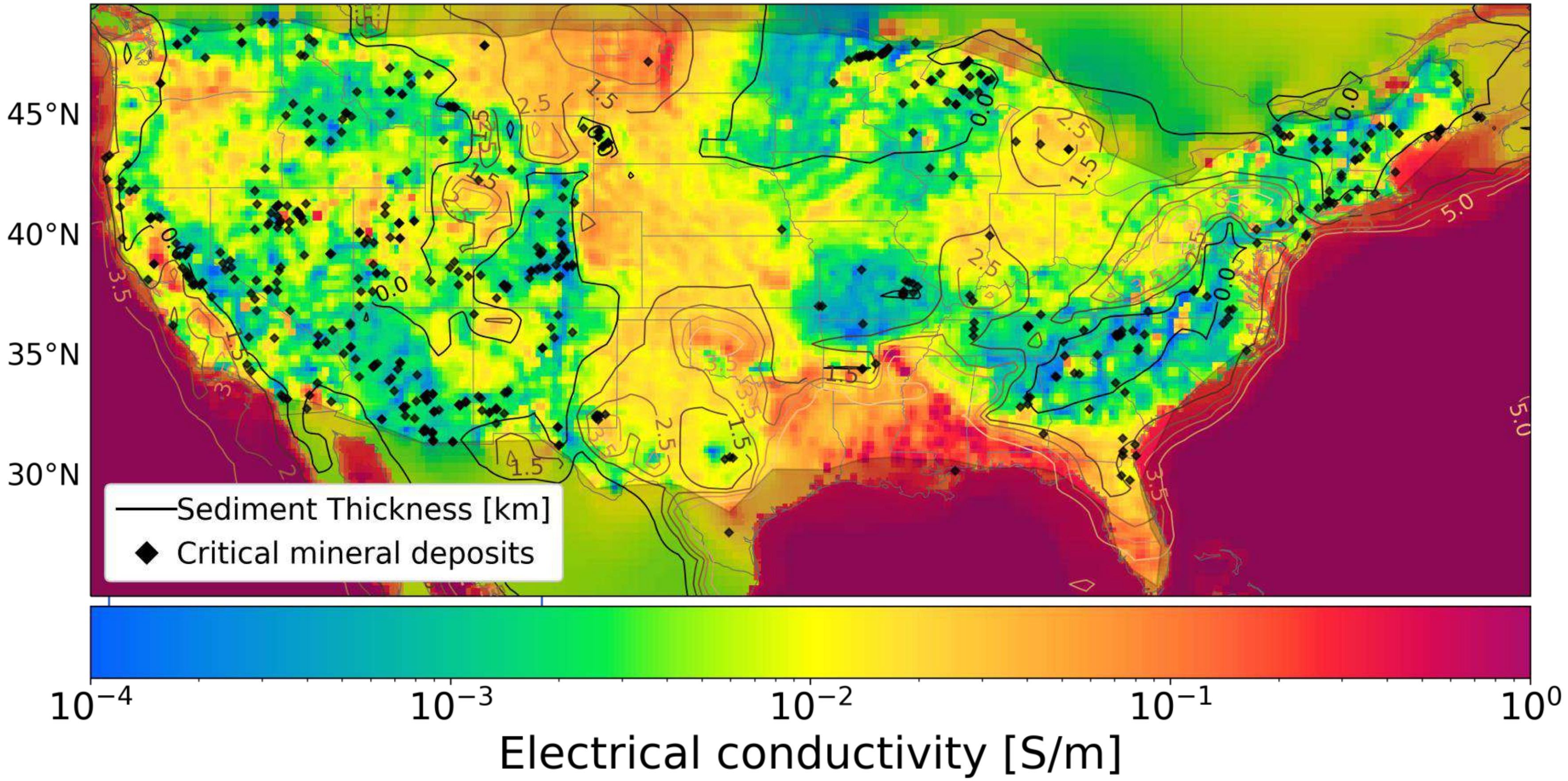
We solve a non-linear inverse problem to find a 3-D electrical conductivity structure that explains the **observed electromagnetic responses**

Electrical conductivity - Crust [4 km depth]



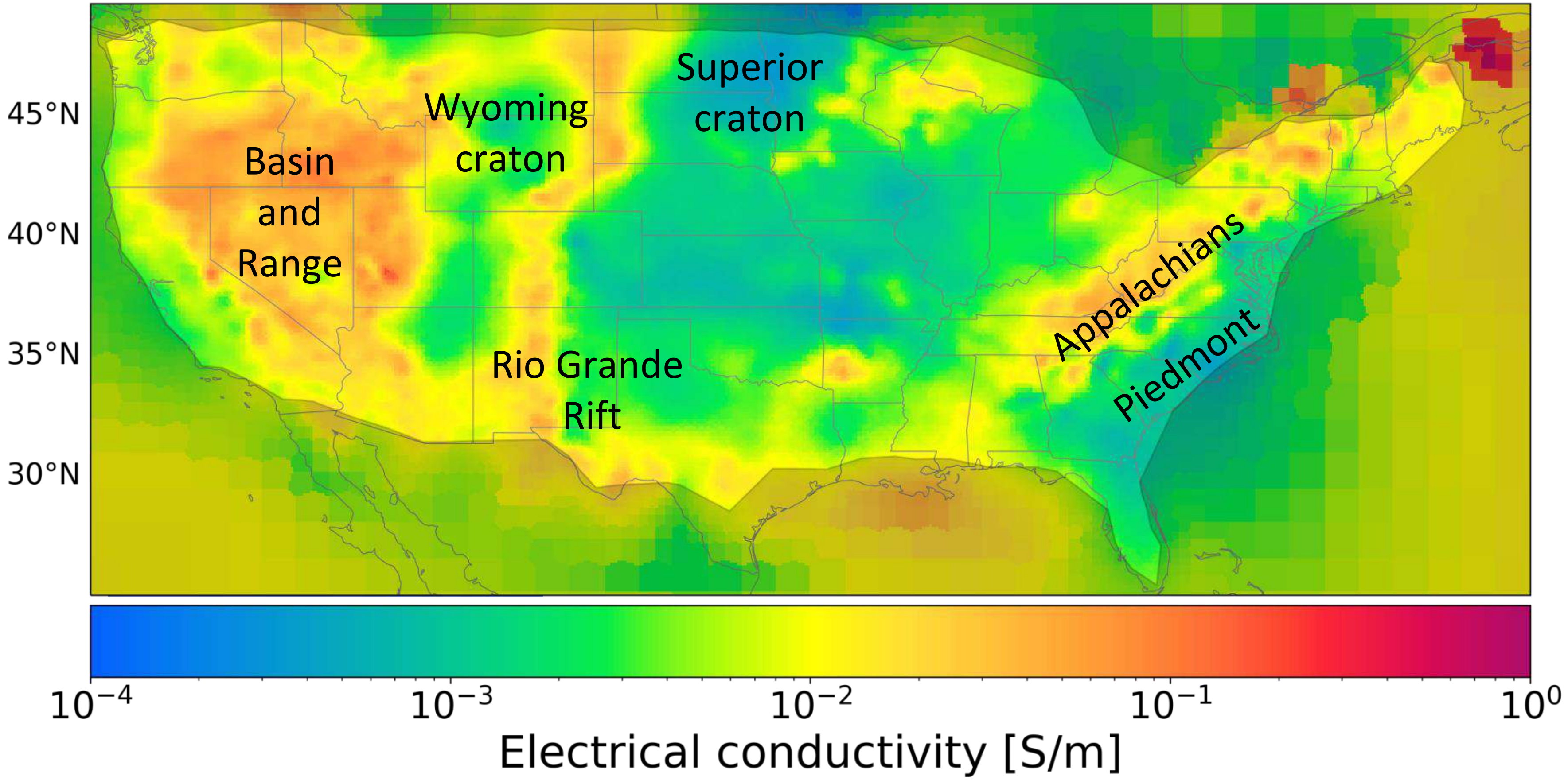
Conductivity variations reflect sediments and igneous/metamorphic rock basement

Electrical conductivity - Crust [4 km depth]



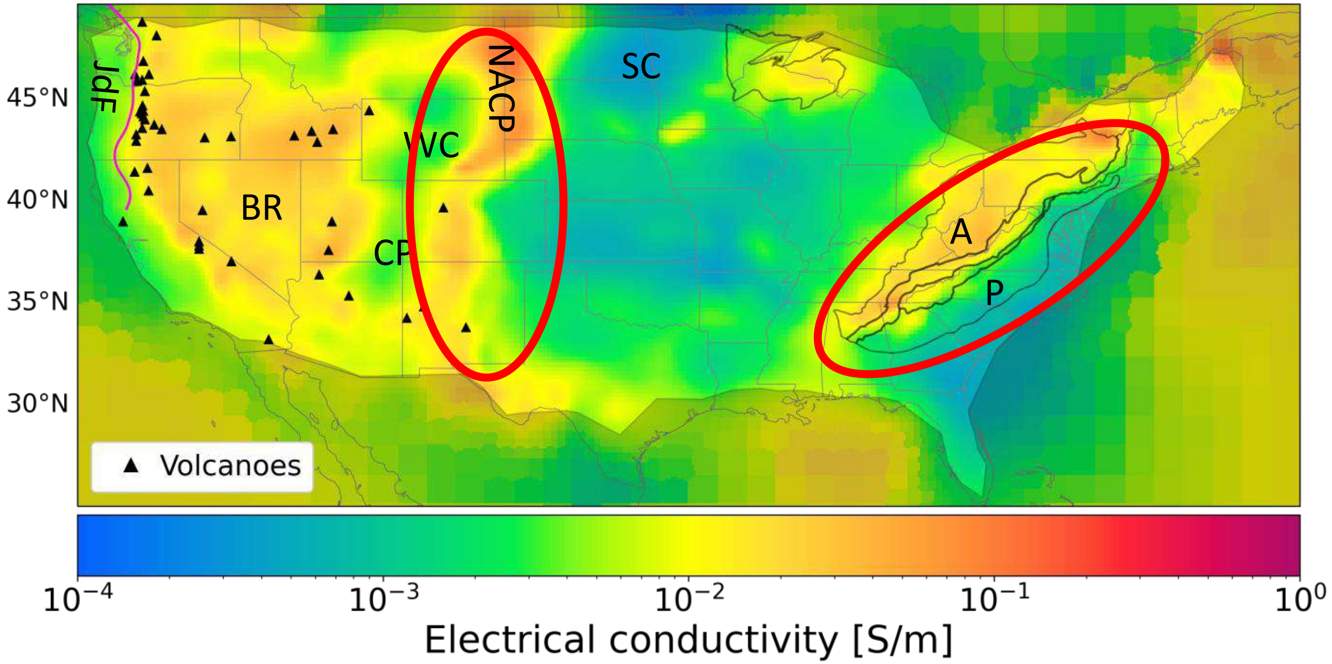
Current ore deposits are mostly found in areas with thin or no sediments:
this model allows to look for deposits under the cover.

Electrical conductivity - Lithosphere [40 km depth]

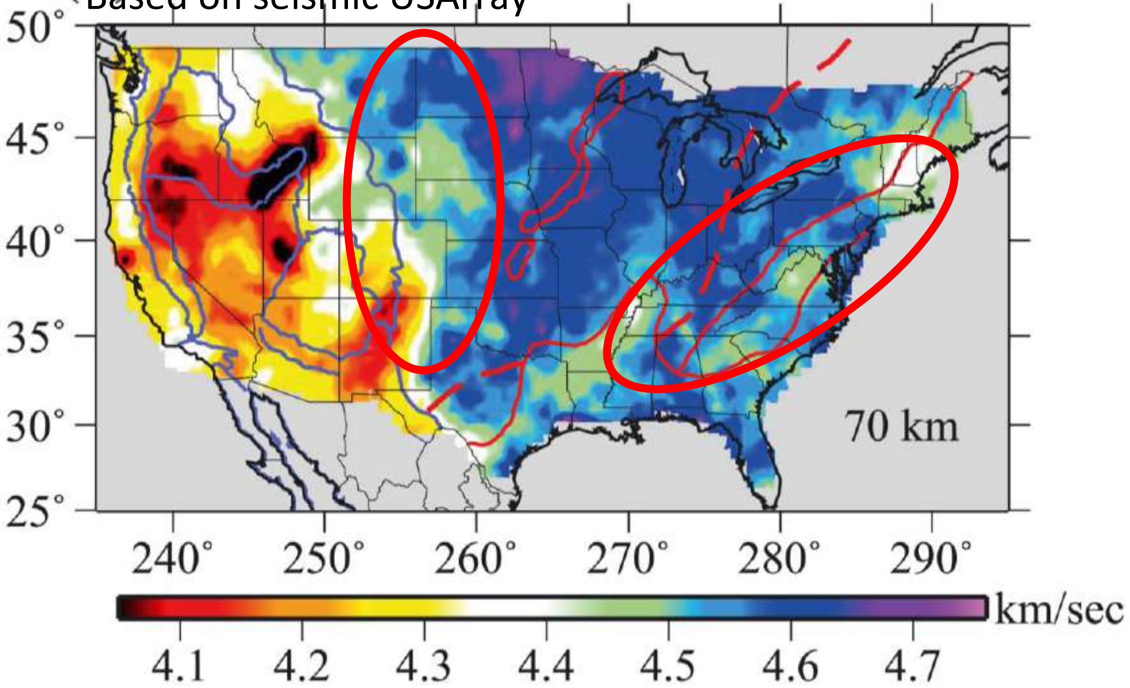


Electrical conductivity - Lithosphere [70 km depth]

Based on MT-USArray



Based on seismic USArray



Shen & Ritzwoller, 2016.

Prominent 3-D features show up in conductivity, but not in seismic tomography models.

What are the underlying processes?

Connecting ground and space

Our goal is model the ground electric fields during geomagnetic storms.

To this end, we combine

External magnetic field variations

(constrained by SWARM & geomagnetic observatories)

+

3-D subsurface conductivity model (MECMUS)

+

Full 3-D EM induction solver

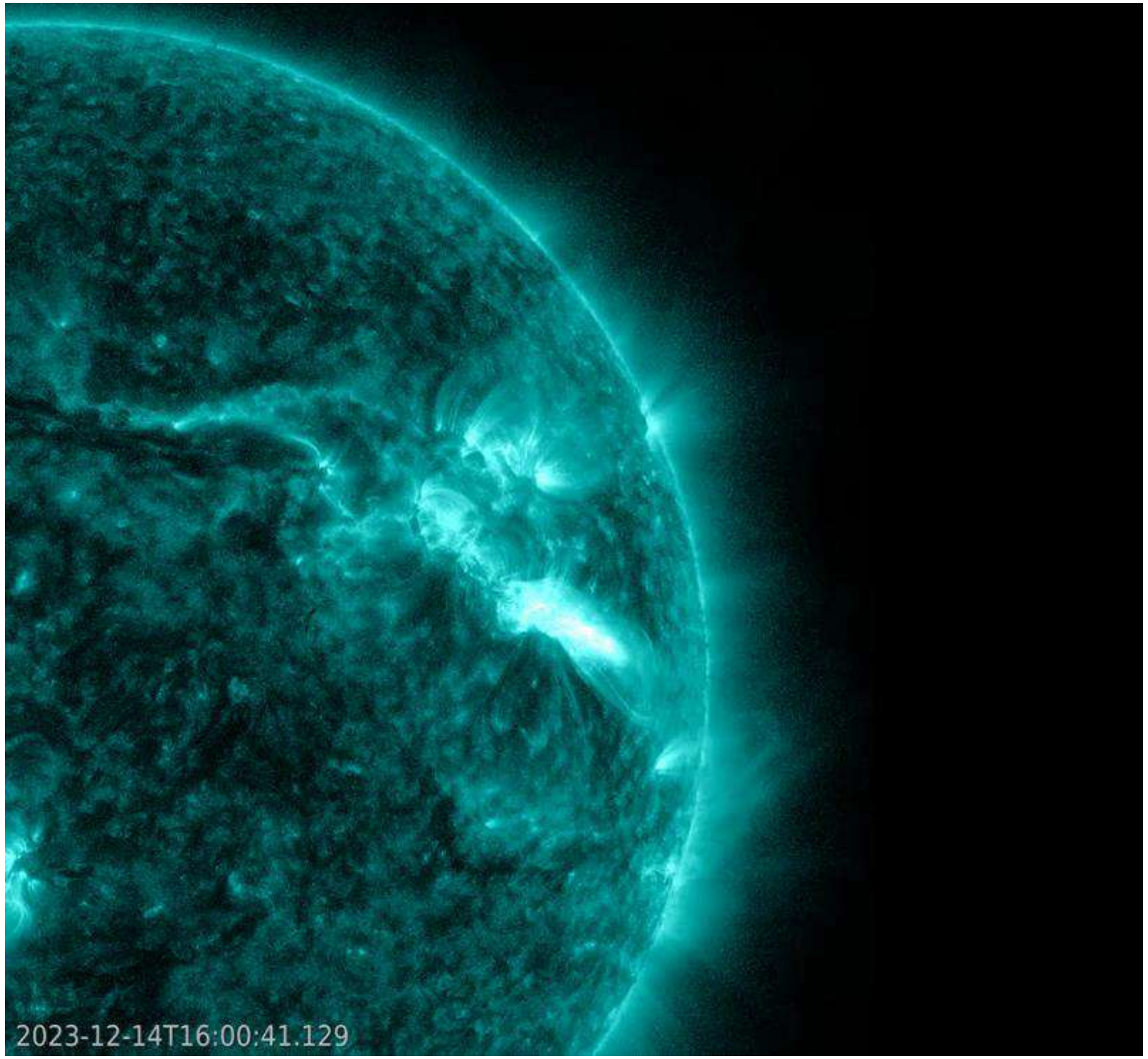
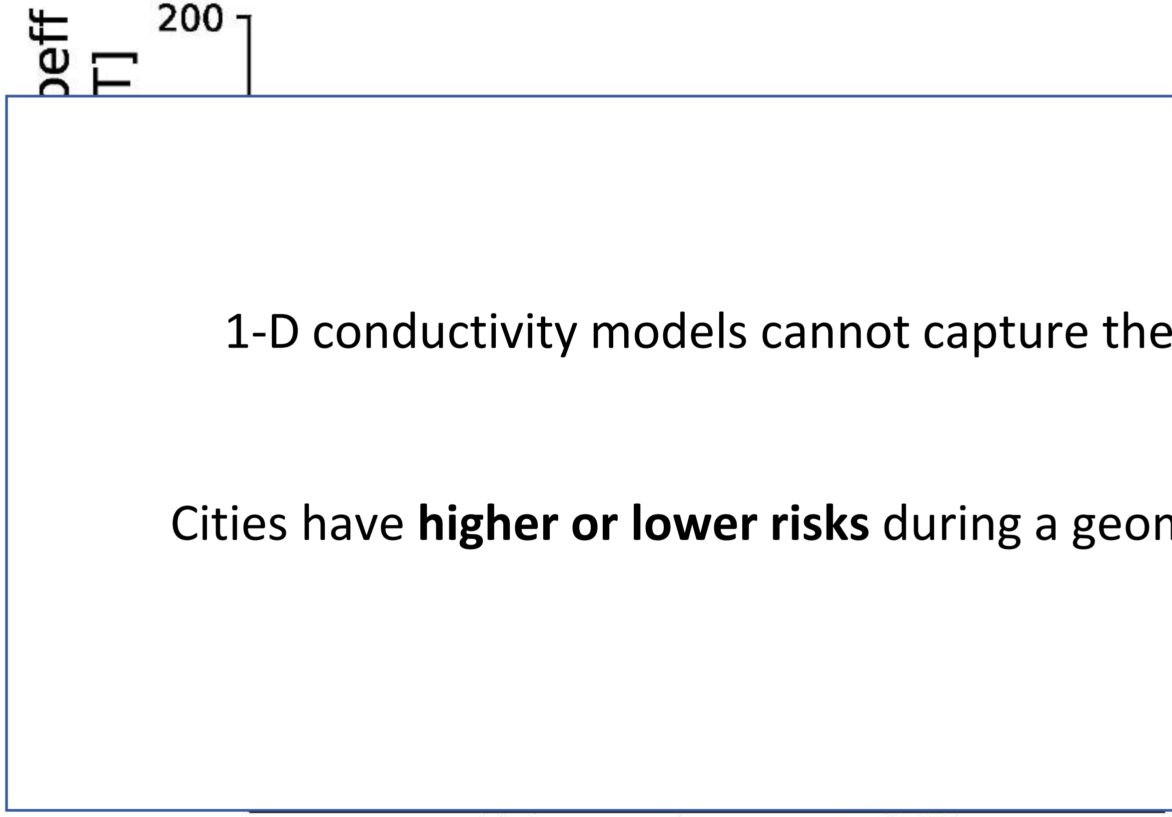


Image Credit: NASA/SDO

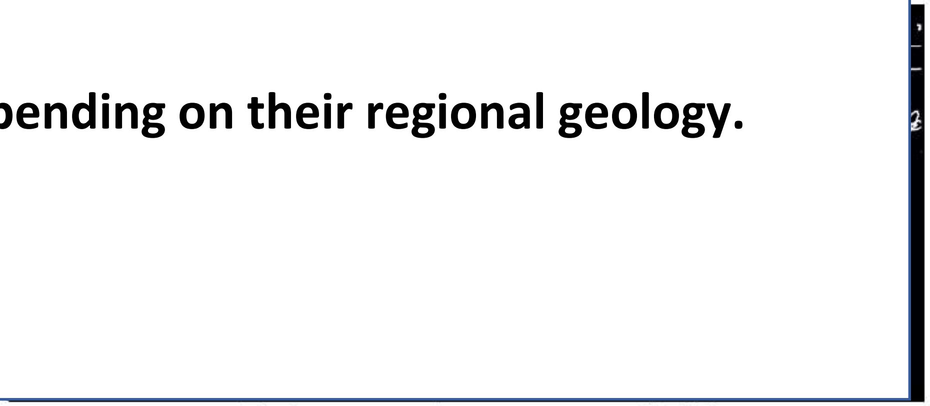
Modelling of St. Patrick’s geomagnetic storm



We model **ground magnetic** and **electric**

1-D conductivity models cannot capture the full complexity of realistic space weather hazards.

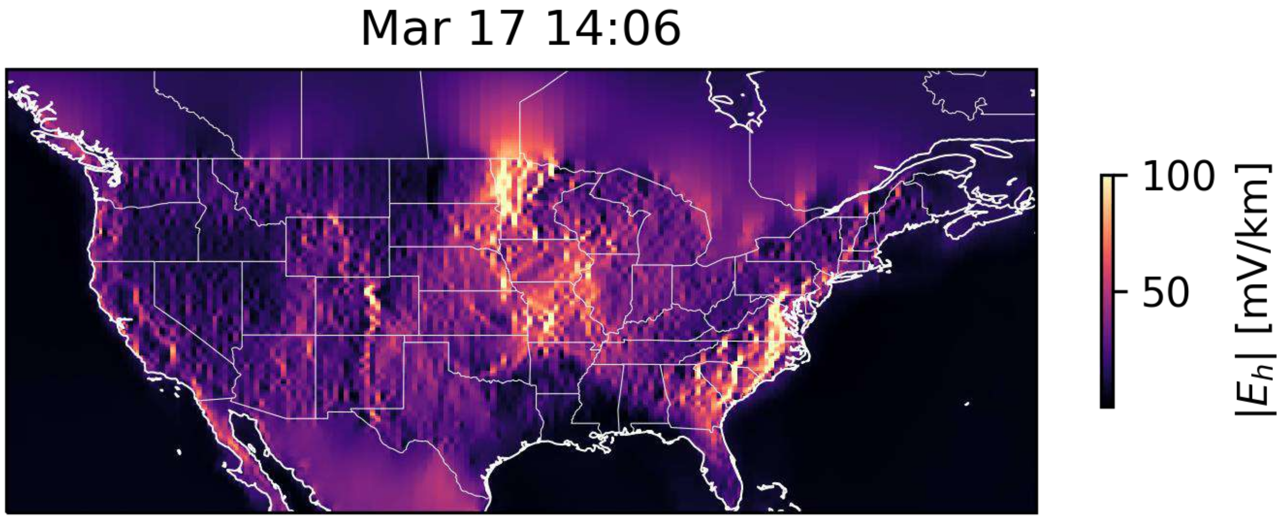
Cities have **higher or lower risks** during a geomagnetic storm **depending on their regional geology.**

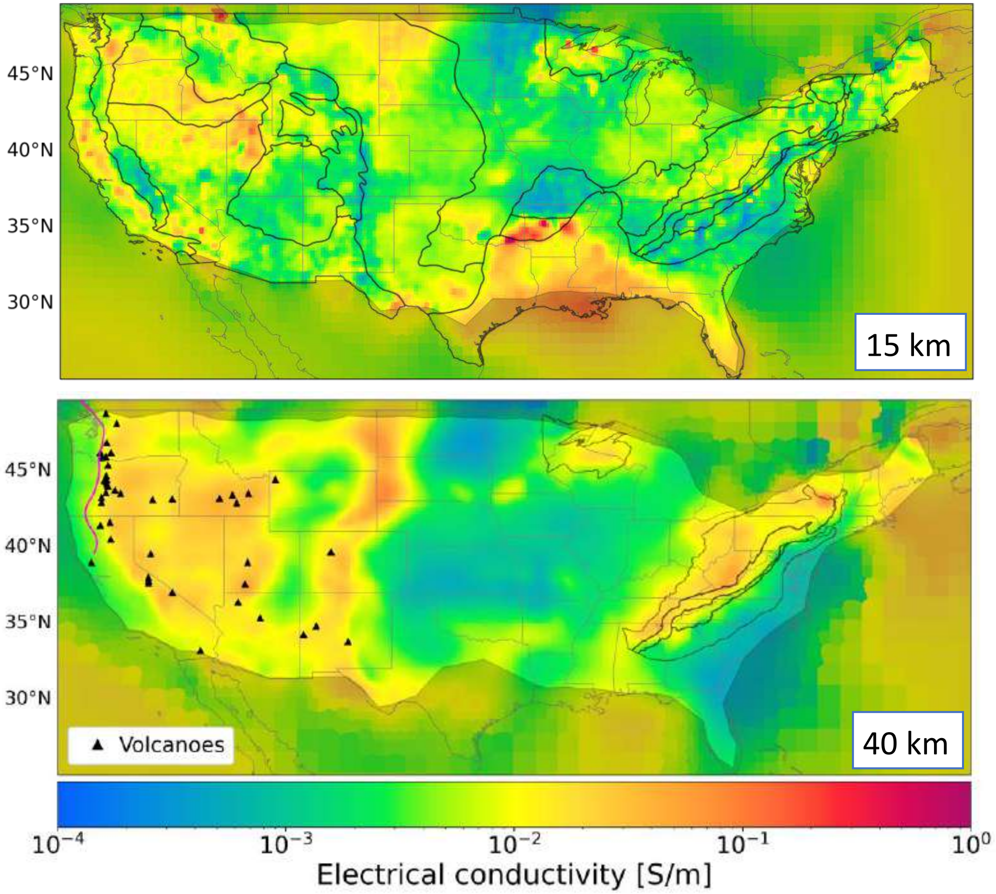


3-D sub-surface conductivity model

1-D sub-surface conductivity model

Modelling Ground Electric Fields





Ground electric fields are controlled by large scale tectonic structures.

Even the deep crustal layers are important for electric field modelling.

Our framework allows for **near real-time modelling (For instance, using Swarm FAST products)**.

Conclusions

- Satellite-based global conductivity models are needed as starting models for continental-scale imaging with ground data.
- Realistic modelling of space weather hazards requires 3-D subsurface conductivity.
- We developed a comprehensive framework to integrate space and ground observations for 3-D conductivity imaging and modelling of GICs.
- These analyses can be extended to other regions (potential product).

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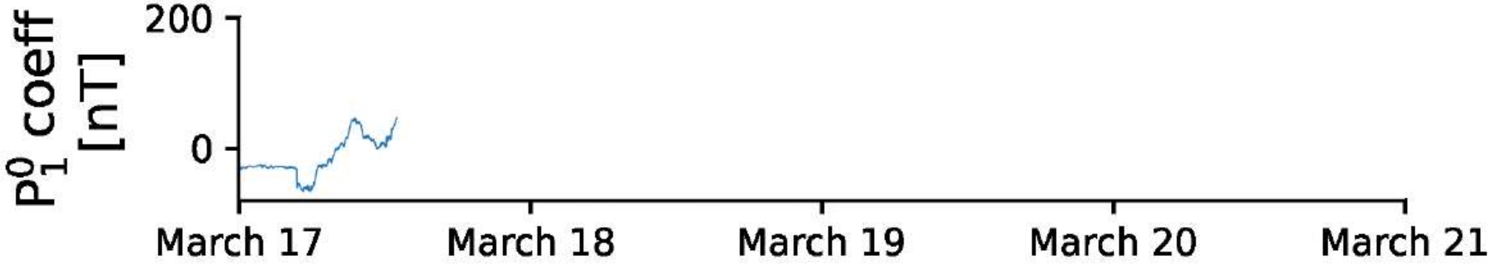
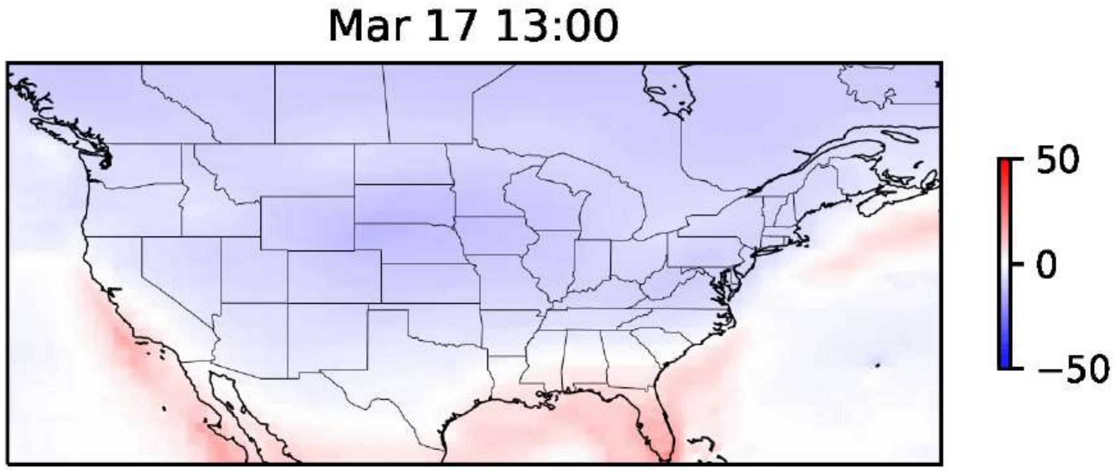
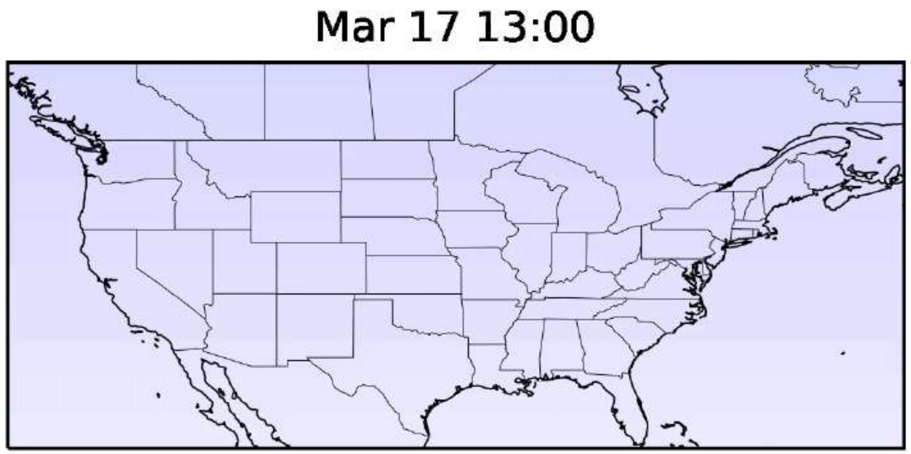
Supplementary Figures

St. Patrick’s geomagnetic storm: Ground Magnetic fields



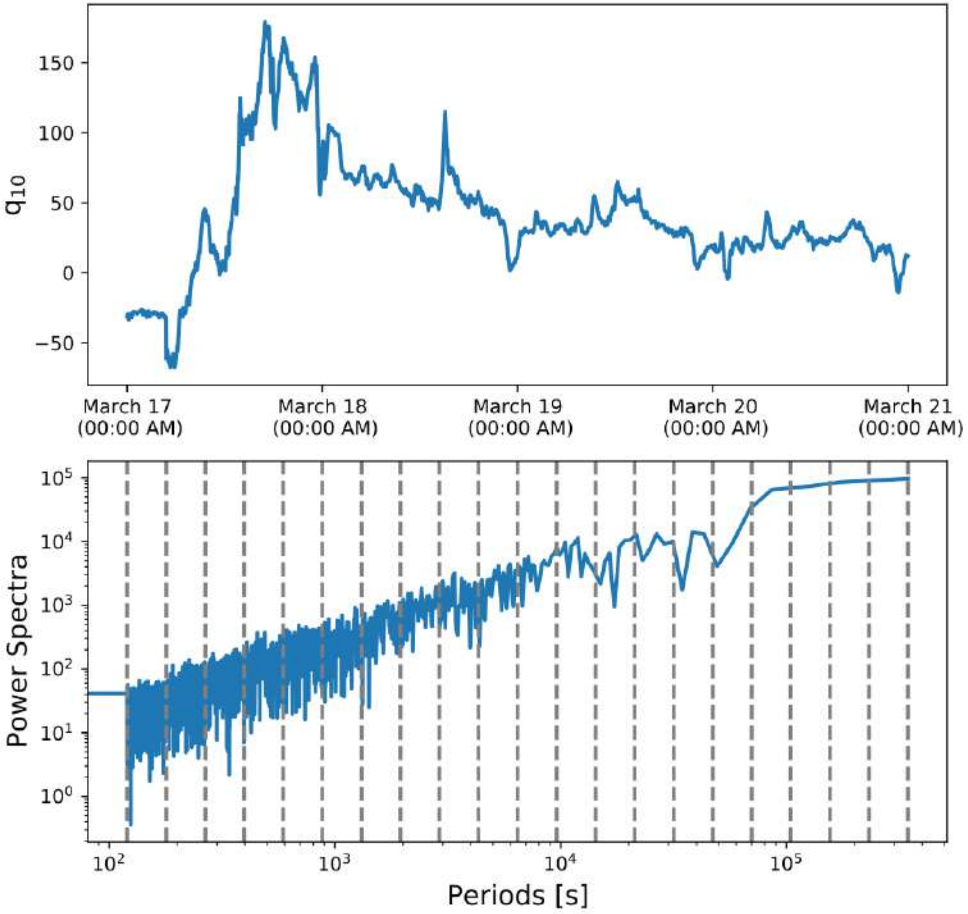


Sub-surface 3D conductivity model



Sub-surface 1D conductivity model

Modelling of ground fields

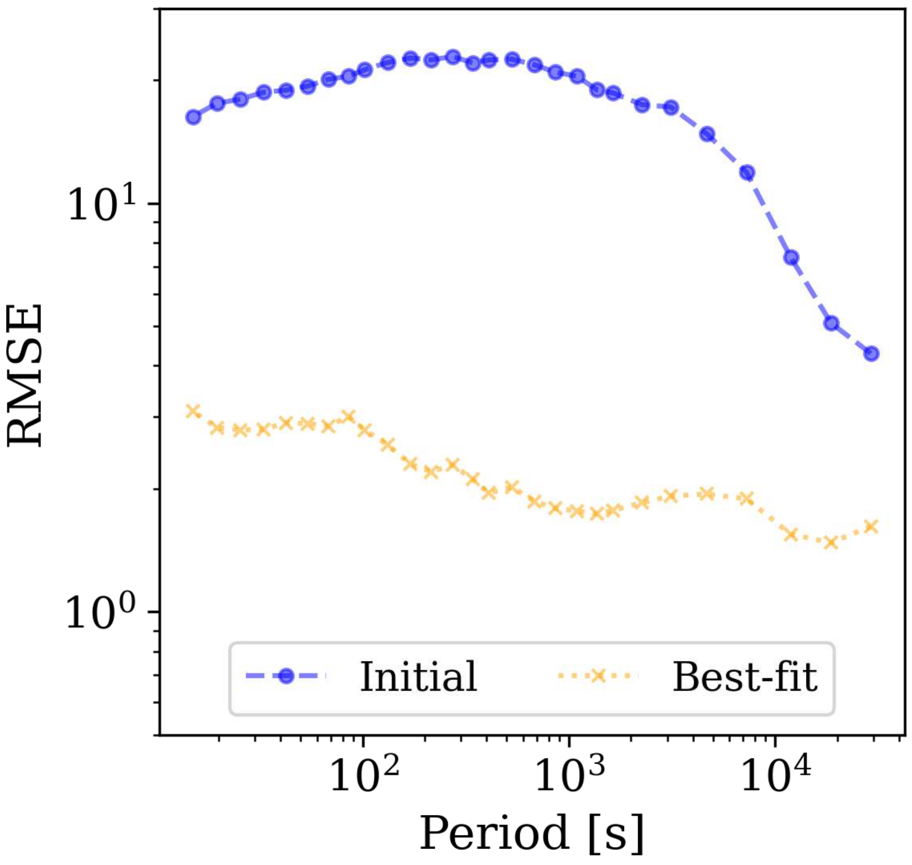


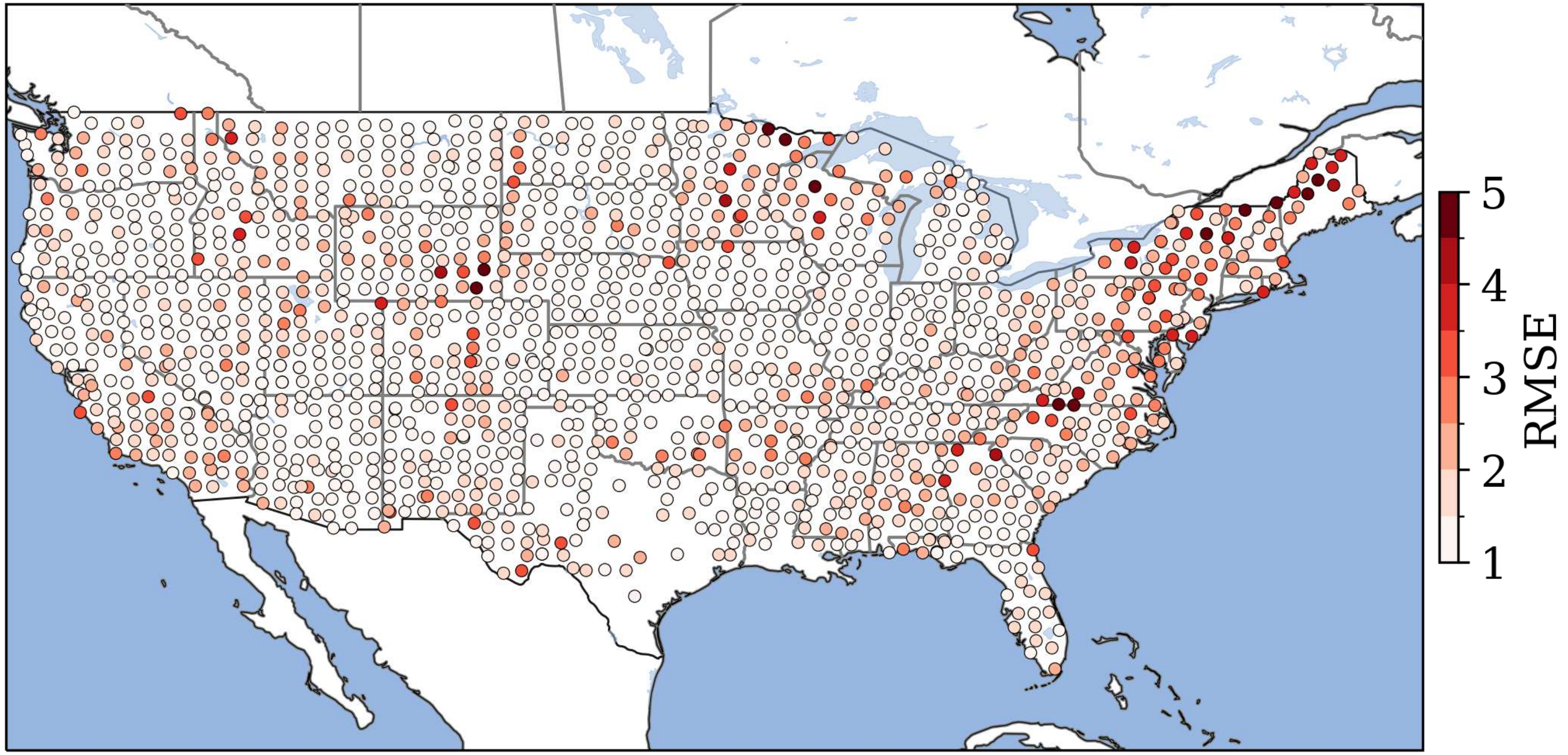
- Compute **unitary responses** at 21 frequencies

- Multiply unitary responses and P_1^0 coefficient (freq domain)

- B-spline interpolation to create the full spectra

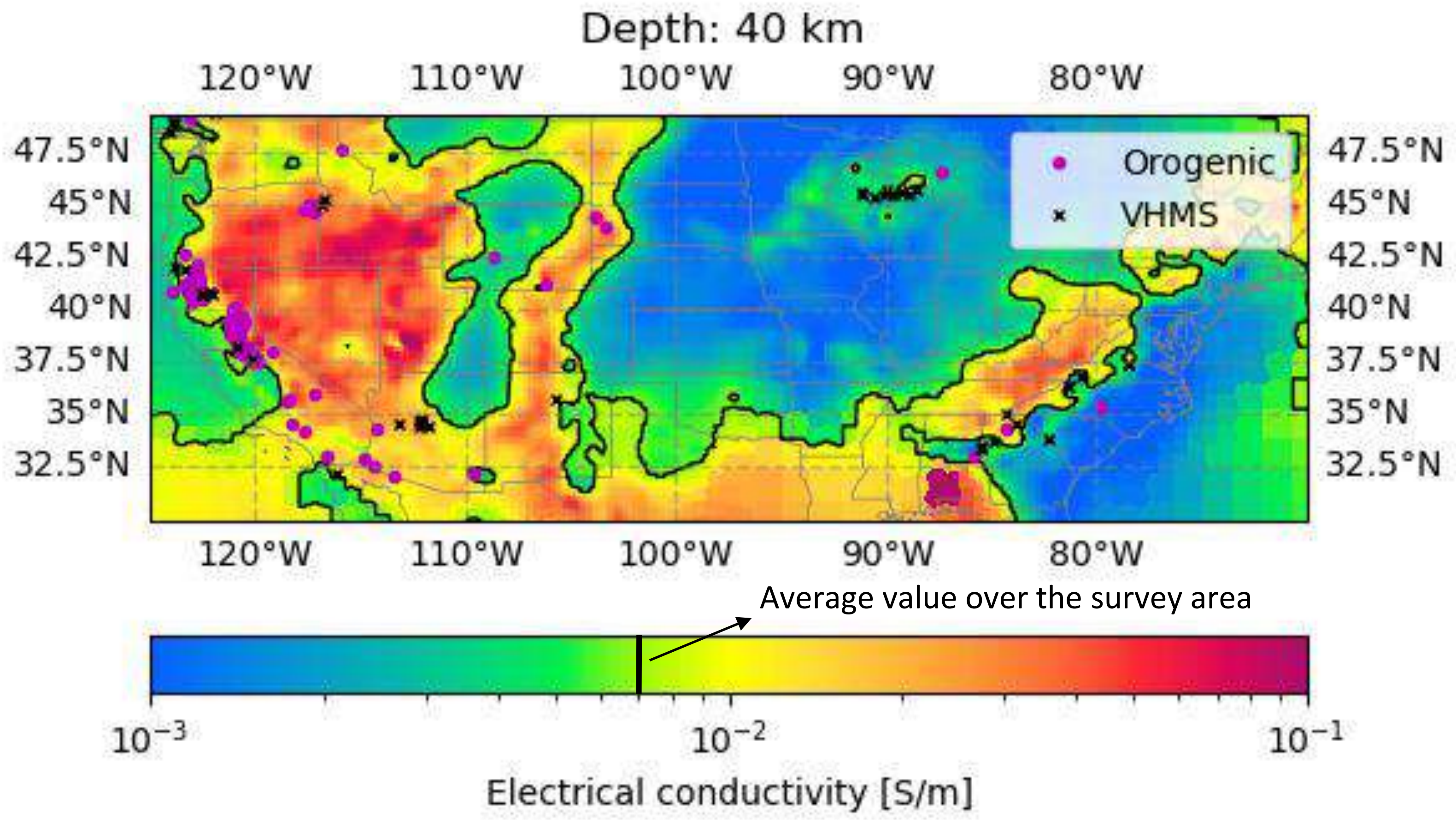
Results - Fit to the data



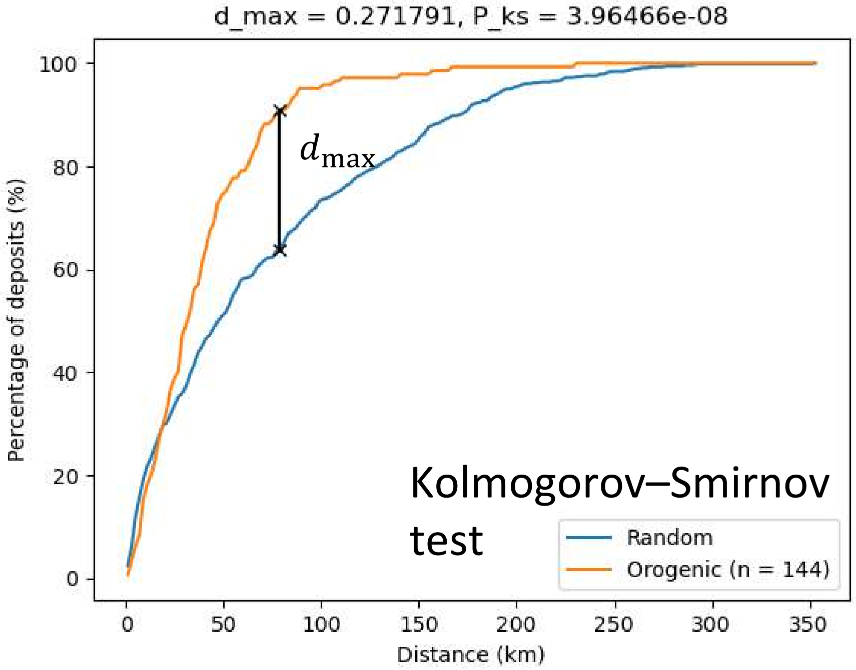


Overall good fit with slightly larger RMSE in some regions

Crustal/lithospheric controls on mineral systems



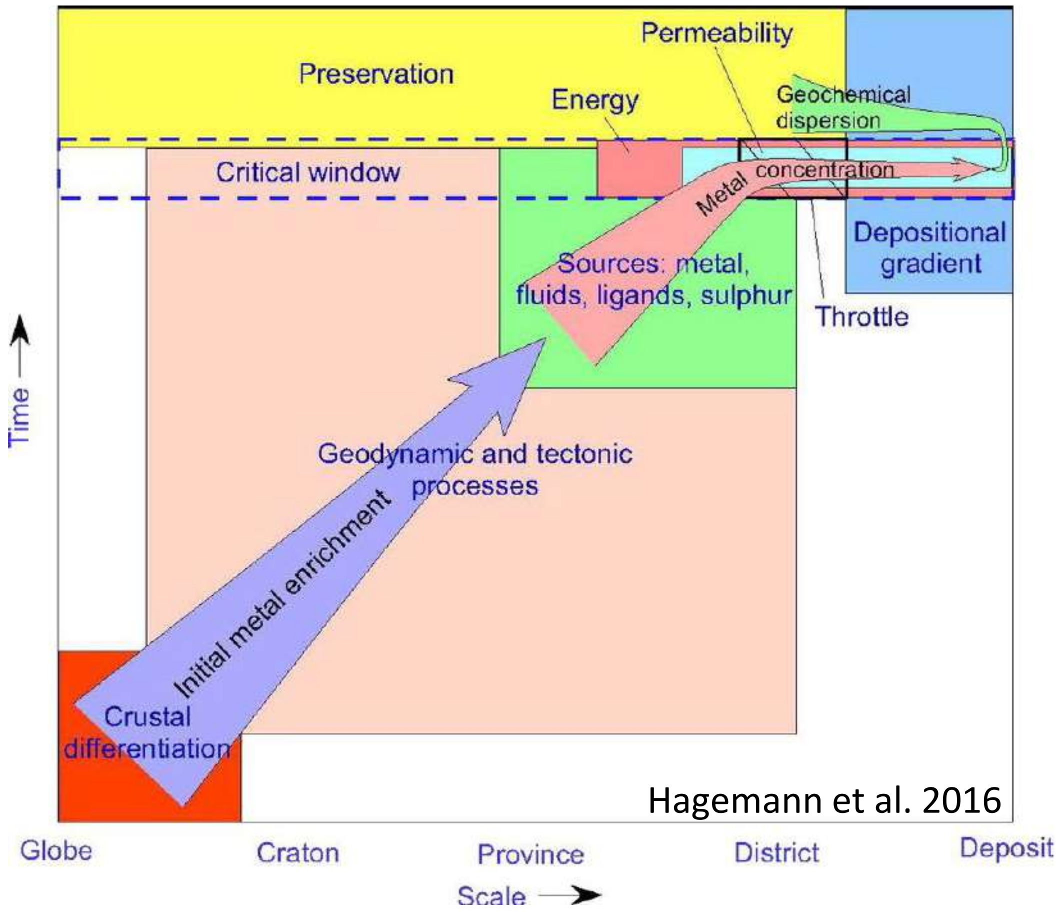
Average value over the survey area



Kolmogorov–Smirnov test

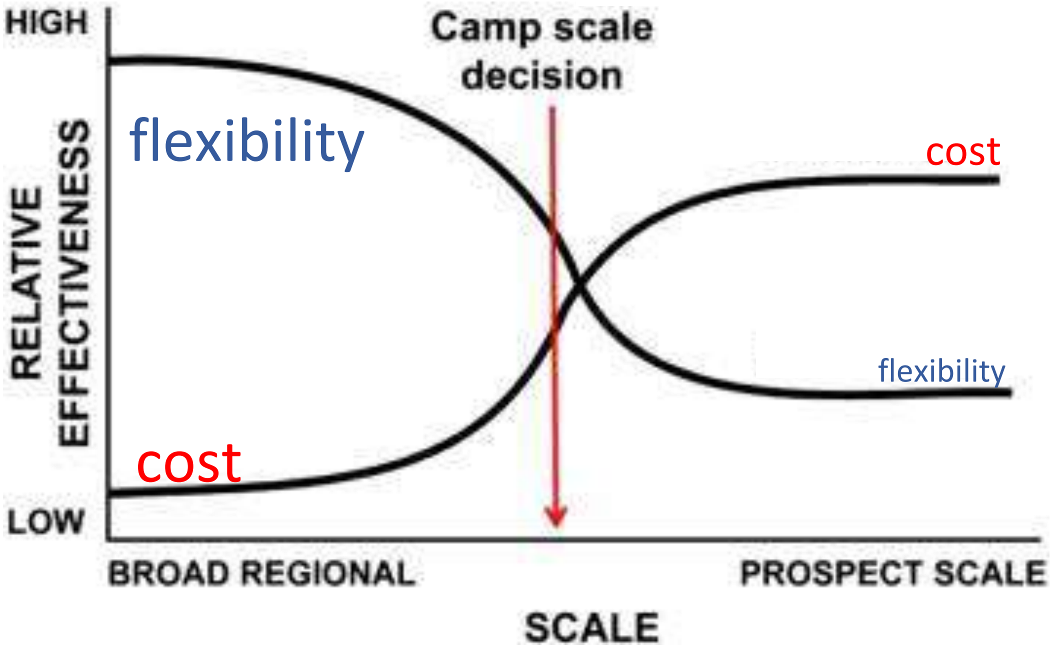
93% of orogenic gold deposits are located < 100 km of the 150 Ωm isoline at 40km depth (Kirkby et al, 2022; Murphy et al., 2022)

Crustal/lithospheric controls on mineral systems



Hagemann et al. 2016

(Kemp scale decision)

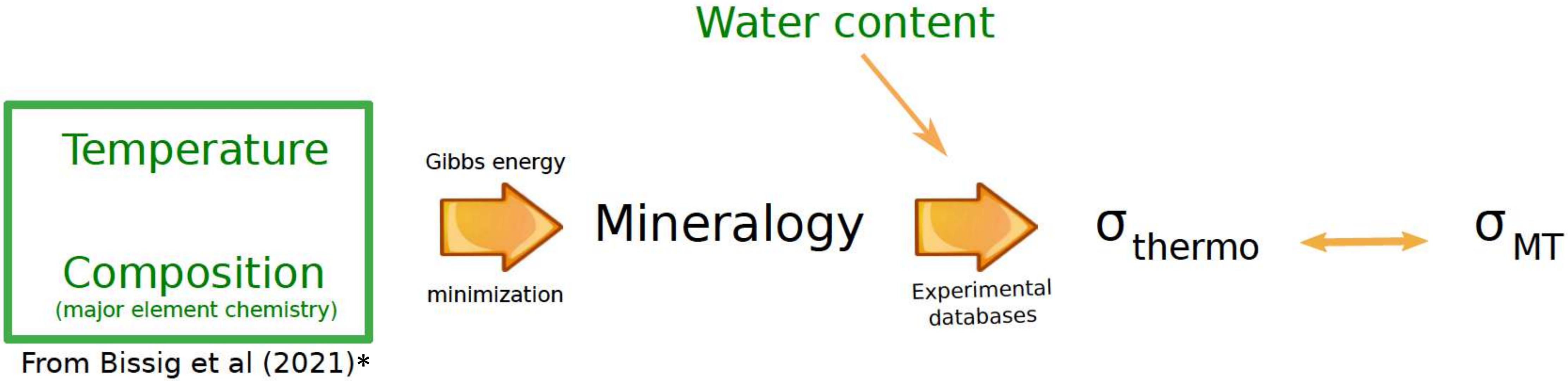


McCuaig et al. 2014

Discerning use of MT can be a powerful tool for mineral exploration and green energy transition

Towards the integration of seismic and EM data

Bissig et al. (2021) inferred mantle temperature and composition from seismic data (Ps and Sp converted waves) recorded at the USArray



Water content

Temperature

Composition

(major element chemistry)

From Bissig et al (2021)*

Gibbs energy minimization

Mineralogy

Experimental databases

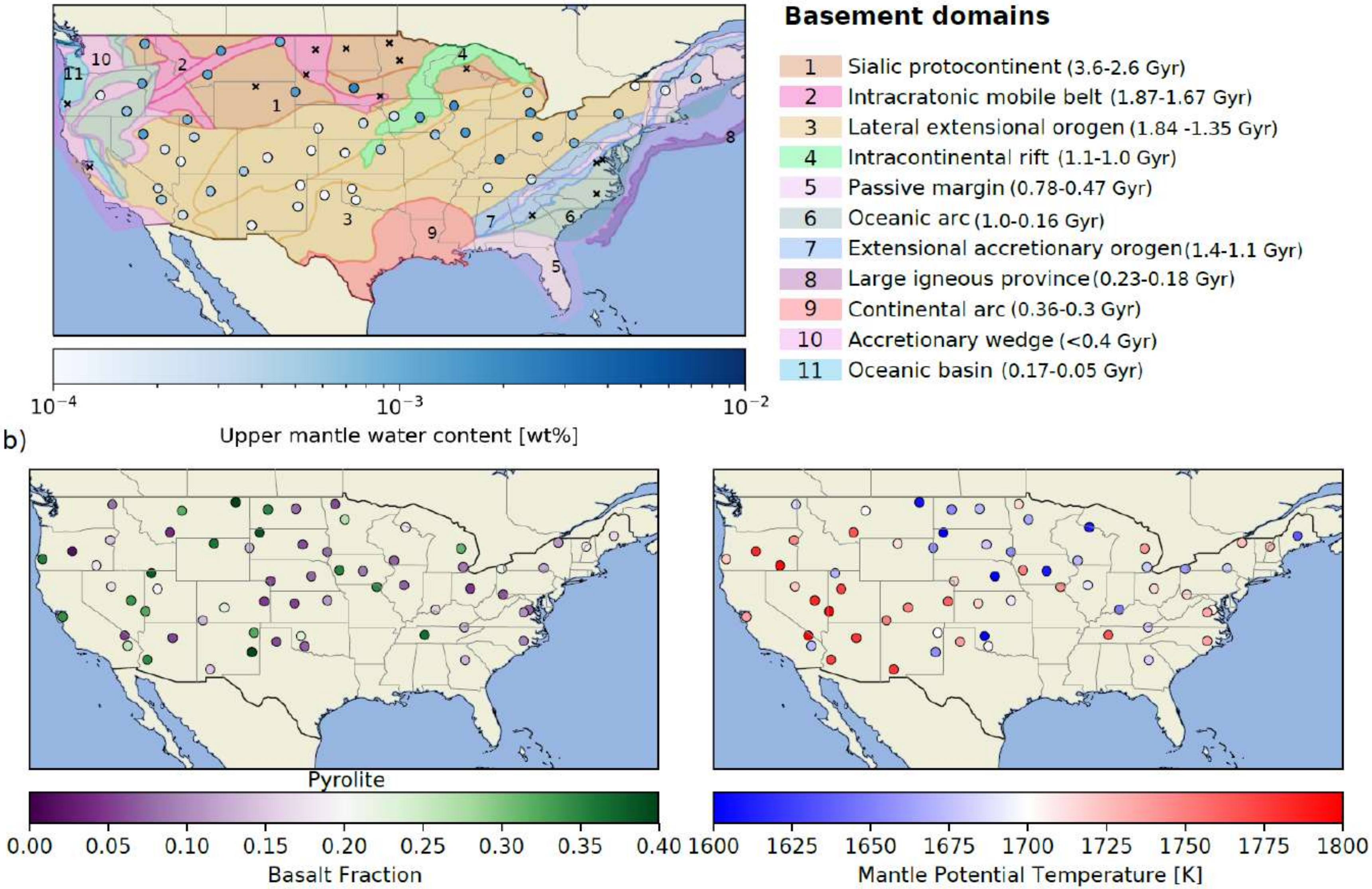
σ_{thermo} ↔ σ_{MT}

What upper mantle (200-350 km depth) water contents best explain the MT-derived electrical conductivities?

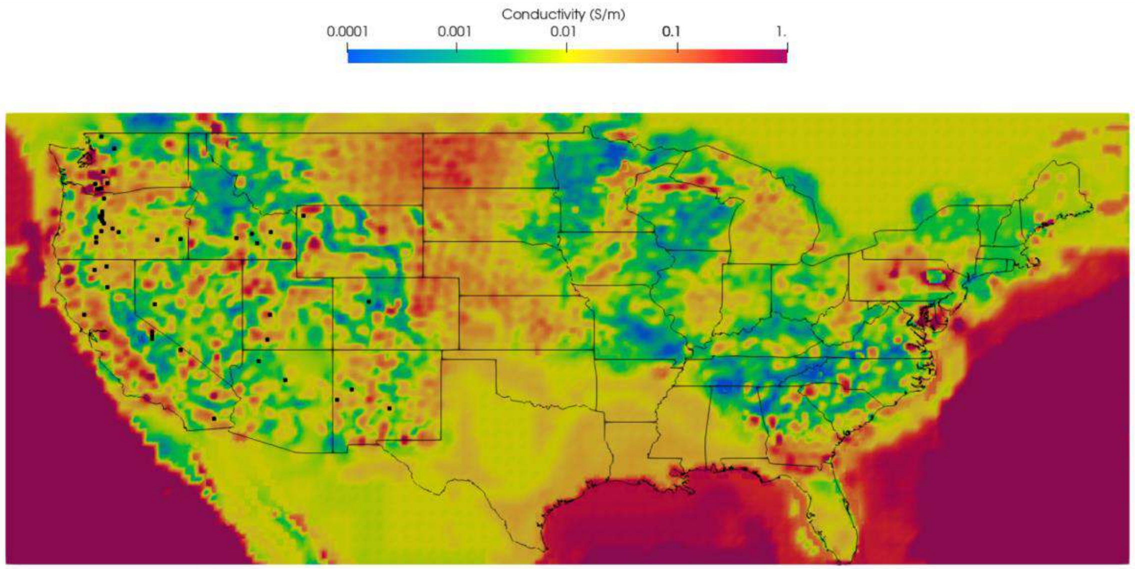
*See also Munch et al (2020, GRL)

Joint Inversion of Daily and Long-Period Geomagnetic Transfer Functions Reveals Lateral Variations in Mantle Water Content

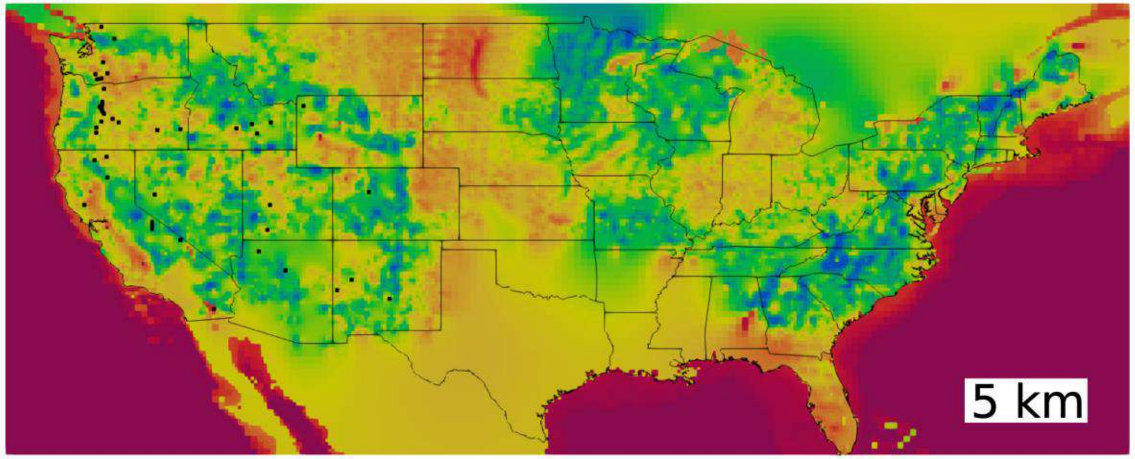
Implications for the upper mantle water content



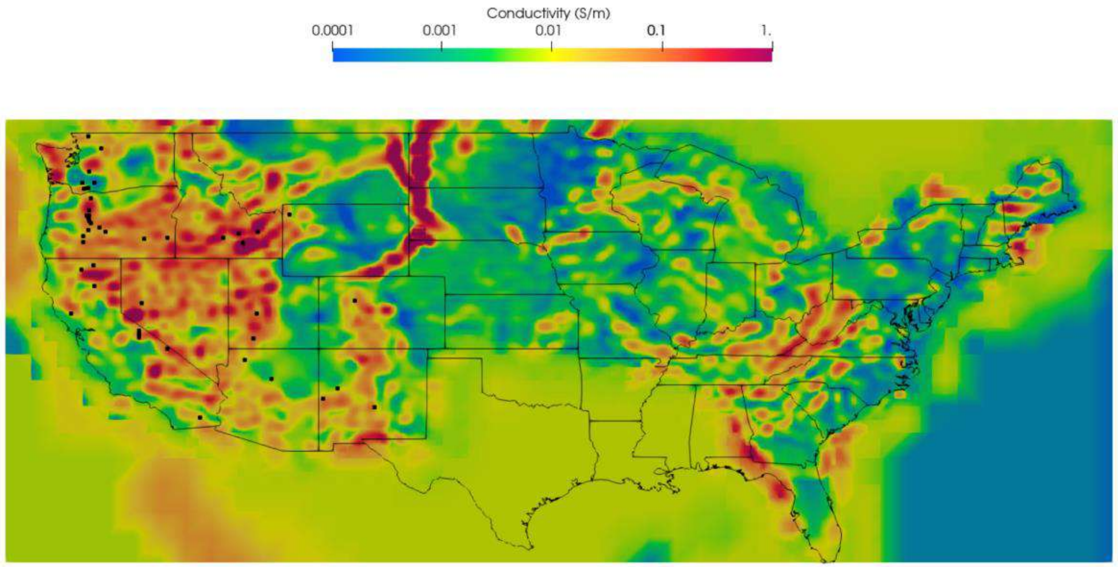
Munch and Grayver (2023, EPSL)



CONUS-MT 2021
(Murphy et al., 2021)



This study



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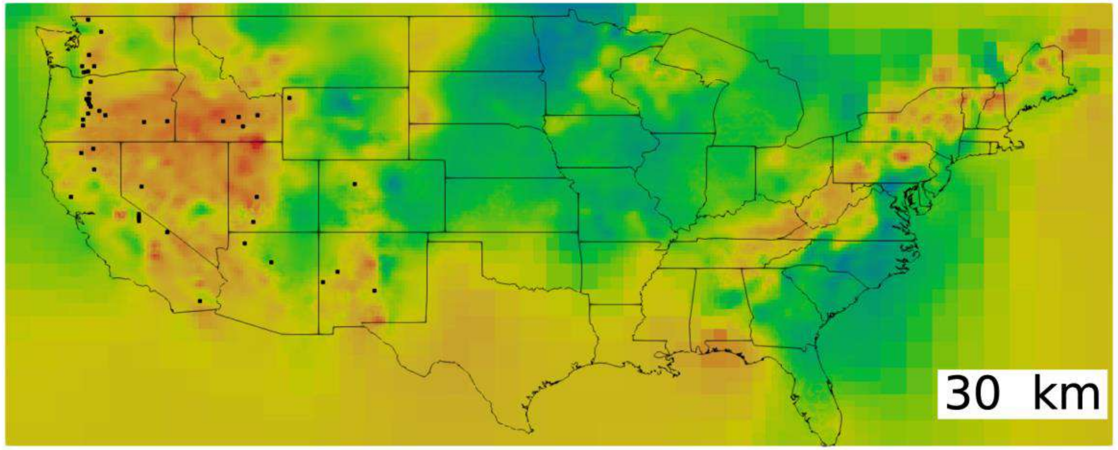

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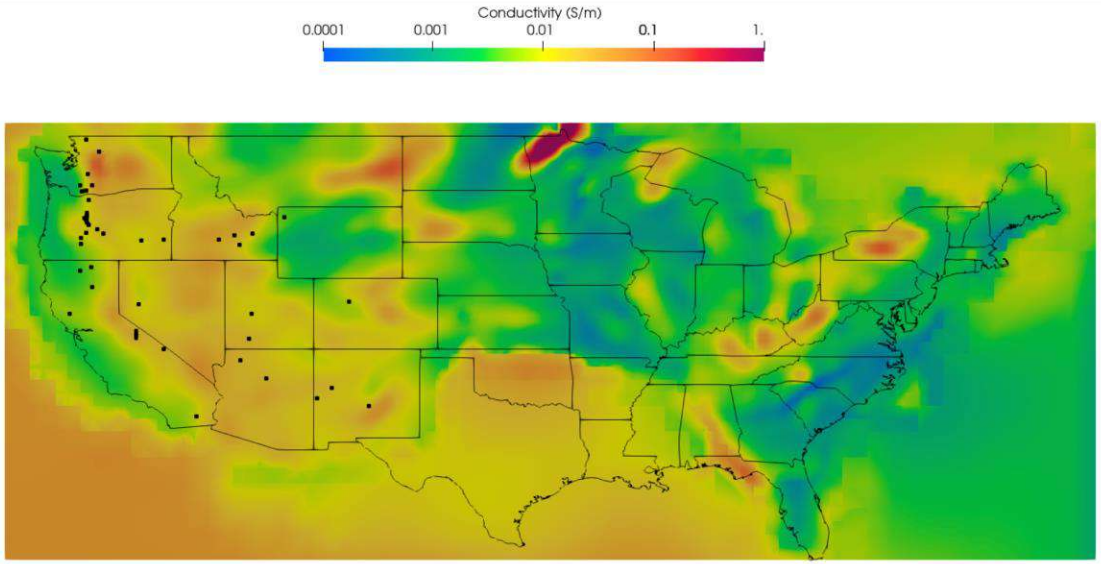

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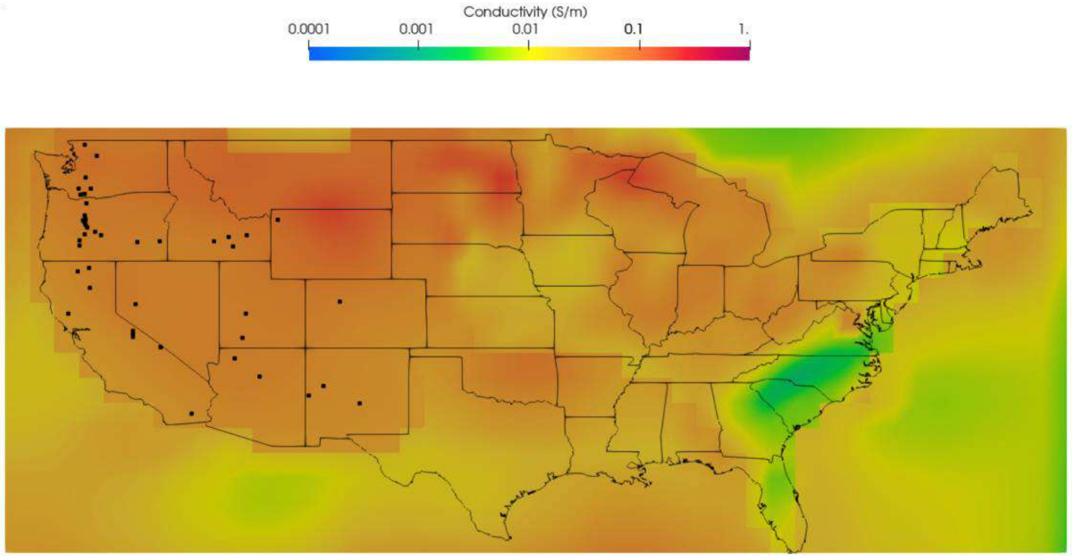

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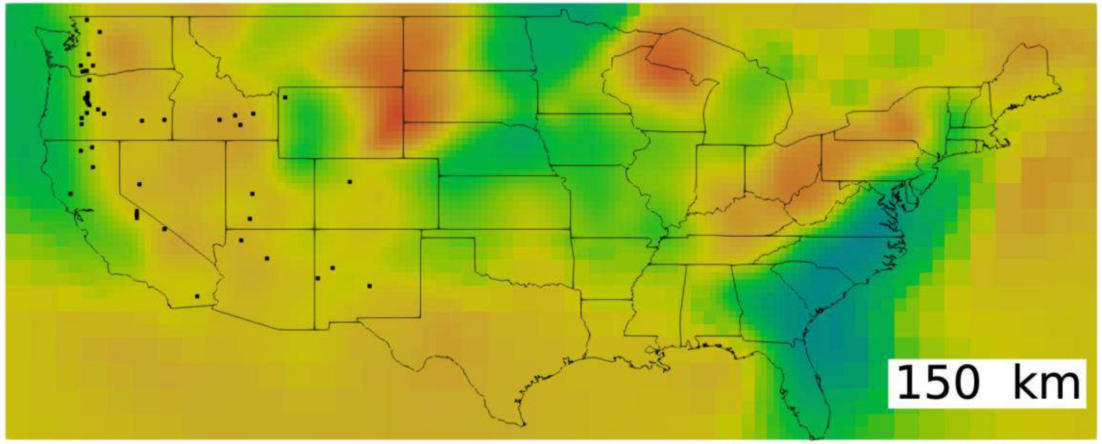

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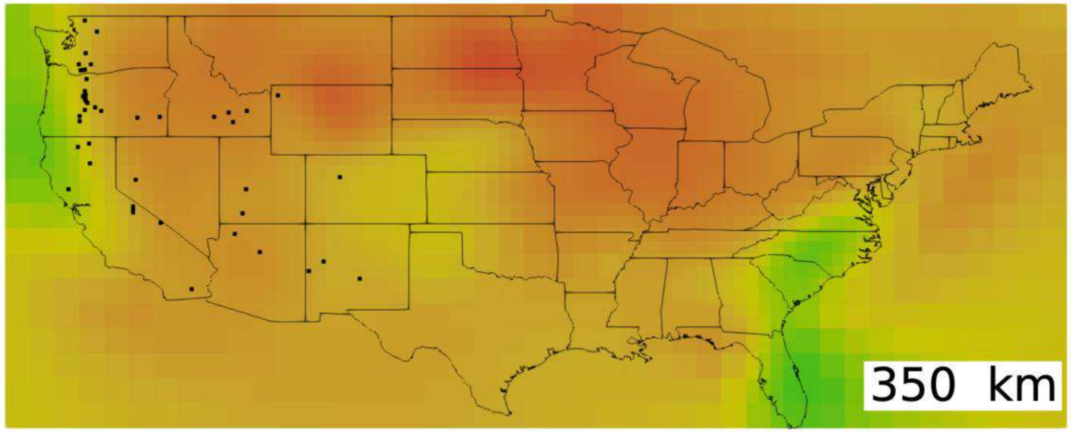

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