Scanning magnetometry of acicular Fe-Ti oxide micro-inclusions in plagioclase

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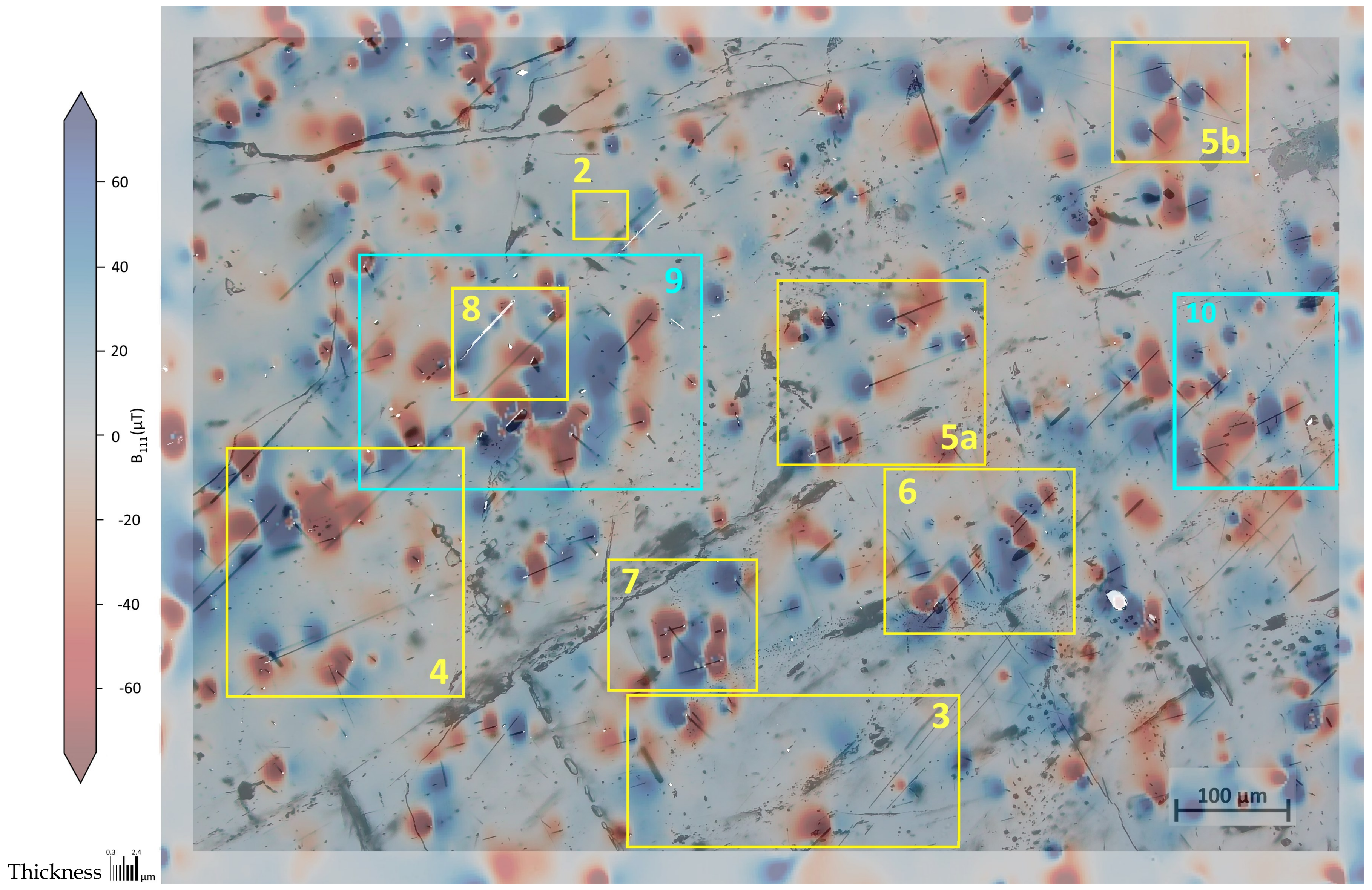
Problem and method

Oriented acicular Fe-Ti oxide (dominantly magnetite) micro-inclusions in plagioclase carry a stable remanent magnetisation and contribute to the rocks' magnetic fabrics. Study of magnetic properties of individual micro-inclusions and their possible interaction is complicated by micrometre size of these magnetic particles. We combined scanning magnetometry using a quantum diamond microscope (QDM) and computed tomography using optical and EBSD data to infer the magnetization of individual micrometre sized magnetite grains.

Fig. 1 Fragment of a plagioclase grain with oriented Fe-Ti oxide micro-inclusions. Combined optical (transmitted and reflected light) images and QDM data overlain. The areas in frames are shown more in detail in the Figs. 2-10.



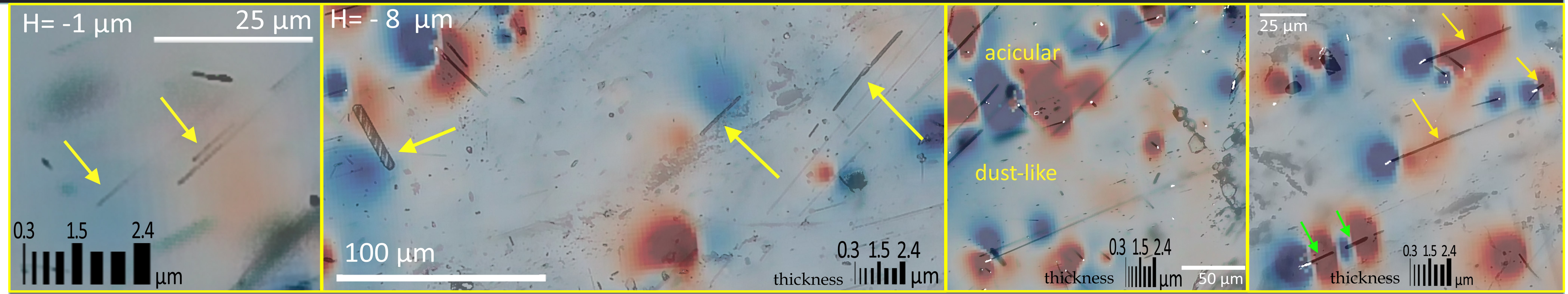


Fig. 2 About 0.3 μm wide needles 1 μm below the thin section surface.

Fig. 3 About 1-3 μm wide needle- and lath-shaped micro-inclusions 8 μm below the thin section surface. "H" is vertical distance from the thin section surface.

Fig. 4 Magnetic flux density in areas of dust–like and acicular inclusions.

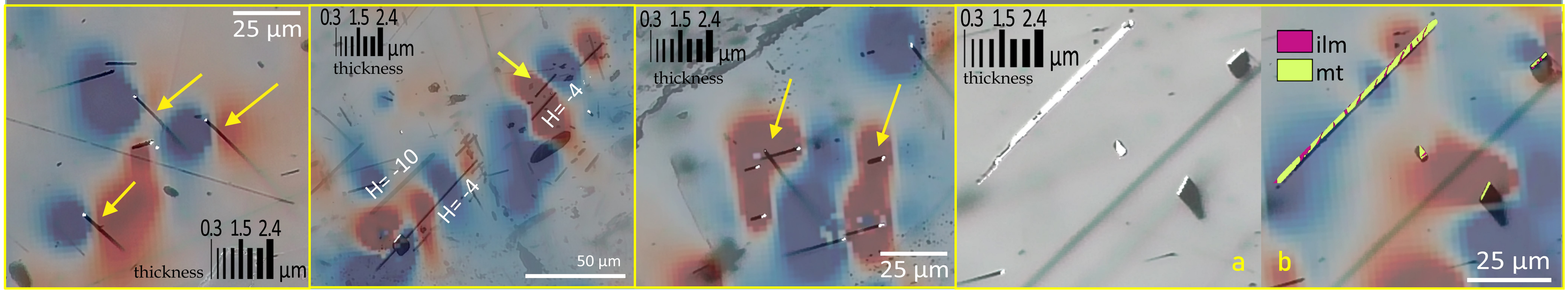
Fig. 5a Similar magnetic patterns for needles of the PL(112)mt orientation class. Green arrows show sections of a discontinuous needle.

Fig. 5b Similar magnetic flux patterns for needles of the PL (1-50)mt orientation class.

Fig. 6 Joined magnetic flux patterns around neighbouring parallel oriented micro-inclusions. The inclusions are 4 - 10 μm below the thin section surface.

Fig. 7 Joined magnetic fluxes in the parallel oriented and crossing micro-inclusions.

Fig. 8 At the spatial resolution of the magnetic surface scan, no correlation is observed between the magnetic flux patterns and the sub-μm sized grain internal microstructures of the micro-inclusions (magnetite matrix with ilmenite lamellae). Combination of transmitted and reflected light (a); and transmitted light, EBSD (phase maps of micro-inclusions) and DQM data (b).



Material

A fragment of a twinned plagioclase grain with abundant oriented Fe-Ti oxide micro-inclusions from an oceanic gabbro dredged at the Mid-Atlantic ridge was studied. The micro-inclusions are acicular and dust-like magnetite, containing oriented ilmenite lamellae. Most inclusions have their elongation direction sub-parallel to the PL(112), PL(-312), PL(1-50), PL(150) plane normal directions and are interpreted as primary inclusions formed above Tc [1]; less numerous micro-inclusions are elongated parallel to the PL[001] and are interpreted as secondary inclusions [2].

Computed tomography

Optical images taken at regular focal depth intervals: Length and spatial orientation of the micro-inclusions

SEM/BSE images: Thickness and shape of the micro-inclusions

EBSD plot: Crystal orientation analysis of PL host → determination of the orientation class of the micro-inclusions

3D reconstruction

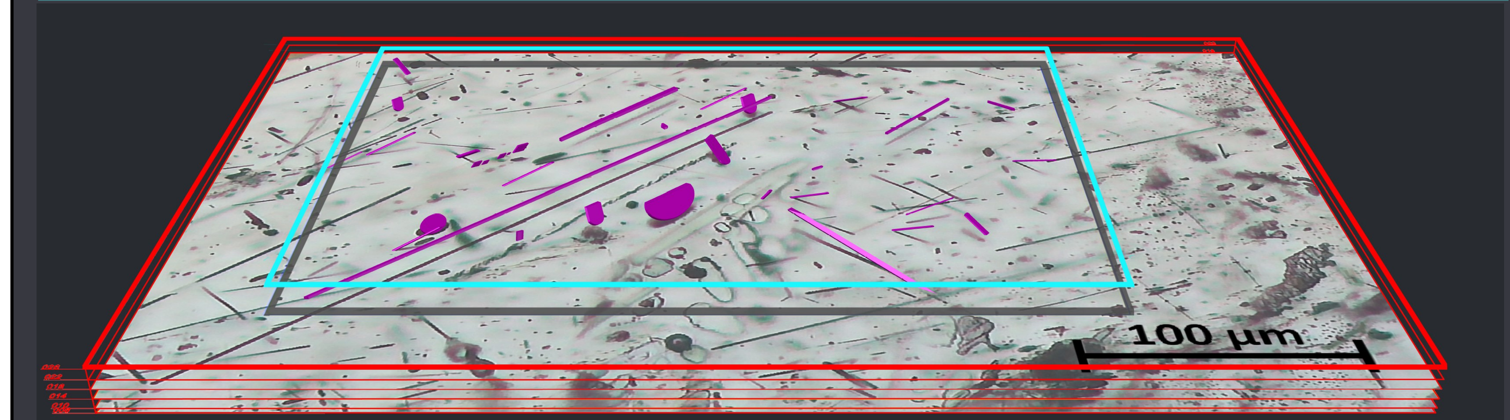


Fig. 9 3D reconstruction (AutoCad) based on stacks of optical images taken at regular focal depth intervals throughout the thin section thickness.

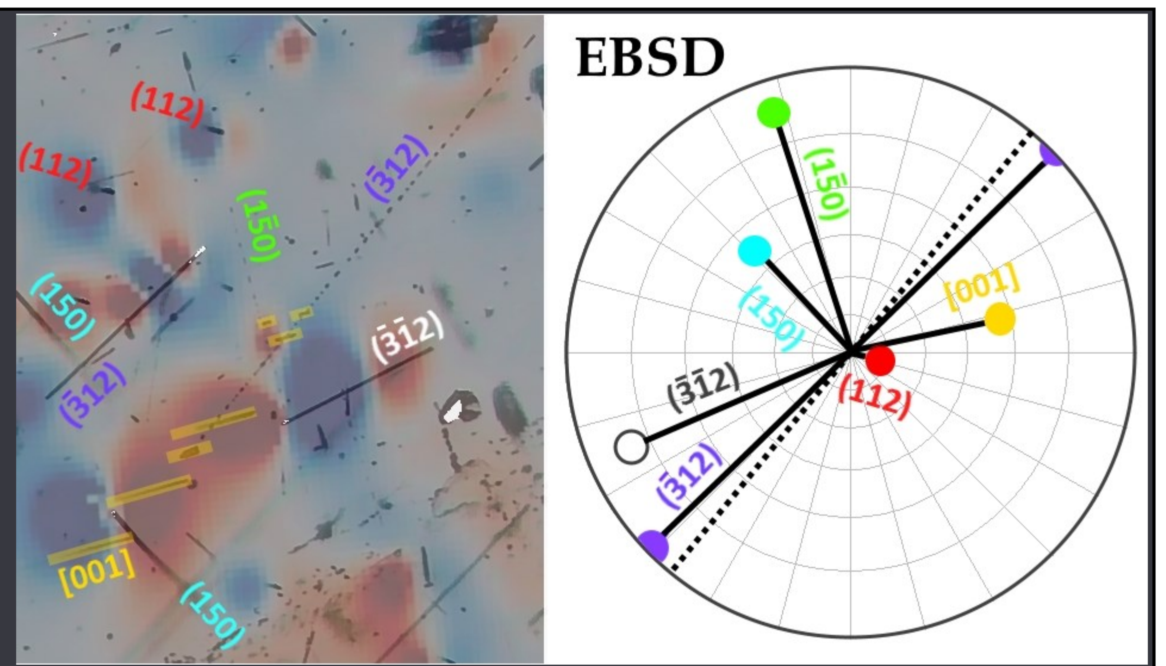


Fig. 10 Combined optical (transmitted and reflected light) and QDM image (left) and EBSD plot (right), allowing to attribute the different magnetite micro-inclusions to the respective orientation classes.

Note, one of the primary[1] micro-inclusions that belongs to the PL(-312)mt orientation class is discontinuous (in the EBSD plot it is shown by dashed line) and is partially replaced by secondary[2] PL[001]mt micro-inclusions (highlighted in yellow lines on the left image) with dense magnetic fluxes.

Results

- Magnetic surface scanning yielded magnetic signals from most of the optically visible micro-inclusions that are located close to the thin section surface (Fig. 1) including 0.3 μm wide needles 0-1 μm (Fig. 2) and 1-3 μm wide laths up to 8 μm (Fig. 3) below the thin section surface.
- The magnetic flux is highest in 10s of micrometres sized domains surrounding the needle-shaped micro-inclusions, and lowest in areas with predominantly dust-like inclusions (Fig. 4).
- The local pattern of the magnetic flux is generally similar for needles belonging to the same orientation class (Fig. 5 a, b).
- 10 - 50 μm long needles oriented sub-parallel to the thin section surface usually show two domains with opposite magnetic flux directions (Fig. 5 a). More such domains exist, when needles are longer than 50 μm, or when needles are discontinuous (Fig. 6).
- Neighboring needles that are separated by less than about 20 μm appear to interact magnetically: If nearby needles are parallel they form a joint magnetic flux pattern as if the two needles were magnetically coupled. Needles with different shape orientation typically show changes in magnetization direction, where they most closely approach each other and their normal distance at their crossing is less than about 20 μm (Fig. 4, Fig. 7).
- The limited spatial resolution of the magnetic surface scan does not allow for correlating the observed magnetic fluxes with sub-μm sized grain-internal microstructures of the micro-inclusions (Fig. 8).
- 3D reconstructions were done using stacks of optical images taken at regular focal depth intervals (> 0.5 microns) throughout the thin section thickness (Fig. 9). This may be complemented by crystal orientation analysis of plagioclase-host (EBSD, Universal stage, petrographic measurements) and assignment of the different magnetite micro-inclusions to the respective orientation classes (Fig. 10).

Conclusions

1. **Scanning magnetometry using the QDM provides data on magnetic flux and its spatial configuration in magnetite-bearing plagioclase, which can be used for inferring the overall remanence and magnetic fabrics of magnetite-bearing plagioclase and of gabbroic rocks.**
2. **Optical images with different focal depth provide data for 3D reconstruction of the shape, shape orientation and spatial distribution of the micro-inclusions that may be used for the micromagnetic tomography. Crystal orientation analysis of the plagioclase-hosts based on EBSD and optical data increases the accuracy of the 3D reconstructions.**

[1] Bian, G., Ageeva, O., Roddatis, V., Li, C., Pennycook, T. J., Habler, G., & Abart, R. (2023). Crystal structure controls on oriented primary magnetite micro-inclusions in plagioclase from oceanic gabbro. *Journal of Petrology*, egad008.
[2] Bian, G., Ageeva, O., Roddatis, V., Habler, G., Schreiber, A., & Abart, R. (2023). Oriented secondary magnetite micro -inclusions in plagioclase from oceanic gabbro. *American Mineralogist*, *108*(9), 1642-1657. gabbro." *American Mineralogist* 108.9 (2023): 1642-1657