Magali: open software for inversion and analysis of magnetic microscopy data 🧲🔬

Yago Moreira Castro, Leonardo Uieda, Gelson Ferreira de Souza-Junior

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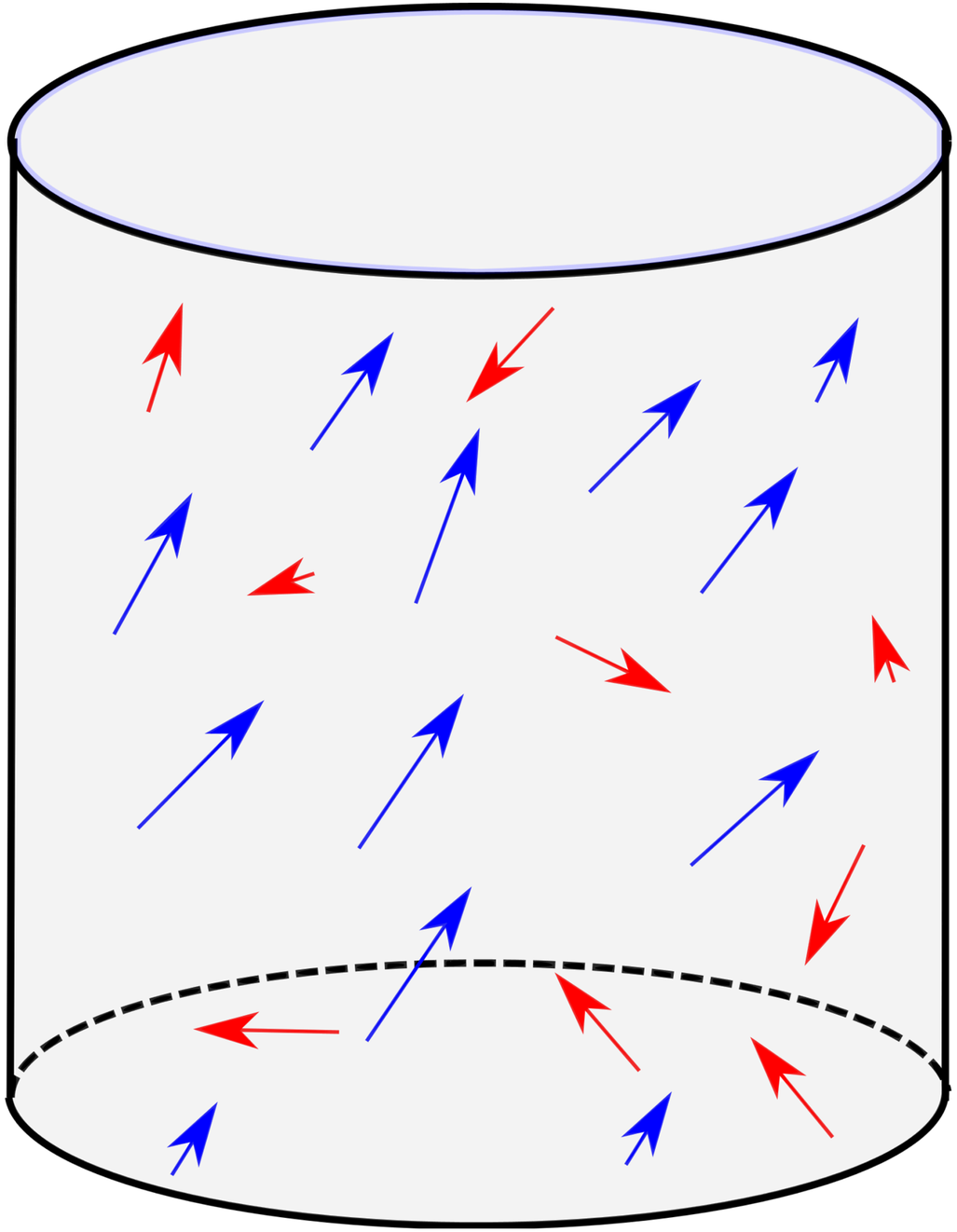
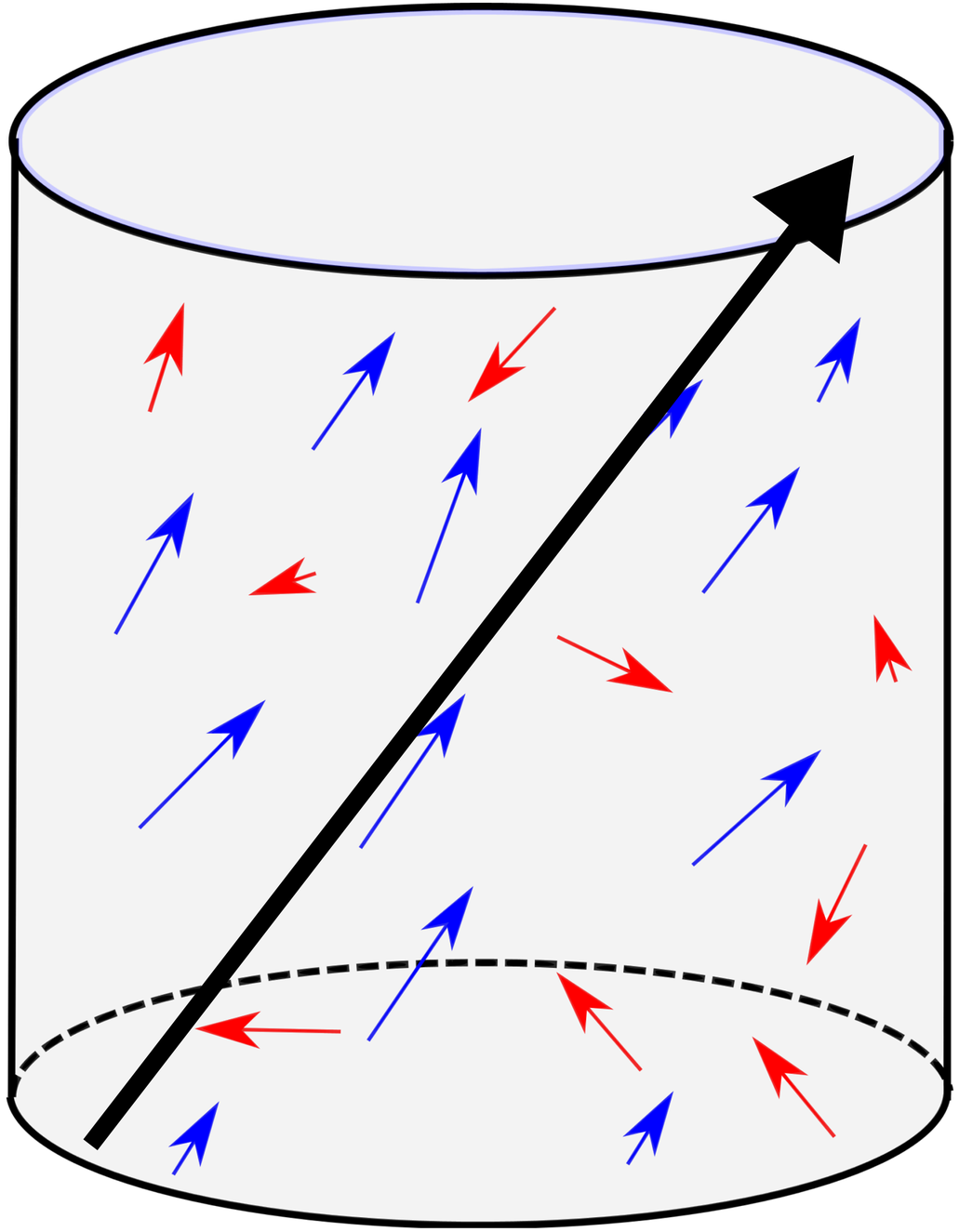
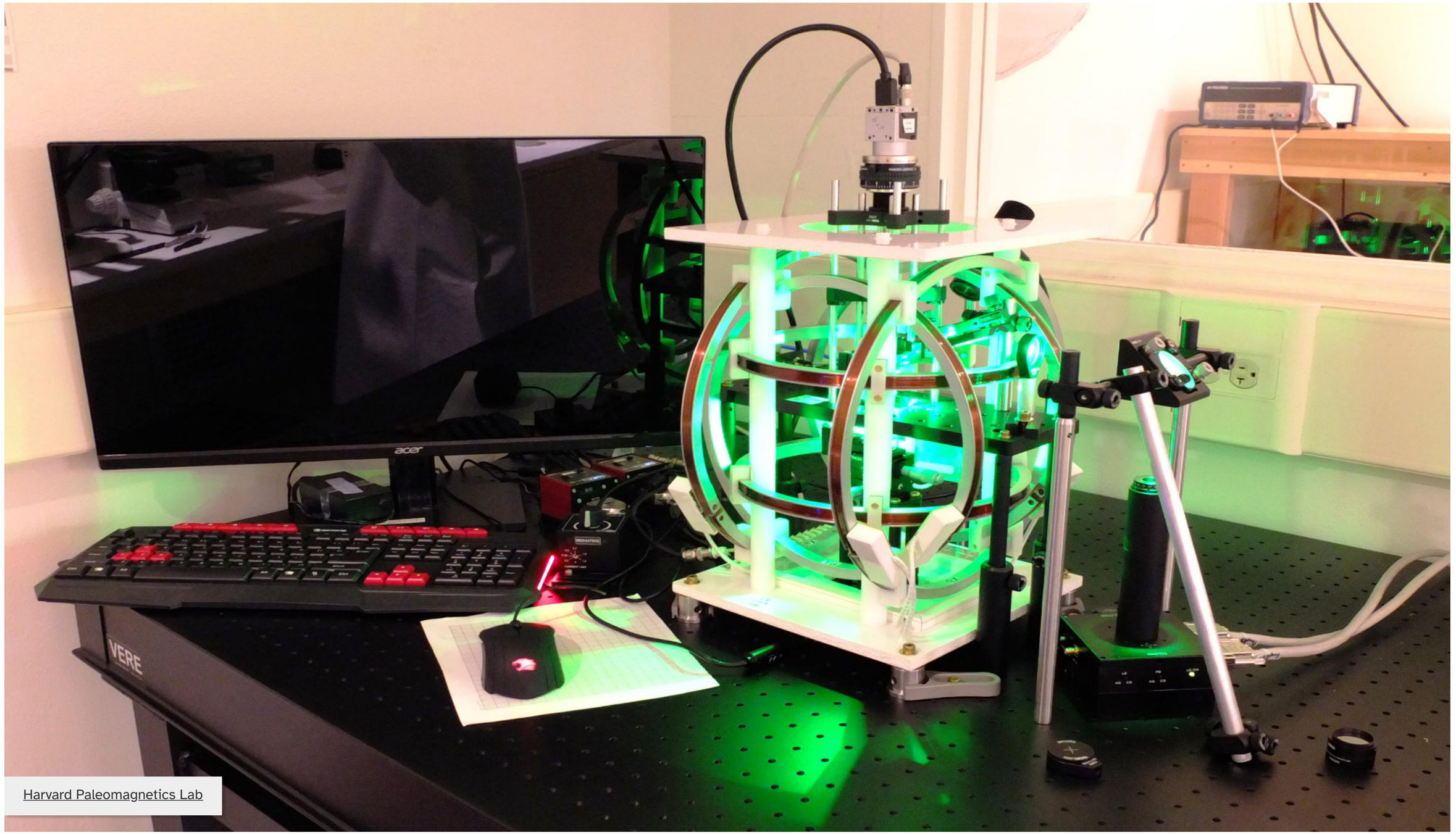
COMPUTER-ORIENTED GEOSCIENCE LAB

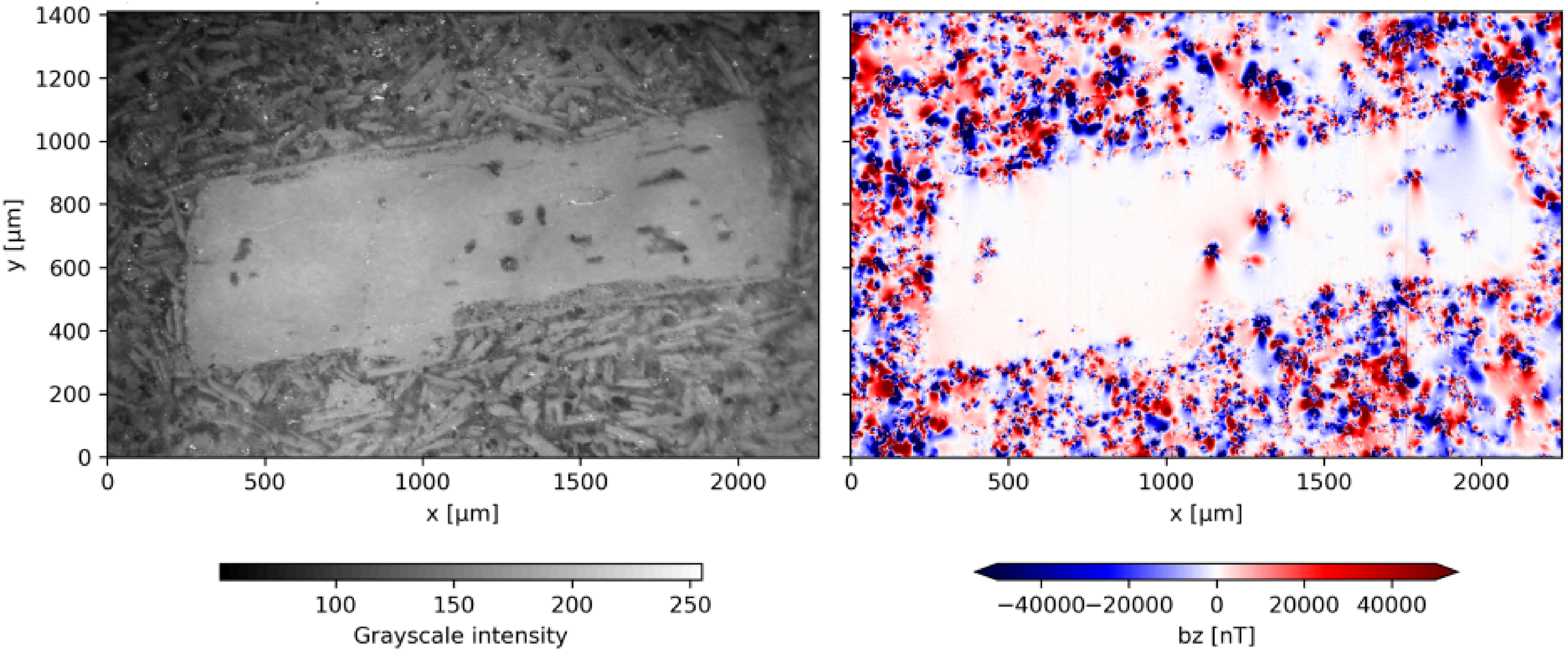
INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS







Harvard Paleomagnetics Lab



Souza-Junior et al 2024

Research Article | Open Access

Does size matter? Statistical limits of paleomagnetic field reconstruction from small rock specimens

Thomas Berndt, Adrian R. Muxworthy, Karl Fabian

First published: 14 December 2015 | https://doi.org/10.1002/2015JB012441 | Citations: 46

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Geophysical Research Letters®

Research Letter | Open Access

Efficiency of Thermoremanent Magnetization Acquisition in Vortex-State Particle Assemblies

U. D. Bellon, W. Williams, A. R. Muxworthy, G. F. Souza-Junior, L. Nagy, L. Uieda, R. I. F. Trindade

First published: 23 April 2025 | https://doi.org/10.1029/2025GL114771 | Citations: 2

Bellon et al. (2025)

- Bellon et al. (2025) modeled vortex-state grains, a more realistic scenario, using micromagnetic simulations.

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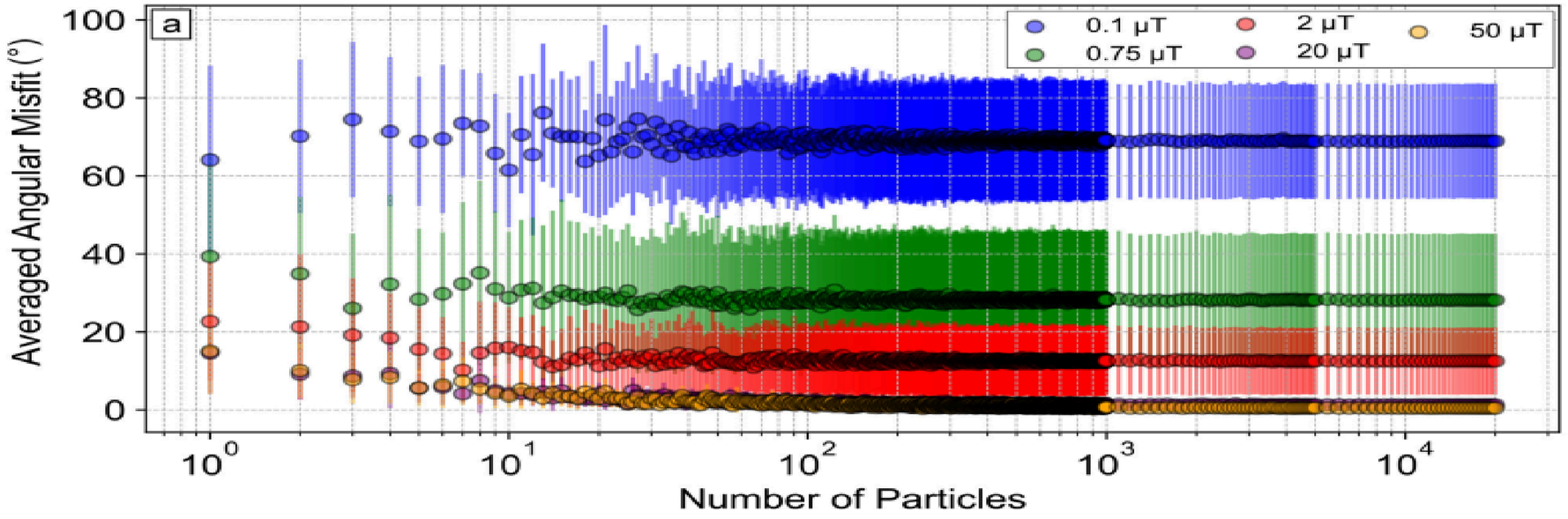
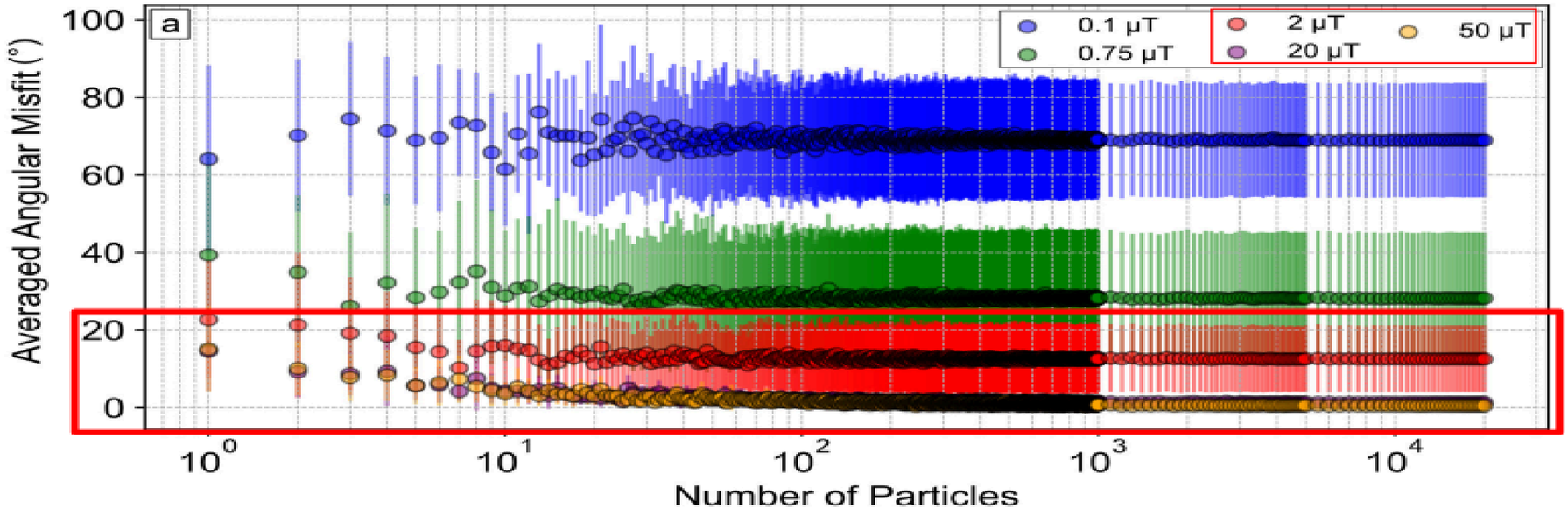
- **Hundreds to thousands** of vortex-state grains record a reliable TRM, indicating that the field was not ultra-weak.

Bellon et al. (2025)


a
0.1 µT
0.75 µT
2 µT
20 µT
50 µT
Averaged Angular Misfit (°)
100
80
60
40
20
0
10^0
10^1
10^2
10^3
10^4
Number of Particles


a
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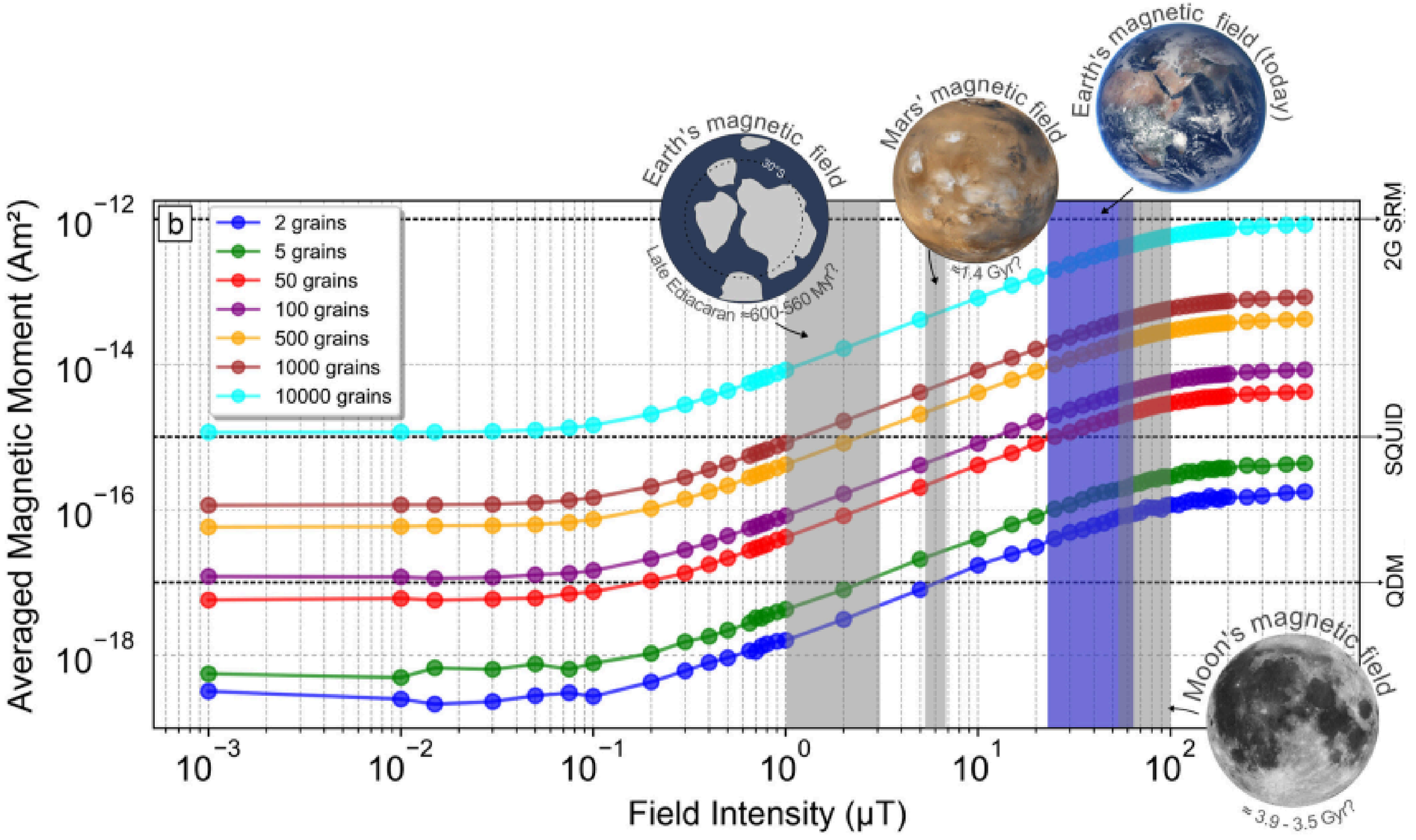
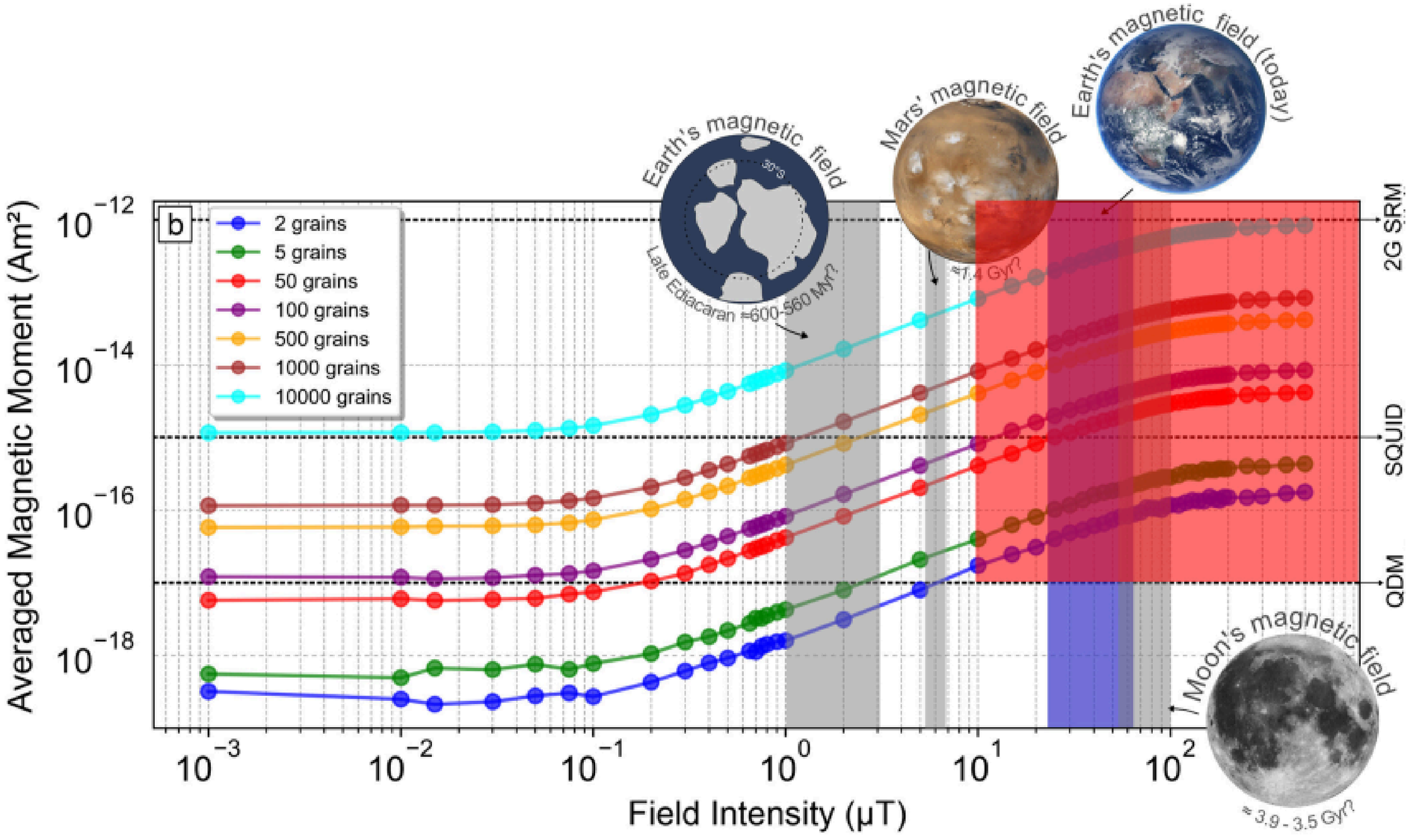

b
2 grains
5 grains
50 grains
100 grains
500 grains
1000 grains
10000 grains
Averaged Magnetic Moment (Am²)
Field Intensity (μT)
2G SRM
SQUID
QDM
Earth's magnetic field
Late Ediacaran ≈600-560 Myr?
Mars' magnetic field
≈1.4 Gyr?
Earth's magnetic field (today)
Moon's magnetic field
≈ 3.9 - 3.5 Gyr?


b
2 grains
5 grains
50 grains
100 grains
500 grains
1000 grains
10000 grains
Averaged Magnetic Moment (Am²)
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
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Full Vector Inversion of Magnetic Microscopy Images Using Euler Deconvolution as Prior Information

Gelson F. Souza-Junior[1], Leonardo Uieda[1,2], Ricardo I. F. Trindade[1], Janine Carmo[1], and Roger Fu[3]

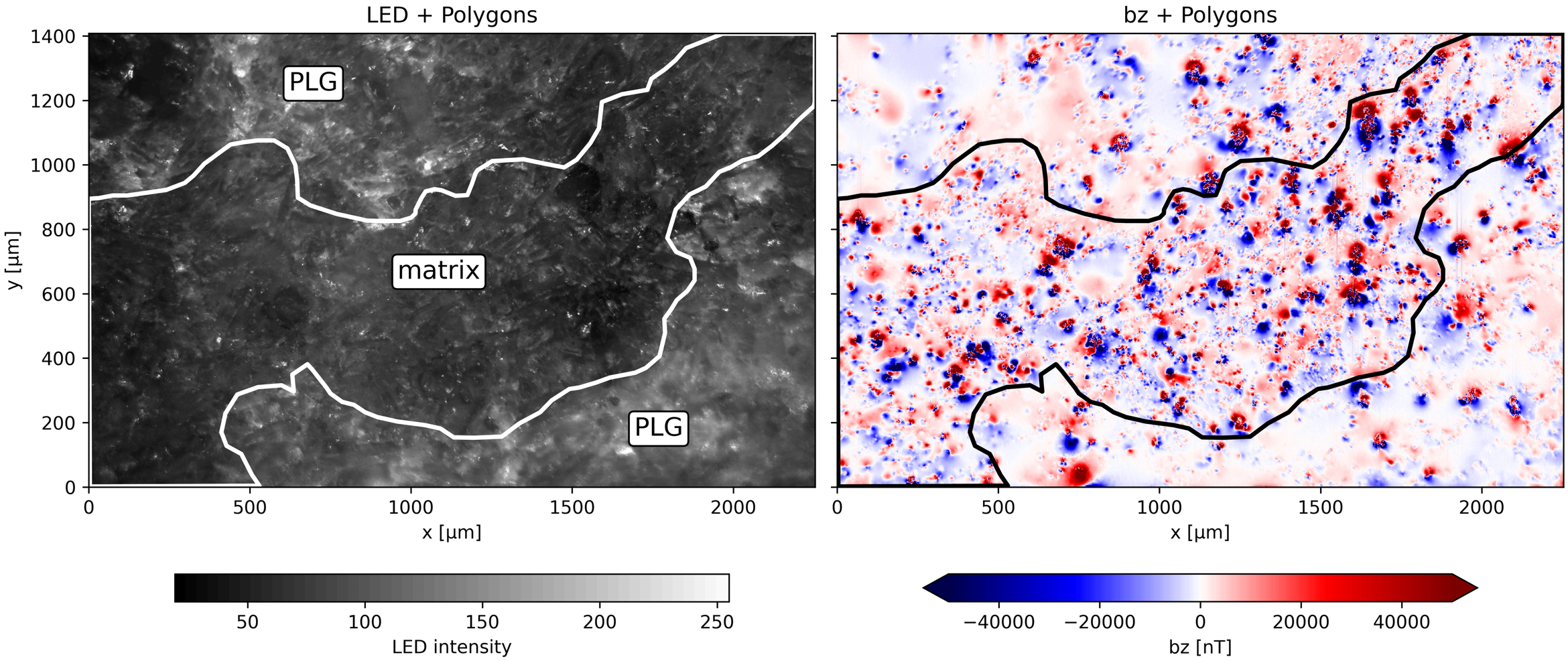
[1]Universidade de São Paulo, São Paulo, Brazil, [2]University of Liverpool, Liverpool, UK, [3]Harvard University, Cambridge, MA, USA

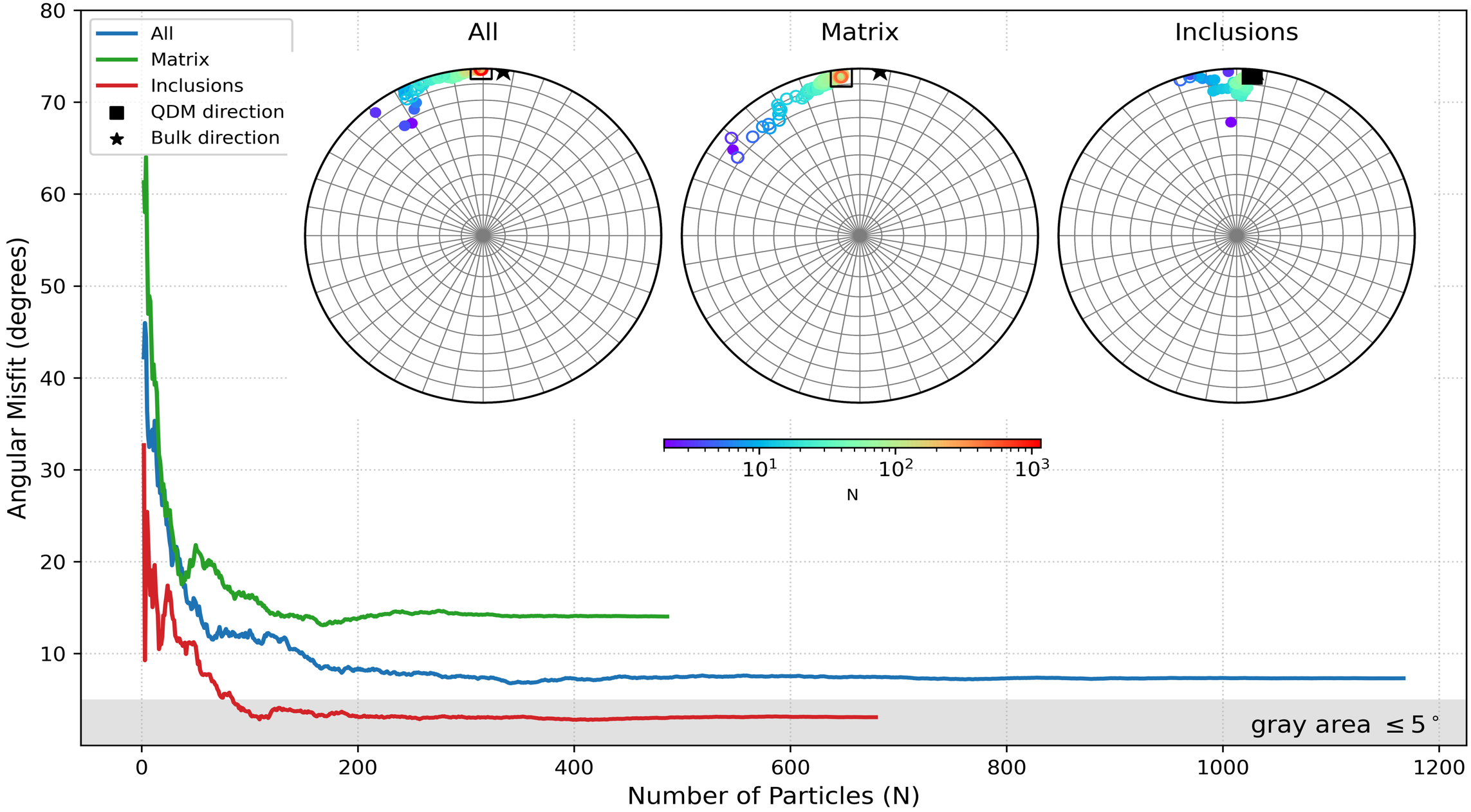
Robust directional analysis of magnetic microscopy images using non-linear inversion and iterative Euler deconvolution

Gelson F. Souza-Junior[1,2], Leonardo Uieda[1], Ricardo I. F. Trindade[1], Roger R. Fu[2], Ualisson D. Bellon[3] and Yago M. Castro[1]

[1] Universidade de São Paulo, Brazil; [2] Harvard University, USA; [3] University of Edinburgh, UK.

Corresponding author: Gelson F. Souza-Junior <gelson.ferreira@usp.br>


LED + Polygons
bz + Polygons
PLG
matrix
PLG
y [µm]
x [µm]
x [µm]
LED intensity
bz [nT]


All
Matrix
Inclusions
QDM direction
Bulk direction
All
Matrix
Inclusions
10^1
10^2
10^3
N
Angular Misfit (degrees)
Number of Particles (N)
gray area ≤ 5 °
0
200
400
600
800
1000
1200
10
20
30
40
50
60
70
80

Needs

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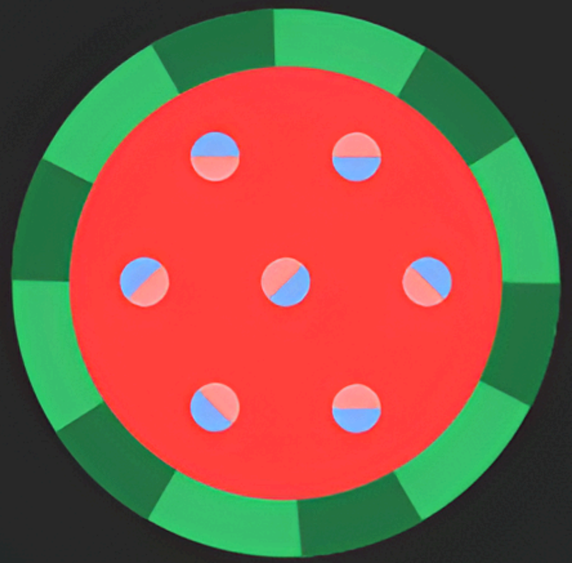
- **Open software** for forward **modelling** and **inversion** techniques specific to magnetic microscopy
- **Data conventions**



magali

What is Magali?

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Free and open source

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Python library

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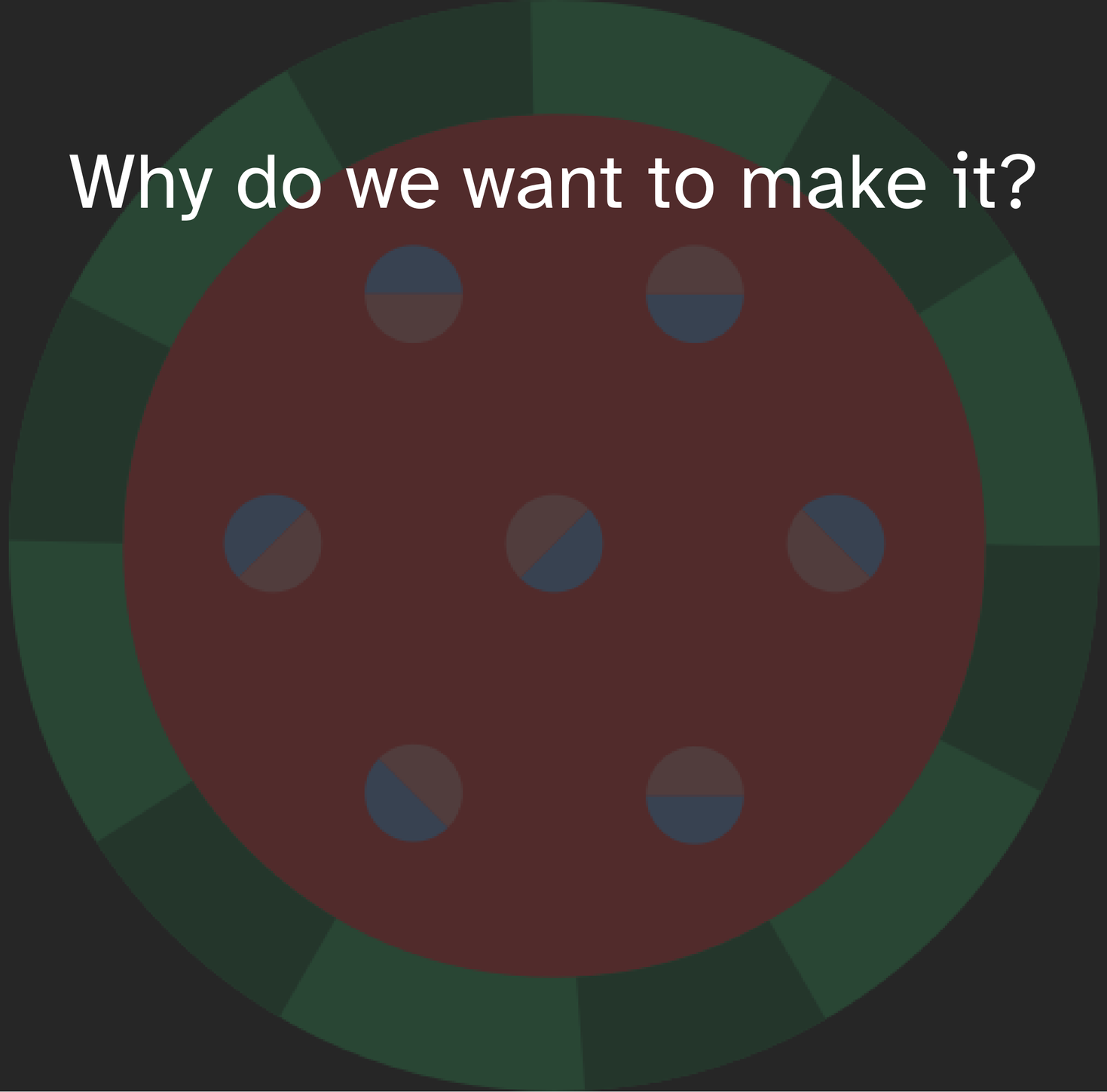
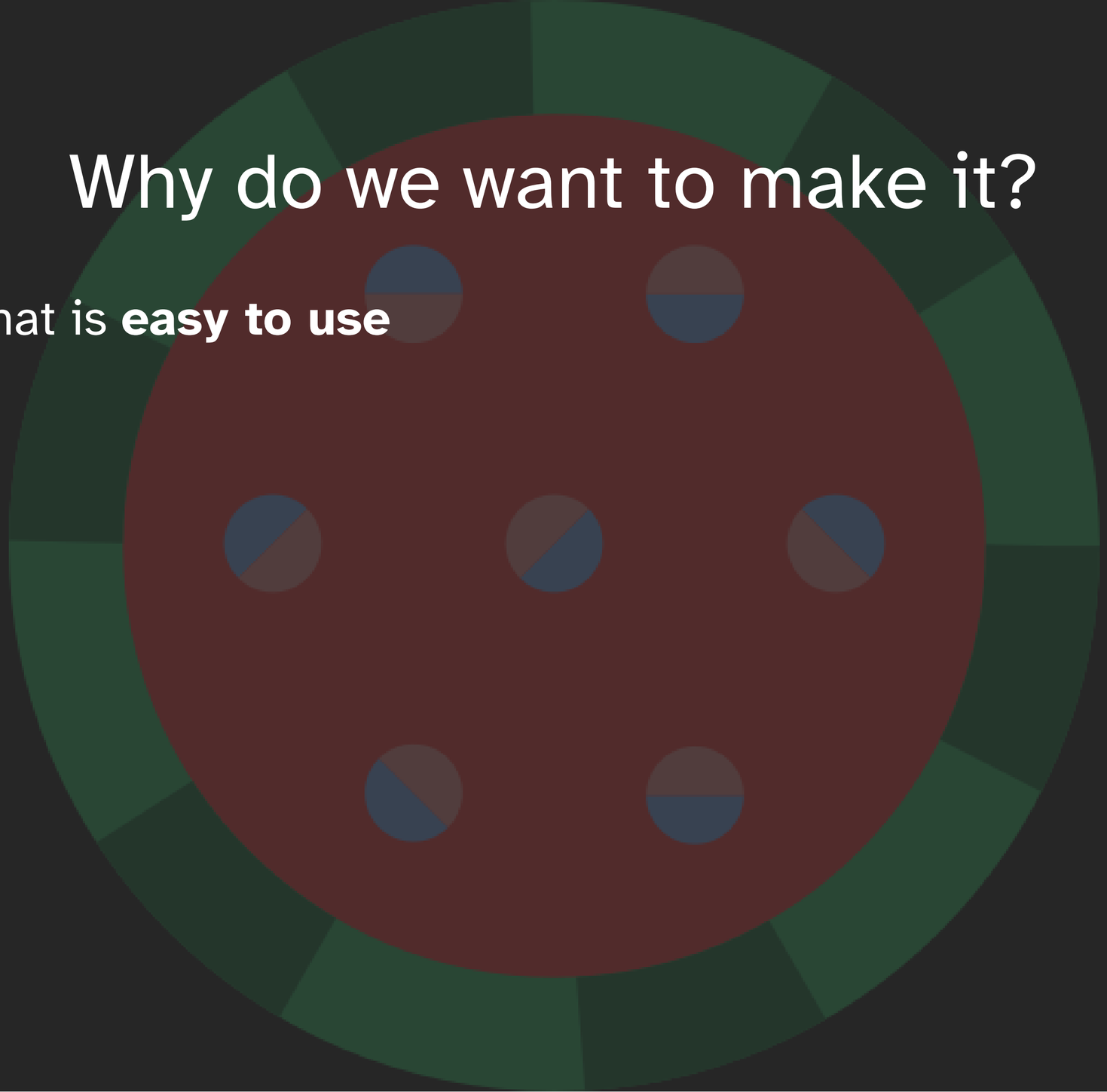
Modelling and processing magnetic microscopy data

Why do we want to make it?



Why do we want to make it?

- Provide code that is **easy to use**



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- Facilitate the creation of **synthetic data**
- Propose a standard **data format**
- Serve as a **foundation** for new methods
- Leverage the potential of emerging **magnetic microscopy** studies

```
# Import standard Python libraries
import numpy as np
import skimage.exposure
import xarray as xr
import matplotlib.pyplot as plt
```

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# Import Fatiando a Terra libraries
import harmonica as hm
import ensaio
import magali
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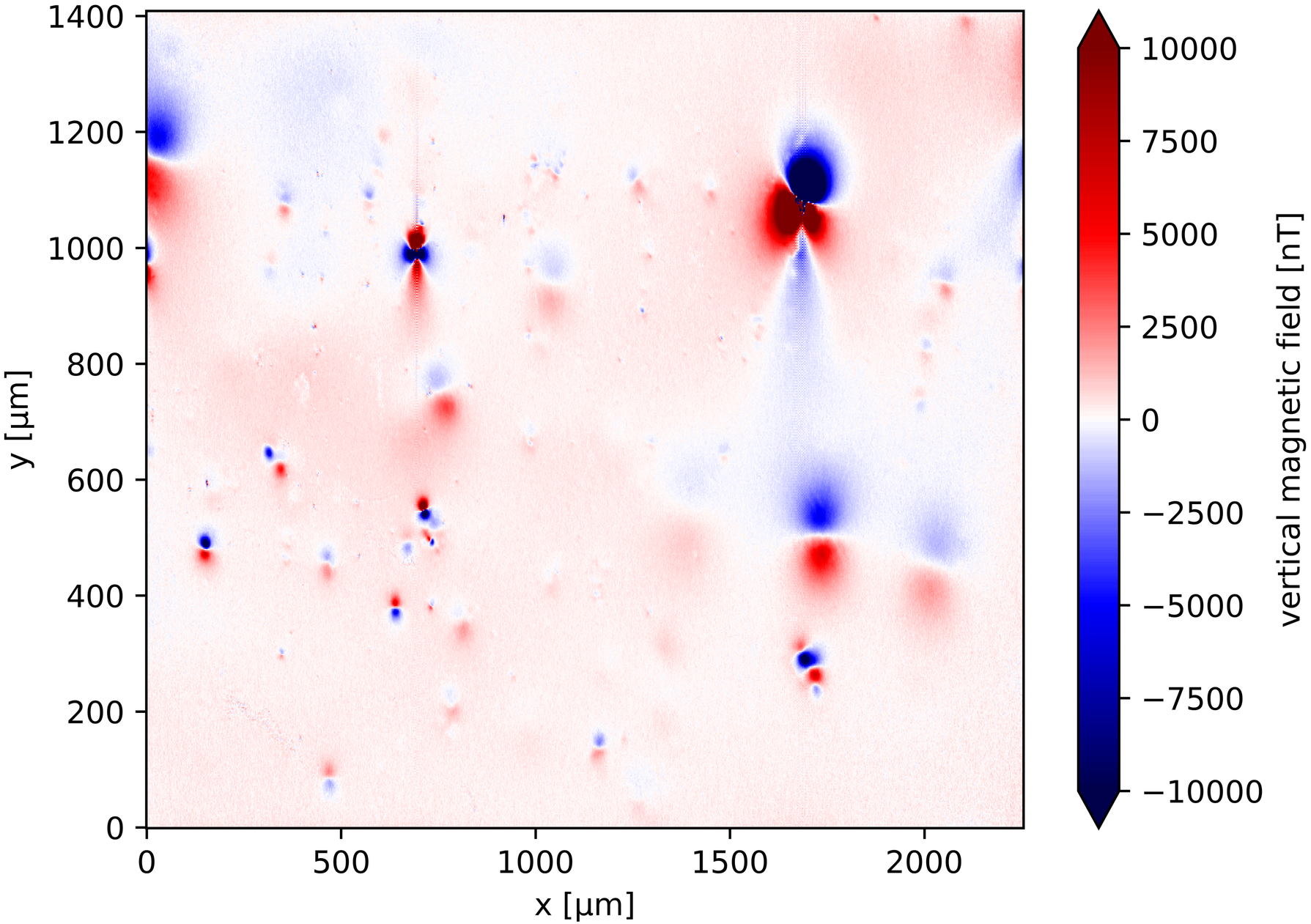
import xarray as xr
import matplotlib.pyplot as plt

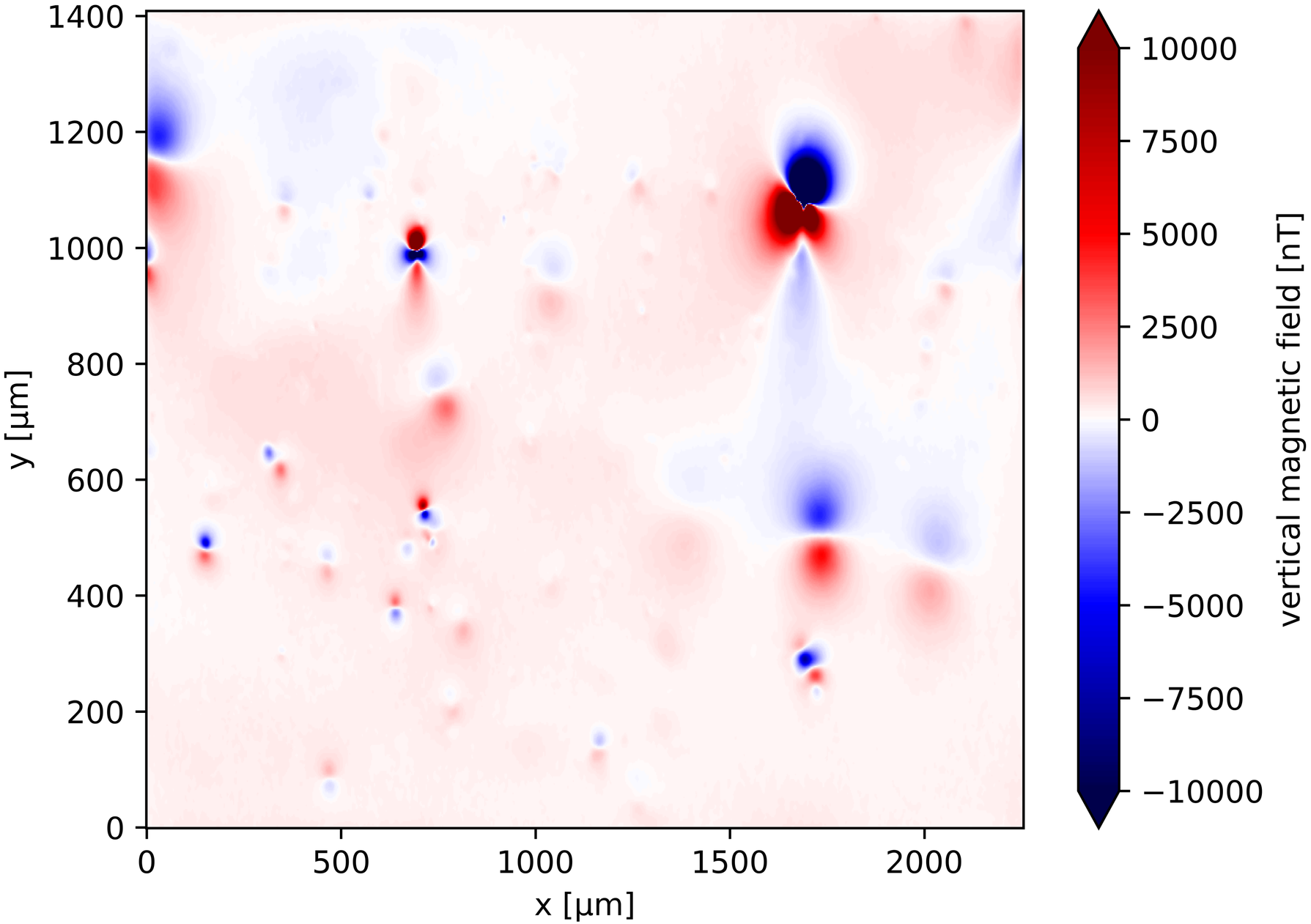
# Import Fatiando a Terra libraries
import harmonica as hm
import ensaio
import magali

# Download the data
fname = ensaio.fetch_morroco_speleothem_qdm(version=1, file_format="matlab")
data = magali.read_qdm_harvard(fname)
```

```
xarray.DataArray 'bz' (y: 600, x: 960)> Size: 5MB
array([[ 352.40587477,   94.8913792 ,   41.61924299, ...,  470.18833933,
         129.20055397,   18.50120941],
       [ 525.04809649,  624.84659897,   53.45418   , ...,  450.42515609,
         240.12455308,  -73.61367693],
       [ 105.0939369 ,  638.76559489,  307.60736872, ...,  236.91326522,
         386.8498122 ,  -86.44215589],
       ...,
       [ -83.74367957,   32.98078244, -411.75073652, ...,  745.99373583,
        1036.20033954, -140.64317643],
       [ 171.17113661, -214.47801235,  159.23437984, ...,  124.58138395,
         258.54331931,  -90.3376945 ],
       [  80.60950354,  273.08367487,  118.23499313, ...,   -4.19572521,
         -53.55728012,    2.10335918]])
Coordinates:
  * x        (x) float64 8kB 0.0 2.35 4.7 7.05 ... 2.249e+03 2.251e+03 2.254e+03
  * y        (y) float64 5kB 0.0 2.35 4.7 7.05 ... 1.403e+03 1.405e+03 1.408e+03
    z        (y, x) float64 5MB 5.0 5.0 5.0 5.0 5.0 5.0 ... 5.0 5.0 5.0 5.0 5.0
Attributes:
    long_name:  vertical magnetic field
    units:      nT
```


1400
1200
1000
800
600
400
200
0
y [µm]
0
500
1000
1500
2000
x [µm]
10000
7500
5000
2500
0
−2500
−5000
−7500
−10000
vertical magnetic field [nT]

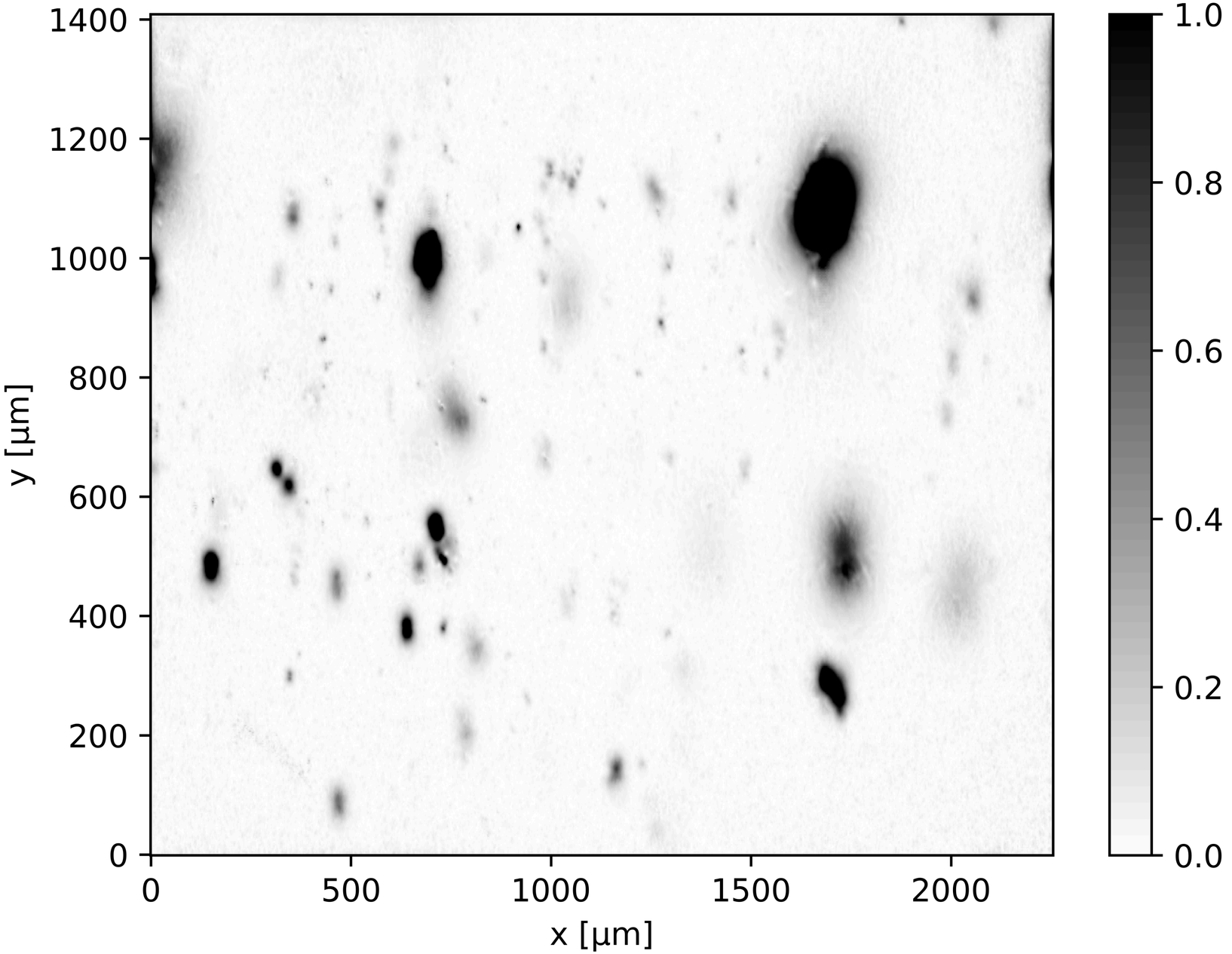
```
# Upward continuation
height_difference = 5.0 # µm
data_up = (
    hm.upward_continuation(data, height_difference)
    .assign_attrs(data.attrs)
    .assign_coords(x=data.x, y=data.y)
    .assign_coords(z=data.z + height_difference)
    .rename("bz")
)
```


1400
1200
1000
800
600
400
200
0
y [µm]
0
500
1000
1500
2000
x [µm]
10000
7500
5000
2500
0
−2500
−5000
−7500
−10000
vertical magnetic field [nT]

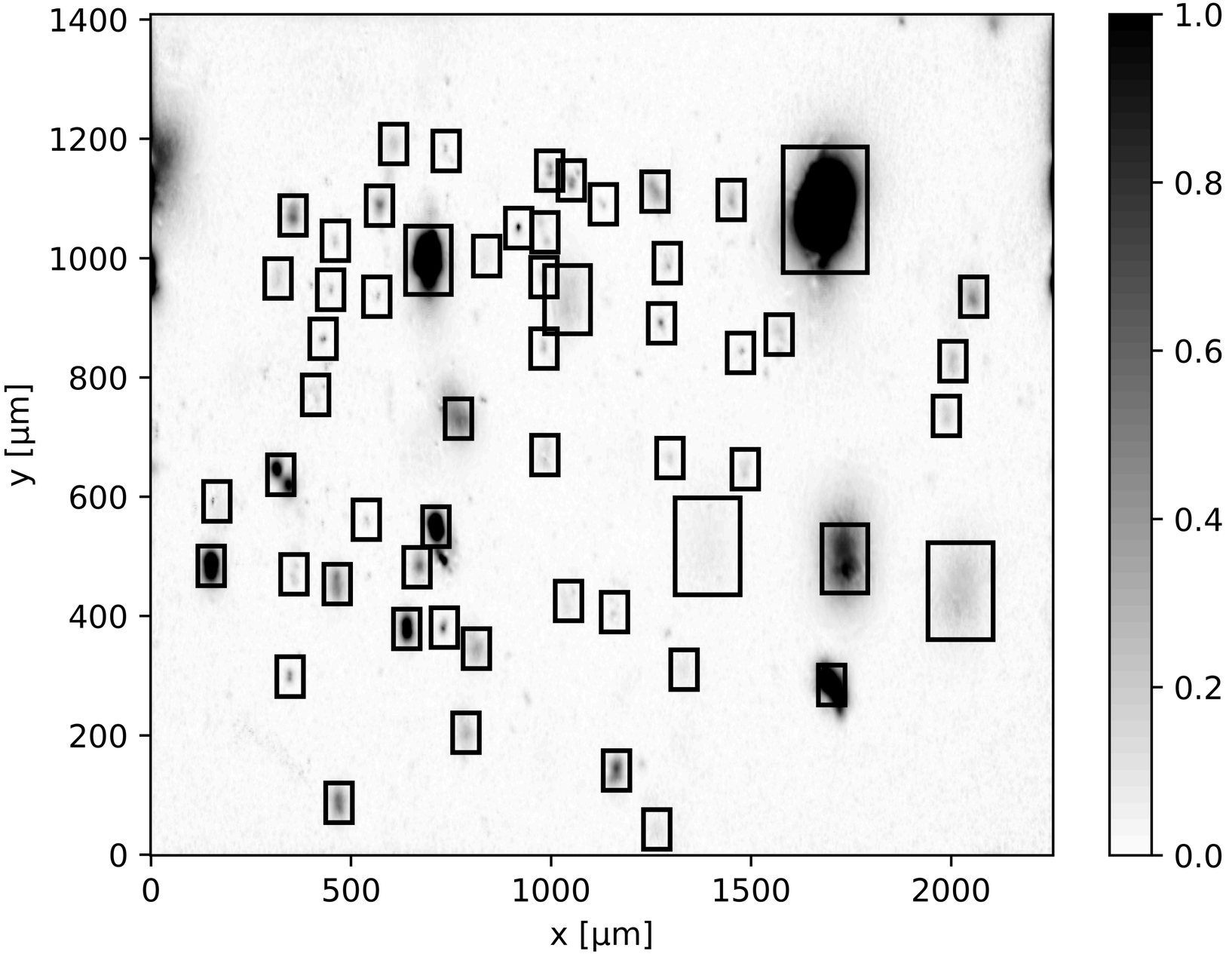
```
# Calculate Total Gradient Amplitude (TGA)
dx, dy, dz, tga = magali.gradient(data_up)
data_up["dx"], data_up["dy"], data_up["dz"], data_up["tga"] = dx, dy, dz, tga
```

```
# Calculate Total Gradient Amplitude (TGA)
dx, dy, dz, tga = magali.gradient(data_up)
data_up["dx"], data_up["dy"], data_up["dz"], data_up["tga"] = dx, dy, dz, tga

# Stretch the contrast of TGA image
stretched = skimage.exposure.rescale_intensity(
    tga, in_range=tuple(np.percentile(tga, (1, 99)))
)
data_tga_stretched = xr.DataArray(stretched, coords=data_up.coords)
```


1400
1200
1000
800
600
400
200
0
y [µm]
0
500
1000
1500
2000
x [µm]
1.0
0.8
0.6
0.4
0.2
0.0

```
# Detect anomalies
bounding_boxes = magali.detect_anomalies(
    data_tga_stretched,
    size_range=[20, 150], # µm
    detection_threshold=0.02,
    border_exclusion=2,
)
```


1400
1200
1000
800
600
400
200
0
y [µm]
0
500
1000
1500
2000
x [µm]
1.0
0.8
0.6
0.4
0.2
0.0

```
# Iterative nonlinear inversion
data_updated, locations_, dipole_moments_, r2_values = magali.iterative_nonlinear_
    data_up,
    bounding_boxes,
    height_difference=height_difference,
    copy_data=True,
)
```

```
# Plot the data
```

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locations_arr = np.array(locations_)
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locations_arr = np.array(locations_)
fig, ax = plt.subplots()
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# Plot the data
locations_arr = np.array(locations_)
fig, ax = plt.subplots()
data.plot.pcolormesh(ax=ax, cmap="seismic", vmin=-10000, vmax=10000)
```

```
# Plot the data
locations_arr = np.array(locations_)
fig, ax = plt.subplots()
data.plot.pcolormesh(ax=ax, cmap="seismic", vmin=-10000, vmax=10000)
magali.plot_bounding_boxes(bounding_boxes, ax=ax, color="black", linewidth=1.5)
```

```
# Plot the data

locations_arr = np.array(locations_)

fig, ax = plt.subplots()

data.plot.pcolormesh(ax=ax, cmap="seismic", vmin=-10000, vmax=10000)

magali.plot_bounding_boxes(bounding_boxes, ax=ax, color="black", linewidth=1.5)

ax.scatter(
    locations_arr[:, 0],  # x
    locations_arr[:, 1],  # y
    c="green",
    marker=".",
    s=60,
    label="Dipole estimated location"
)
plt.legend()
```

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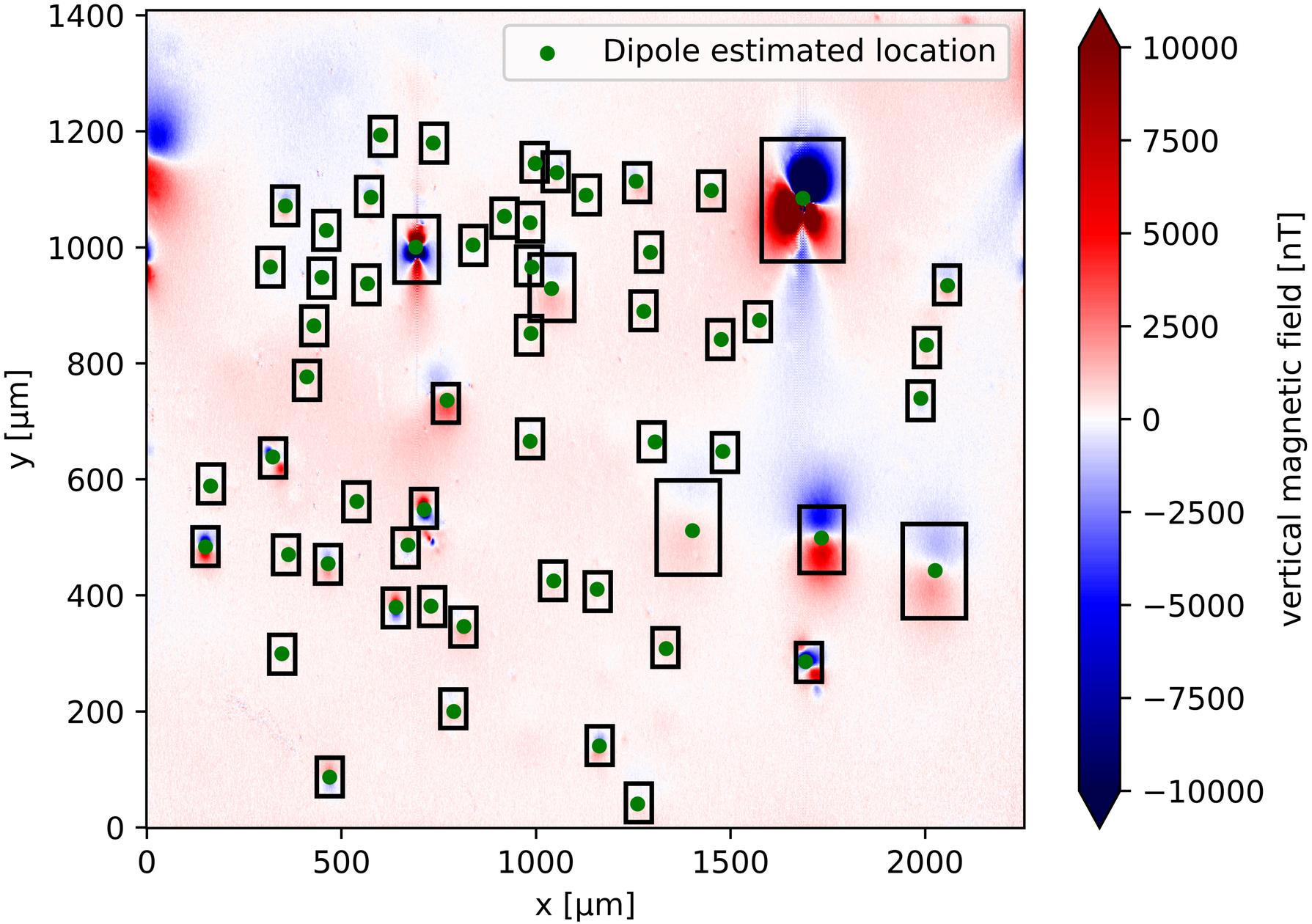
plt.show()
```


Dipole estimated location
1400
1200
1000
800
600
400
200
0
y [µm]
0
500
1000
1500
2000
x [µm]
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7500
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vertical magnetic field [nT]

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FAIR: **F**indable, **A**ccessible, **I**nteroperable and **R**eusable

Conclusions

- Magnetic microscopy lets us investigate magnetism at the grain scale
- **Magali** brings automation, reproducibility, and speed to these analyses
- It integrates open tools, FAIR data, and transparent workflows for magnetic research

Future work

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- Add more datasets to **Ensaio** for testing and **community use**
- Release **Magali 1.0** with improved docs and structure

Acknowledgements

Obrigado! ¡Gracias! Thank you!

Contact: yagomcastro1@gmail.com

Source code for this presentation:
github.com/YagoMCastro/latinmag-magali-presentation

github.com/fatiando/magali