Modeling the Distribution of Iron-oxides in Basalt by combining FIB-SEM and MicroCT Measurements

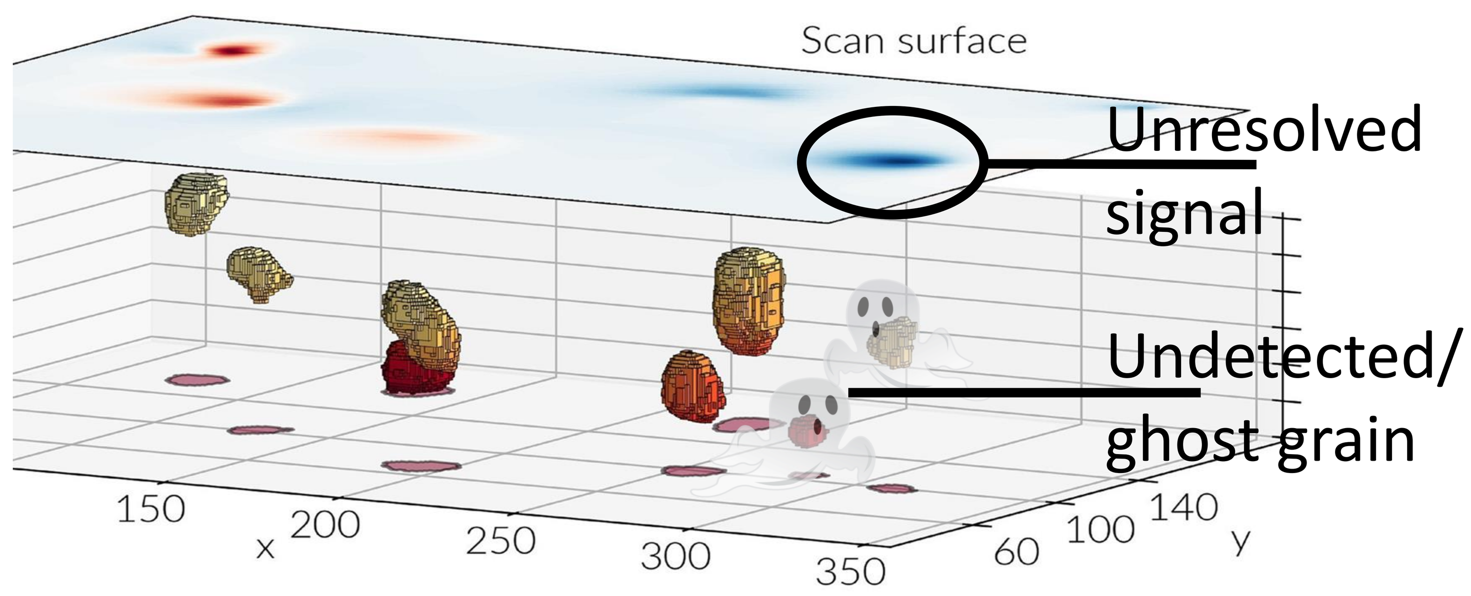
Universiteit Utrecht

How Micromagnetic Tomography deals with Ghosts

Frenk Out, Rosa de Boer, John Walmsley, and Lennart de Groot

The problem

Micromagnetic Tomography (MMT) infers the magnetic moment per grain through a well-posed inversion[1] by employing magnetometry at the surface of the sample and MicroCT for the position of all relevant grains. However, MicroCT detects iron-oxide particles > 1 micrometer, while the smallest, signal carrying, particles are 40 nm[2]. Therefore, small grains are not solved, although their magnetic signal is still present. Furthermore, we do not yet know how many of these small (ghost) grains are present in natural Hawaiian basaltic lava, a frequently used sample for MMT studies and development[3,4].



Example of how the signal of ghost grains appear in the surface magnetic field. Modified from Cortés-Ortuño et al. (2022).

Why should you care?

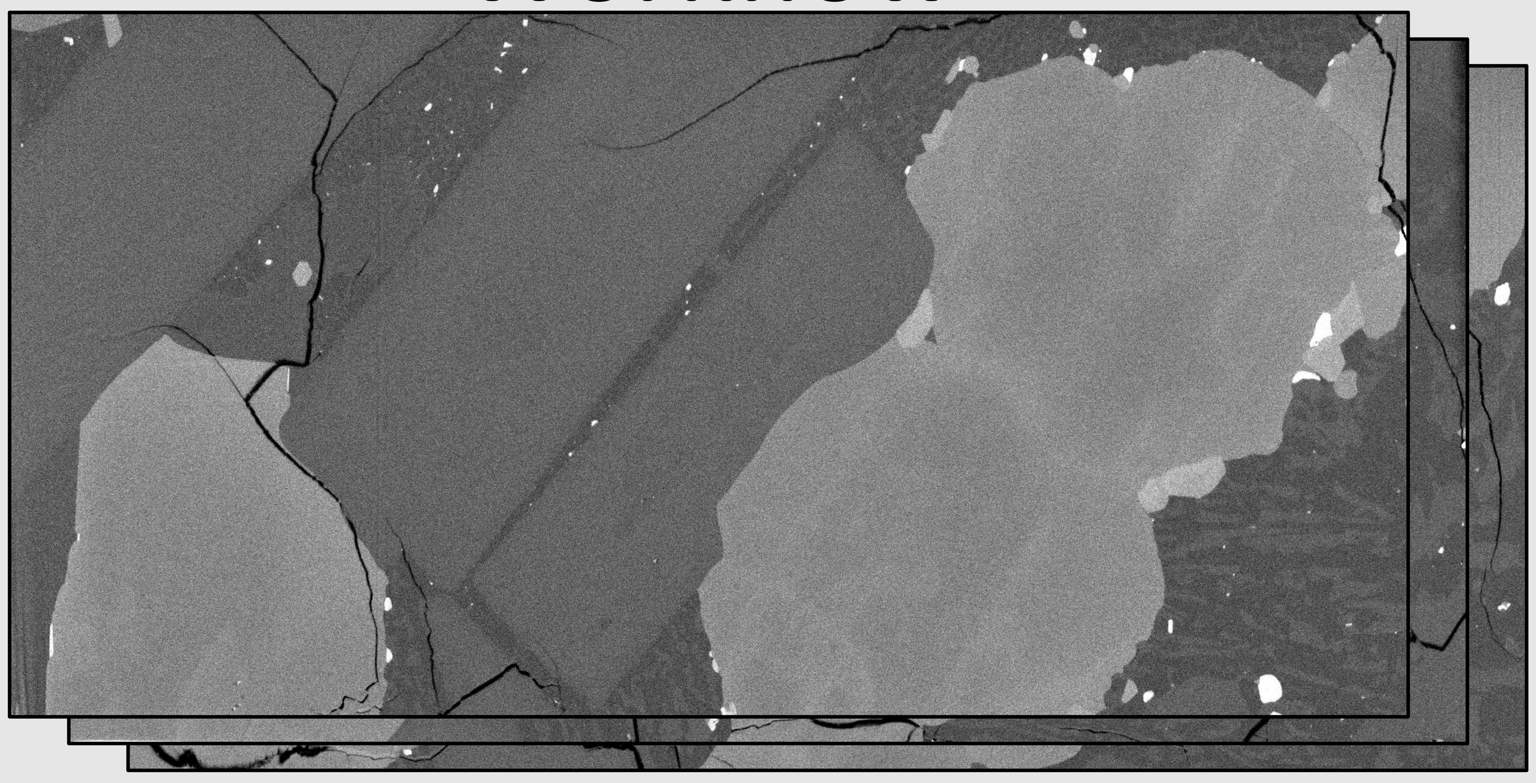
Paleomagnetism is an important tool for dating rocks, understanding Earth's magnetic field behavior, and providing constraints for tectonic plate reconstructions. By measuring the signal produced by magnetic minerals (iron-oxides) in a volcanic rock sample, we might learn the direction and intensity of Earth's magnetic field stored many years ago when the rock solidified. Unfortunately, many iron-oxides incorrectly store the magnetic signal leading to failed experiments. Luckily, with Micromagnetic Tomography we can study the signal of individual iron-oxides and only focus on the good recorders[3,5]. However, there are still some hurdles on the way (see The problem).

Methods

We applied the slice-and-view procedure[6] on a Hawaiian volcanic sample using **FIBSEM**. We have analyzed a 26 x 10 x 10 µm subdomain with 20 nm pixel size. We extracted 1841 iron-oxides and observed that **these particles reside on large mineral interfaces** with a surface area of 1.53 * 10^{-3} mm^2 (see central figure). We also employed **MicroCT** data on a 60 µm thick slice of Hawaii 3[7]. We extracted 1646 iron-oxides and 4.00 mm^2 mineral interfaces.

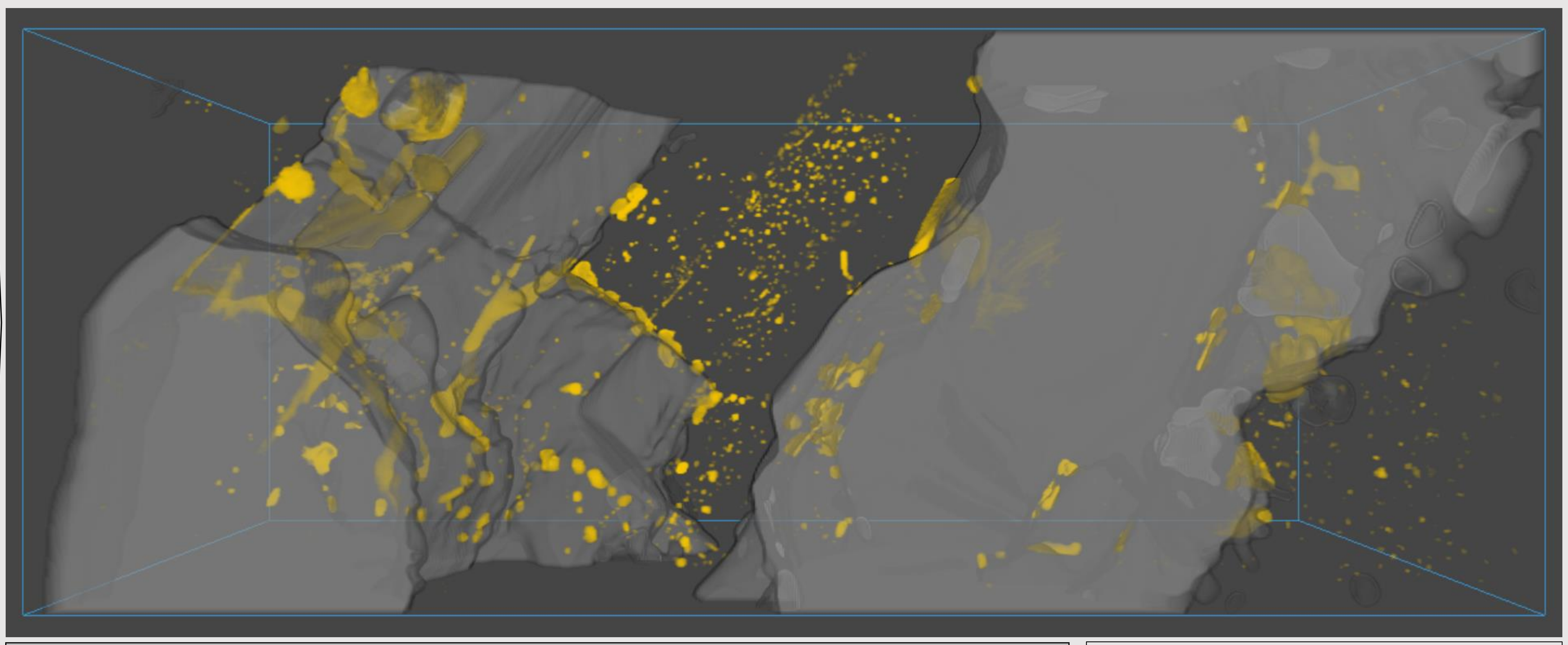
To create a grain-size distribution from 20 nm to 10 µm MicroCT and FIBSEM data must be linked; FIBSEM detects grains between 20 nm to 1 µm and MicroCT detects grains larger than 1.5 µm. **We decided to link the grains using mineral interface area**: we calculated the number of grains per mineral interface area present in FIBSEM. Then, we scaled that number to the mineral interface area visible in MicroCT data to obtain our scaled grain distribution.

Workflow



Raw FIBSEM data using backscattered electrons obtained at the WEMS facility of the University of Cambridge under an EXCITE project. White indicates iron-oxides.

Aligning, denoising, thresholding



Extract iron-oxides & scale to MicroCT

Reconstructed volume of iron-oxides (yellow) with mineral interfaces (grey). Most grains are located on the interface of large minerals. Created with DragonFly software.

Ghost FAQ

1. Wait?! Ghosts?

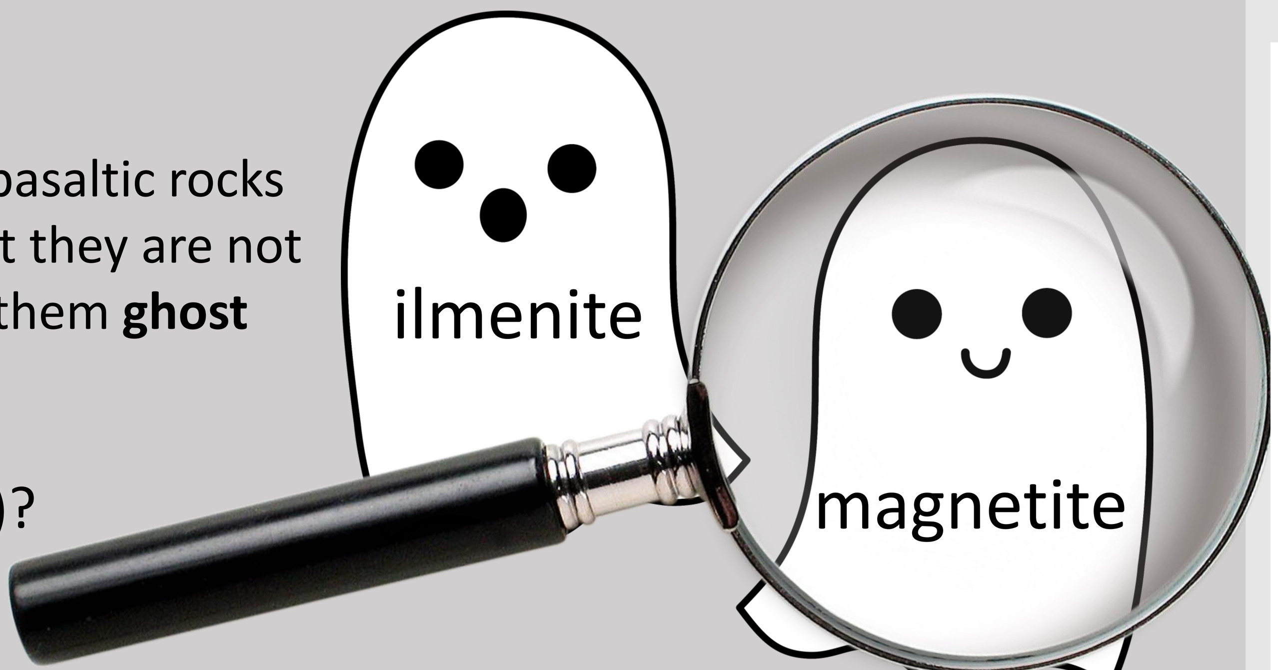
➢ Iron-oxides < 1 µm are present in basaltic rocks and produce a magnetic signal, but they are not registered by MicroCT. So, we call them **ghost grains.**

2. Where do we see a ghost (grain)?

➢ They cluster on **mineral edges**.

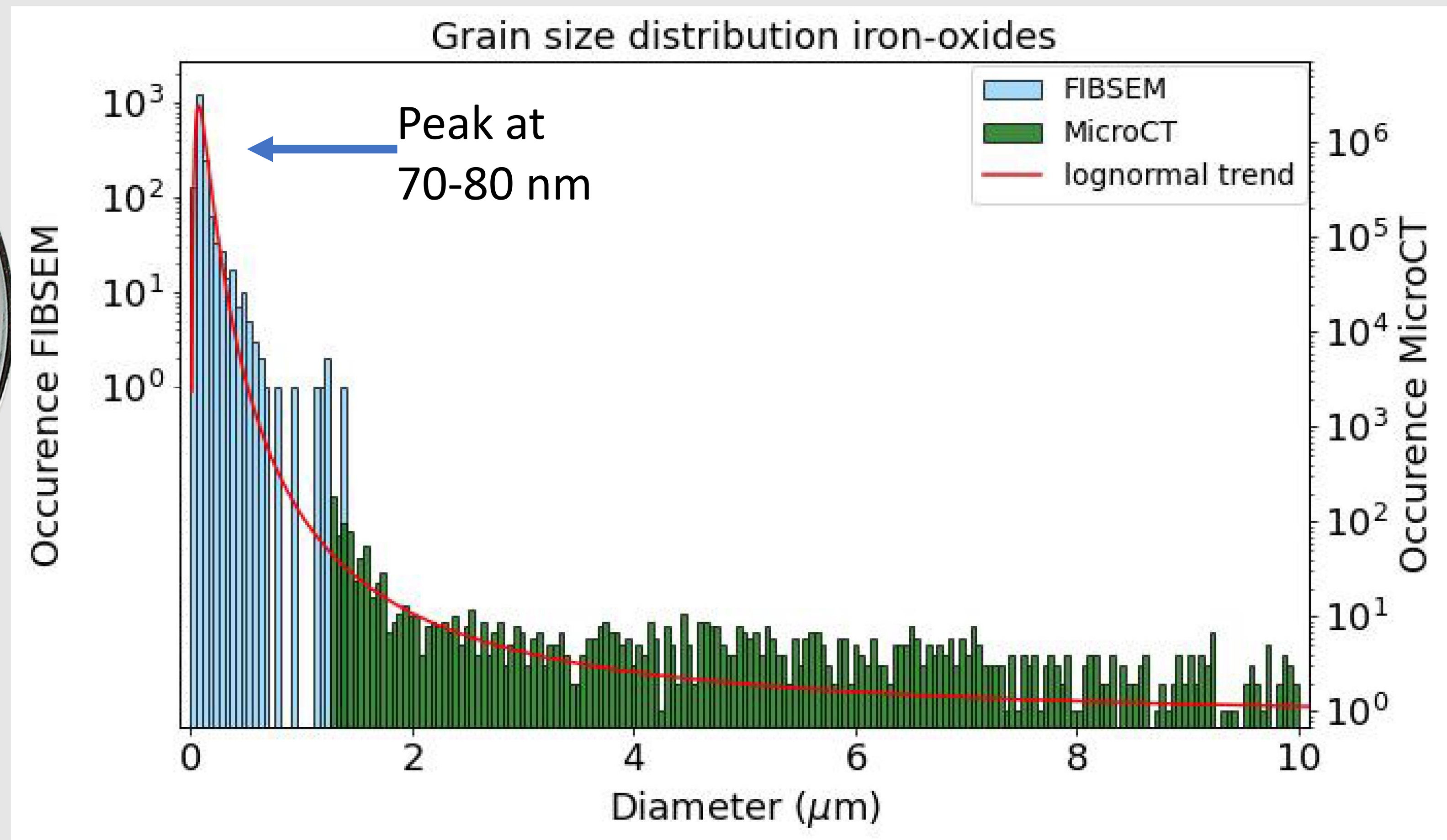
3. How many ghost grains are in a MicroCT image of a volcanic Hawaiian basalt?

➢ This depends on the mineral surface area and the resolution of your MicroCT image. Assuming a resolution of 1 µm, **you are probably haunted by 1.2 million ghosts** per mm^2 mineral surface area.



4. What should I do now?

➢ **We do not know!** Their presence might disturb the magnetic moment solutions of other larger grains obtained with MMT.



Grain size distribution of iron-oxides in the Hawaii sample. By scaling the particles in the FIBSEM image to the particles in the MicroCT we have acquired a range from 0.02 to 10 µm.

Results and Discussion

We fitted a lognormal-like trendline to the data with the following formula:

$$p = 3.51 * 10^{-6+\frac{5.61}{d\sqrt{2\pi}} e^{-\frac{\ln^2(0.60d)}{6.29}}} \quad \text{if } d : [0, 10]$$

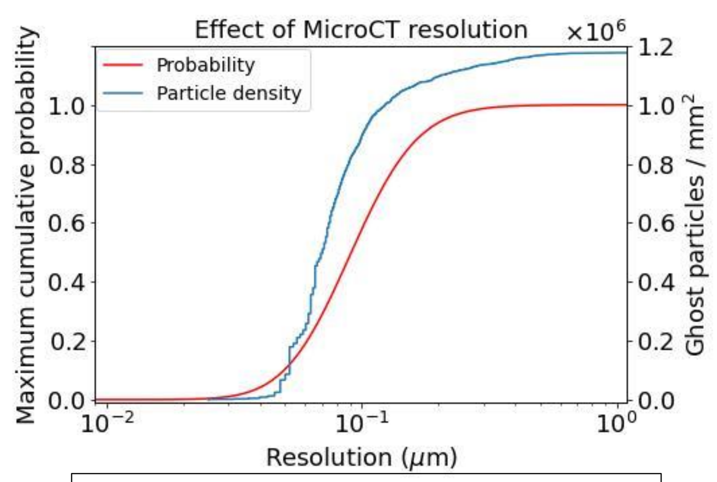
➢ This formula captures the peak in grain size at 70 nm, and the exponential decay for larger grain sizes. With this formula we can **create rock models** by placing ghost grains on mineral edges of existing MicroCT images, in addition to the larger visible iron-oxides.

We are providing an **upper estimation of the real distribution**, because:

1. The studied FIBSEM area, contained relatively many iron-oxides.
   ➢ But scaling factor should dampen this influence.
2. Not all particles are magnetic and can store a magnetic field.

With this distribution, we estimated that in the MMT articles of Kosters et al. (2023) and de Groot et al. (2021), there exists a maximum of 3000 ghost grains per detected particle. (They studied a Hawaiian basalt; HW-03)

➢ However, exact influence[8] of ghost grains is yet to be investigated.



Maximum probability and particles per mm^2 mineral interface area as function of MicroCT resolution. Based on this figure we can determine how many grains have to be sampled from the provided grain-size distribution. By providing the maximum cumulative probability to the grain-size distribution, we can select the maximum grain size that should be sampled.

Conclusions & Key points

➢ We employed FIBSEM to obtain iron-oxides in the range 20 nm to 1 µm. These iron-oxides are clustered at large mineral interfaces.

➢ We scaled the number of iron-oxides acquired with FIBSEM and MicroCT to create a grain size distribution for iron-oxides from 20 nm to 10 µm.

➢ With this distribution we can build grain models of basaltic rocks.

Authors info

This research is conducted through collaboration of **Frenk Out**[a], Rosa de Boer[a], John Walmsley[b], and Lennart de Groot[a].

f.out@uu.nl

[a] Paleomagnetic laboratory Fort Hoofddijk, Utrecht University, NL

[b] Department of Materials Science & Metallurgy, University of Cambridge, UK

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