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### **Key Points:**

- Plagioclase from oceanic gabbro contains needle shaped magnetite inclusions that render plagioclase grains ferromagnetic
- Most of the needle elongation directions lie within or near the plagioclase (010) plane leading to pronounced magnetic anisotropy
- The remanent magnetization direction of the magnetite-bearing plagioclase is controlled by magnetic anisotropy

#### Supporting Information:

Supporting Information may be found in the online version of this article.

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# **Oriented Magnetite Inclusions in Plagioclase: Implications for the Anisotropy of Magnetic Remanence**

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**Abstract** Micron to sub-micron sized ferromagnetic inclusions in rock forming silicate minerals may give rise to particularly stable remanent magnetizations. When a population of inclusions have a preferred crystallographic or shape orientation in a rock, the recorded paleomagnetic direction and intensity may be biased by magnetic anisotropy. To better understand this effect, we investigated plagioclase grains from oceanic gabbro dredged from the Mid-Atlantic Ridge at 11°–17°N. The plagioclase grains contain abundant needle and lath shaped magnetite inclusions aligned along specific directions of the plagioclase lattice. Electron back scatter diffraction and anisotropy of magnetic remanence measurements are used to correlate the orientation distribution of the magnetite inclusions in the host plagioclase that contains multiple twin types (Manebach, Carlsbad, Albite, and Pericline) with the bulk magnetic remanence has oblate shapes that parallels the plagioclase (010) plane. It is suggested that recrystallization of magnetite inclusions during hydrothermal overprint shifts the relative abundance of the inclusions pertaining to the different orientation classes. We show that the maximum axis of the anisotropy ellipsoid of magnetic remanence parallels the plagioclase [001] direction, which in turn controls the recorded remanent magnetization direction. Our results are relevant for paleointensity and paleodirection determinations and for the interpretation of magnetic fabrics.

**Plain Language Summary** Understanding how the Earth's magnetic field has varied in the past depends on the recording fidelity of the remanent magnetization held within the magnetic minerals in rocks, with magnetite being the most common. Magnetite may occur as tiny inclusions in host minerals such as plagioclase, and when they do, they are particularly robust magnetic recorders. Plagioclase from mafic plutonic rocks often contains needle-shaped magnetite inclusions whose orientations are fixed along specific crystallographic directions of the plagioclase, which leads to extreme magnetic anisotropy. The anisotropy can significantly bias magnetic recording by deflecting the magnetization direction into the magnetic foliation plane or the lineation direction, which may be at high angles from the magnetic field direction. By combining optical and electron microscopy with magnetic measurements of individual magnetite bearing plagioclase grains, we show that different types of crystallographic twinning in plagioclase dictates different crystallographic orientation directions of the magnetic inclusions; the resultant anisotropic distribution of magnetite crystals in turn controls the direction of the magnetic remanence.

# 1. Introduction

The remanent magnetization of rocks is primarily carried by magnetite. In mafic intrusive rocks, magnetite may be present in the form of millimeter sized matrix grains and/or magnetite may be present as micron to sub-micron sized inclusions hosted within silicate phases. Due to their multidomain characteristics the magnetite grains in the matrix are poor recorders of the paleomagnetic field. In contrast, the silicate hosted inclusions typically fall into the single to pseudo single-domain size range and thus have very good magnetic recording properties (Davis, 1981; Dunlop & Özdemir, 2001; Feinberg, Harrison, et al., 2006; Fleet et al., 1980; Kent et al., 1978; Knafelc et al., 2019; Lappe et al., 2011; Renne et al., 2002; Usui et al., 2015). They exhibit high coercivity and have particularly stable remanent magnetizations (Feinberg et al., 2005; Özdemir & Dunlop, 1997). In addition, the silicate-hosted magnetite inclusions are protected from fluid-mediated alteration by their host crystals.

Silicate-hosted, magnetite inclusions are thus robust carriers of the natural remanent magnetizations in mafic intrusive rocks (Biedermann et al., 2016, 2020; Cottrell & Tarduno, 1999; Feinberg et al., 2005; Gee et al., 2004; Renne et al., 2002; Selkin et al., 2008; Tarduno et al., 2006; Usui et al., 2015; Xu et al., 1997).

Magnetic anisotropy influences paleomagnetic recording. Depending on their formation pathways, the silicate-hosted, magnetite inclusions may have different shapes, different crystallographic orientation relationships (CORs) or different shape orientation relationships (SORs) to their silicate host grains. When the magnetite inclusions have isometric shape and/or are randomly oriented, the magnetic anisotropy ellipsoid is isotropic, and the grain may serve as a bias-free recorder of the paleomagnetic field. If, however, the magnetite inclusions have needle or plate shapes with systematic SOR and/or COR to their silicate host crystal, the inclusions may have substantial magnetic anisotropy. In such cases, the remanent magnetization vector recorded by the inclusion-bearing silicate grain may deviate from the direction of the paleomagnetic field and bias the recorded direction and intensity (Fuller, 1960, 1963; Hargraves, 1959; Rogers et al., 1979). Knowledge of the origin and extent of magnetic anisotropy is therefore crucial to correct and interpret paleomagnetic data (e.g., Usui et al., 2015).

In pyroxene, needle-shaped magnetite inclusions typically have one, or rarely two, types of SOR and COR with respect to the host crystal (Ageeva et al., 2017; Bolle et al., 2021; Feinberg, Harrison, et al., 2006; Fleet et al., 1980), which may give rise to single grain and bulk-rock magnetic anisotropy (Biedermann et al., 2016, 2019; Ferré, 2002; Hirt & Biedermann, 2019; Maes et al., 2008; O'Driscoll et al., 2015). Indeed, a correlation between the magnetic fabric and the alignment of pyroxene grains in layered igneous rocks has been observed (Gee et al., 2004; Selkin et al., 2014). In contrast, at least eight different SOR and COR types have been identified in plagioclase with magnetite inclusions (Ageeva et al., 2016; Ageeva, Bian, et al., 2020; Feinberg, Wenk, et al., 2006; Sobolev, 1990; Usui et al., 2015), and their potential contribution to bulk magnetic anisotropy of magnetite bearing plagioclase is less clear (Biedermann et al., 2016; Hirt & Biedermann, 2019).

In this study, we analyzed the SOR and COR of a multitude of needle and lath shaped magnetite inclusions in plagioclase grains from oceanic gabbros that were dredged from the Mid-Atlantic Ridge. The relative abundances of different SOR and COR types were compared with measurements of the anisotropy of magnetic remanence (AMR) of the magnetite bearing plagioclase grains. Based on the combined evidence, the influence of the orientation distribution of the needle and lath shaped magnetite inclusions on the magnetic signature of magnetite bearing plagioclase grains is discussed. Multiple twinning mechanisms in plagioclase complicate the links between the SOR and COR of magnetite inclusions in a plagioclase host. The shape orientations of the magnetite needles were thus investigated on the scale of single twins and on the scale of a plagioclase crystal comprising multiple twin domains. Inclusion orientations were observed with correlated optical microscopy and scanning electron microscopy (SEM) including crystal orientation analysis based on electron backscatter diffraction (EBSD). Finally, we discuss how the orientation of the magnetite inclusions hosted by twinned plagioclase grains may contribute to the bulk magnetic properties of gabbro and how the AMR ellipsoid correlates with the distribution of the magnetite inclusions.

# 2. Materials and Methods

#### 2.1. Geological Background and Sampling

The studied gabbro samples were dredged during the 26th, 30th, and 32nd cruises of the Research Vessel Professor Logachev (Beltenev et al., 2007, 2009; Cipriani et al., 2009). The samples were collected from gabbro-peridotite outcrops along the Mid-Atlantic Ridge (Table S1 in Supporting Information S1). Dredge site L-2612 is within a lithospheric section exposed by the Vema Transform Fault (Bonatti et al., 2005; Cipriani et al., 2009). Sites L30-277 and L32-101 are within oceanic core complexes (OCCs) at 13°N and 13°30'N in the footwalls of low-angle, large-offset extensional faults that are typical for slow-spreading ridges (Karson & Lawrence, 1997; MacLeod et al., 2009). See Escartín et al. (2017); MacLeod et al. (2009), Ondréas et al. (2012), and Pertsev et al. (2012) for more information on the geology of OCC 13°N and OCC 13°30'N. Samples 1514-17 and 1419-10 were dredged from the Ashadze complex (Table S1 in Supporting Information S1). Samples L30-277-7, L30-277-10, 1514-17, 1419-10, and L32-101-1 are regarded as gabbroic intrusions in peridotite.

#### 2.2. Polarization Microscopy

The shape orientations of the magnetite inclusions in plagioclase were obtained using transmitted light polarization microscopy on petrographic thin sections. In cuts approximately perpendicular to the albite twin boundaries, several orientation classes of the magnetite inclusions that play a role in the formation of magnetic anisotropy can be discerned based on the angles between the inclusion elongation direction and the albite twin boundary and between the inclusion elongation direction and the plane of the thin section cut. The procedure is described in the supplementary material and illustrated in Figure S1 in Supporting Information S1. For other cuts, optical measurements were performed using a universal stage. Thin sections of 26 samples were analyzed using these optical methods.

#### 2.3. Anisotropy of Magnetic Remanence (AMR) and Alternating Field (AF) Demagnetization

We drilled cylindrical cores from the bulk samples L30-277-7, 1514-17, 1419-10 4 mm in diameter and 3.5 mm in height, to achieve a height to diameter ratio of 0.88 making the samples void of shape anisotropy (Collinson, 2013). The samples were positioned into a non-magnetic wood inserts and placed on the SushiBar at LMU Munich (Wack & Gilder, 2012), which can automatically demagnetize rocks with an alternating field (AF) and impart anhysteretic remanent magnetizations to measure the anisotropy of magnetic remanence (AMR) based on a homemade coil and a 2G Enterprises, Inc, superconducting magnetometer. The samples were first stepwise AF demagnetized using 11 steps of incrementally higher peak fields up to 90 mT. Next, the samples were subjected to a 12-direction, AMR protocol following Wack and Gilder (2012) using an AF field that decayed from 90 to 0 mT with a 50  $\mu$ T bias field applied as the AF waveform decayed from 85 to 20 mT. The same AMR protocol was repeated three times to assess reproducibility. AMR tensors were calculated according to the projection method of Wack (2015), which calculates the ARM tensors individually, without assuming a priori knowledge of the measurement scheme.

#### 2.4. Electron Backscatter Diffraction Analyses (EBSD)

An EBSD study including crystal orientation point analyses and crystal orientation mapping was applied to samples L30-277-7, L30-277-10, L-2612-41, L-2612-49, L32-101-1, 1514-17, and 1419-10. EBSD analyses were performed on chemo-mechanically (Syton<sup>TM</sup>) polished and carbon-coated thin sections using an FEI Quanta 3D FEG instrument at the University of Vienna. The Schottky-type field-emission gun scanning electron microscope (FEG-SEM) is equipped with an Ametek-EDAX Digiview 5 EBSD camera (CCD sensor with max. 1392 × 1040 pixels) mounted at 5° elevation, and an Ametek-EDAX Apollo X silicon drift detector for energy-dispersive X-ray spectrometry (EDX). An OIM DC 7.3.1 SW was used for contemporaneous EBSD and EDX data collection and composition-assisted reindexing (ChI-Scan SW). EBSD and EDX analyses were collected with electron beam settings of 15 kV accelerating voltage and 4 nA probe current, while the sample was at a 70° stage tilt and 14 mm working distance.

Crystallographic orientations of magnetite inclusions and adjacent plagioclase host were collected as manually selected single point analyses using  $2 \times 2$  EBSD camera binning, that is, the signal intensity of each 4 pixels of the CCD sensor were summed to obtain the intensity of one pixel of the Kikuchi pattern. The latter were collected by averaging over eight or ten image frames at 237 ms exposure time per frame. In addition, static and dynamic background subtraction filters and histogram intensity normalization were applied in order to maximize the contrast of the Kikuchi pattern. Hough-transform based band detection was performed at a binned pattern size of  $140 \times 140$  pixels, 1° theta step size using the central 83%–91% of the spherical Kikuchi pattern cross section, applying a  $9 \times 9$  pixel convolution mask. For EBSD indexing 3–16 reflector bands at a minimum peak distance of 10 pixels in Hough space were used while allowing for 2° interplanar angle tolerance. The reliability of the orientation solution was checked for each analysis based on the number of band triplets and the angular misfit between the detected bands and the reference crystal structure.

In addition to the single point analyses, plagioclase orientations and their 2D distribution were determined by automated crystal orientation mapping (COM). Using an  $8 \times 8$  EBSD camera binning and an exposure time of 25–26 ms for collecting single image frames, indexing rates of 33–38 points per second were achieved. Thus, EBSD data from  $14 \times 8$  mm sized sample areas were automatically stitched from a  $0.5 \times 0.5$  mm<sup>2</sup> sized matrix of submaps. In certain regions of interest, EDX energy spectra were simultaneously collected for each COM



datapoint. Subsequently, the EBSD data set was reindexed by considering only datapoints that pertain to the particular major element composition of plagioclase using the OIM ChI-Scan tool. With this approach, the plagioclase orientations in  $28 \times 7 \text{ mm}^2$  sized areas for three samples were determined at step sizes of 20 or 40 µm. Additionally, some detailed scans with step sizes of 0.3 or 0.5 µm were collected from selected, smaller sample areas. In order to remove single misindexed datapoints from maps and pole figure plots, a confidence index (CI) standardization routine was applied before filtering the data set for CI - values >0.1 or 0.05.

#### 3. Results

### 3.1. Mineralogy and Petrography

Samples L32-101-1, L-2612-41, and L-2612-49 were described in Ageeva et al. (2016, 2017), Pertsev et al. (2015), and Pertsev et al. (2021). Sample L32-101-1 is a coarse-grained gabbro-norite injected by fine-grained felsic stringers. The gabbro-norite consists of plagioclase (pl, 50 vol%), clinopyroxene (cpx, 20–30 vol%), orthopyroxene (opx, 20–30 vol%), and minor interstitial ilmenite (ilm, <1 vol%). The felsic stringers are mostly <2 mm wide with some parts broadened up to 5 mm. They are fine-grained with variable mineral modes from plagioclase + quartz + biotite to local clinopyroxene-rich and zircon-rich plagiogranite micro-lithologies (Aranovich et al., 2015; Pertsev et al., 2021). Samples L-2612-41 and L-2612-49 are coarse-grained oxide gabbros consisting of plagioclase, clinopyroxene, and minor orthopyroxene. Original prismatic pyroxenes and tabular pl grains are rarely preserved due to deformation and partial replacement by late-stage minerals. Late-magmatic processes are manifest by intracrystalline deformation of titanium-rich hornblende and interstitial Fe-Ti oxides. In sample L-2612-41, hydrothermal processes locally produced fayalite coronas between magnetite and opx as well as cracks filled with hornblende enriched in Fe<sup>2+</sup> and Cl (Pertsev et al., 2015). Sample 1514-17 is a coarse-grained oxide gabbros; sample 1419-10 is a medium-grained gabbro without signs of late magmatic or hydrothermal processing.

Sample L30-277-7 is a gabbro-norite comprising plagioclase, pyroxene, amphibole, and minor Fe-Ti-oxides (<0.5 vol.%). The plagioclase is generally labradorite in tabular or rare subhedral 0.5–5 mm sized grains, which are clouded with abundant opaque inclusions. The anorthite contents range from  $An_{60}$  in the cores to  $An_{46}$  in the rims and along healed cracks. The plagioclase grains are typically twinned. Large plagioclase grains are divided into Manebach or Carlsbad twins and the different twin individuals usually show internal Albite or Albite-Pericline twinning. Clinopyroxene and rarely orthopyroxene occur as prismatic and subhedral 3–5 mm sized grains with a dense cleavage network. In cpx, lamellae of opx occur parallel to the (100) plane and vice versa. Clinopyroxene contains less than about 5  $\mu$ m sized needle and lath shaped magnetite inclusions and ilmenite plates. Locally, rare magnesio-hornblende replaces clinopyroxene. In the rock matrix, up to about 1 mm sized ilmenite, magnetite and exsolved titanomagnetite grains typically occupy interstitial positions between the rock-forming silicate minerals. In places, pyroxene is partially replaced by actinolite indicating incipient low-temperature hydrothermal alteration.

In most samples, the plagioclase hosted magnetite inclusions are represented by micron to sub-micron sized needle- or lath shaped crystals with shape orientations following several well-defined directions in the plagioclase host. The magnetite needles are typically less than 1  $\mu$ m wide and several tens of  $\mu$ m long, often terminating at plagioclase twin boundaries. The magnetite inclusions show systematic SORs and CORs with the plagioclase host, where eight different orientation classes can be discerned (Ageeva et al., 2016; Ageeva, Bian, et al., 2020; Sobolev, 1990; Wenk et al., 2011). Samples L-2612-41 and L-2612-49 are special in that the magnetite inclusions are present as relatively short needles, which are aligned parallel to a single crystallographic direction in the plagioclase. The magnetite inclusions often contain ilmenite and rarely ulvospinel lamellae, which usually represent less than 15 vol.%. In contrast, the magnetite inclusions in samples L-2612-41 and L-2612-49 show complex magnetite-illmenite-ülvospinel intergrowths. In addition to the needle and lath shapes, the magnetite inclusions may be isometric—these are referred to as *dust-like inclusions*.

#### 3.2. Shape Orientation Relationships

More than 95% of the magnetite inclusions pertain to one of the eight *orientation classes*, most of which were described in Ageeva, Bian, et al. (2020) (Figure 1). Seven of these orientation classes correspond to magnetite





**Figure 1.** (a) Optical image under combined reflected and transmitted light showing magnetite inclusions in an untwinned domain of plagioclase in sample L30-277-10. (b) Same as in (a) with the magnetite needles color coded according to the orientation class they pertain to. (c) Pole figure of the needle orientations. Note that the number of observed pl(112)n-mt needles is less than their true bulk concentration due to their orientation subparallel to the plane of the thin-section, which is only about 30  $\mu$ m thick, while the field of view is about 300  $\times$  300  $\mu$ m<sup>2</sup>.

inclusions that are elongated parallel to the normal directions of specific low-index lattice planes of plagioclase, including pl(112), pl( $\overline{3}$ 12), pl(150), pl(1 $\overline{5}$ 0), pl(1 $\overline{1}$ 2), pl( $\overline{3}$ 12), and pl(100). We denote these inclusion types as "pl(hkl)n-mt," where "pl(hkl)n" is the plagioclase (hkl) plane-normal direction parallel to the needle elongation direction. It should be noted, that for magnetite, which has cubic symmetry, all crystallographic directions [uvw] are parallel to the normal of the lattice planes (hkl) if h = u, k = v, l = w(Figure S2 in Supporting Information S1). By contrast, no such correspondence exists between crystallographic directions and plane normals for triclinic plagioclase, where all unit cell angles are different from 90° (Figure S2 in Supporting Information S1). We use round brackets (hkl) and square brackets [uvw] to distinguish crystallographic planes and directions respectively, while (hkl)n indicates the normal direction to the (hkl) plane.

Magnetite inclusions pertaining to the above orientation classes are referred to as *plane-normal type* inclusions. Sobolev (1990) described several of the plane-normal inclusion types in plagioclase from a layered gabbro-norite intrusion. The eighth orientation class is represented by magnetite inclusions that are elongated parallel to the pl[001] direction. Magnetite inclusions with this orientation were described by Ageeva, Bian, et al. (2020), Biedermann et al. (2016), Sobolev (1990), and Wenk et al. (2011). Very rarely, needles elongated parallel to the normal direction of the pl(010) plane are observed.

#### 3.3. Crystallographic Orientation Relationships

Ageeva, Bian, et al. (2020) demonstrated that the elongation direction of the plane-normal type magnetite inclusions is parallel to one of the mt[111] directions. In contrast, pl[001] inclusions are elongated parallel to one of the mt[011] directions. All magnetite inclusions pertaining to the same shape orientation class are aligned parallel, with a maximum deviation of a few degrees from the average (Figure 1). Crystallographic orientations of the magnetite needles show some rotational dispersion around the needle elon-

gation direction. Figures 2a-2c show the distribution of the crystallographic orientations of pl(112)n-mt needles in an untwinned plagioclase domain. The crystallographic orientations cluster at different positions that related to each other by a rotation about the pl(112) pole (Figure 2a). The clusters correspond to CORs where the magnetite mt(011) planes are parallel to low-index planes of plagioclase (Figure 2b). In some needles one of the mt[001] directions lies nearly parallel to the plagioclase [14 10 7] direction (Figure 2c). According to Ageeva, Bian, et al. (2020), this orientation ensures a good fit of FeO<sub>6</sub> octahedra of the magnetite crystal structure in channels in the plagioclase crystal structure running parallel to pl[001] and is referred to as *nucleation orientation*. The magnetite inclusions of other orientation classes show similar rotation and orientation clustering with respect to their elongation axis.

#### 3.4. Crystallographic Orientation Relationships of Dust-like Magnetite Inclusions

Apart from the needle and lath shaped magnetite inclusions, equant, or so-called *dust-like*, magnetite inclusions are present in the plagioclase host. As compared to the needle shaped magnetite inclusions, the dust-like inclusions generally have different and more variable CORs with respect the plagioclase host, but some preferred orientations can still be discerned. For example, in one of the studied plagioclase grains dusty magnetite inclusions with mt(111) parallel to pl(120) dominate (Figures 2d–2f). This type of inclusions also has two mt[001] directions parallel to the plagioclase directions pl[023] and pl[023]. Another type of COR that was often observed between the dust-like inclusions and plagioclase host is characterized by the parallel alignment of mt(111) and mt(110) with pl(010) and pl(100), respectively.





**Figure 2.** (a–c) Stereographic projections (upper hemisphere) showing the orientation distribution function (halfwidth =  $3^\circ$ , N = 17) of pl(112)n-mt inclusions in an untwinned domain of plagioclase (sample L30-277-10) for (a) mt(111), (b) mt(011) and (c) mt(001). Red circles and red labels indicate the orientations of crystallographic planes and directions of the plagioclase host. All symmetrically equivalent crystallographic planes of the cubic magnetite are shown. In this domain of the plagioclase grain, most needles cluster so that mt(011) parallels pl(131). (d)-(f) Stereographic projection (upper hemisphere) showing the orientation distribution function (halfwidth =  $2^\circ$ , N = 15) of the dust-like magnetite inclusion relative to the plagioclase grain: (d) mt(111), (e) mt(011), and (f) mt(001). Note that no correspondence with the crystallographic orientation relationships of the needle-shaped inclusions is observed. Most dust-like inclusions have mt(111) parallel to pl(120). Sample L30-277-10.

#### 3.5. Shape Orientation Distribution of the Magnetite Inclusions

The magnetite inclusions pertaining to the different orientation classes are present in different proportions (Table 1). In most samples, except for those that experienced hydrothermal overprinting (L-2612-41, L-2612-49), the inclusions of the pl(112)n-mt class are the most abundant and represent ~50% of all needle or lath shaped inclusions. The second most abundant inclusion type is pl( $\overline{3}12$ )n-mt, which represents up to 20% of the

inclusions. The pl $(1\overline{5}0)$ n-mt and pl(150)n-mt inclusions together represent about 20%, and pl $(\overline{312})$ n-mt and pl $(\overline{112})$ n-mt together represent up to 10%.

#### Table 1

Distribution of Needle-Shaped Magnetite Inclusions (%) According to Orientation Class With Low (A), Moderate (B) and High (C) Proportions of pl[001]-Mt Inclusions (N = 20 Studied Grains)

	А	В	С	"Pl(010) girdle"
pl(112)n-mt	40-45	35	0–5	+
$pl(\overline{3}12)n-mt$	25	15	-	+
pl(150)n-mt and pl(150)n-mt	15	2	-	-
$pl(\overline{312})n-mt$ and $pl(\overline{112})n-mt$	10	3	-	+
pl(100)n-mt	0–5	5	-	+
pl[001]-mt	5	40	95-100	+

The pl[001]-mt inclusions are distributed heterogeneously. Some plagioclase grains host hardly any individuals of this type (Figure 1), in other cases, they occur at moderate amounts (Figure 2 in Ageeva, Bian, et al., 2020). The pl[001]-mt inclusions are the more typical inclusion type in the external parts of the plagioclase grains and in areas surrounding cracks. Moreover, this inclusion type dominates samples that experienced high temperature hydrothermal processing (L-2612-41, L-2612-49). The pl(100)n-mt inclusions also have quite heterogeneous distributions and usually accompany the pl[001]-mt inclusions (Figure 2 in Ageeva, Bian, et al., 2020).

The elongation directions of the magnetite inclusions from six out of the eight orientation classes lay approximately parallel to the pl(010) plane and form a  $\sim 30^{\circ}$  wide girdle distribution parallel to this plane (Figure 3a). The most





**Figure 3.** (a) Shape orientations of the magnetite inclusions of the different orientation classes in untwinned plagioclase viewed in a projection along the pl[001] direction. (b) Schematic orientation distribution inferred from statistical data (upper hemisphere). The  $30^{\circ}$  girdle parallel to the pl(010) plane (gray shaded area) comprises the pl(112)n-mt, pl( $\overline{3}12$ )n-mt, pl(100) n-mt, pl( $\overline{1}2$ )n-mt, pl( $\overline{3}12$ )n-mt, and pl[001]-mt type inclusions. (c) Transmitted plane-polarized light image of a twinned domain in plagioclase composed of Carlsbad-1 and -2 twins and albite twins (Ab1 and Ab2) in the Carlsbad-2 twin (Sample L30-277-7). The stereographic projections (upper hemisphere) show the different inclusion types. The needle directions are color coded according to their elongation directions (labeled in the left plot). The orientation of the twin boundaries is pl(010)—similar for all individual twins.

abundant inclusion types, pl(112)n-mt and  $pl(\overline{3}12)n-mt$  plane-normal type inclusions as well as the pl[001]-mt inclusions, which dominate in other domains, pertain to this girdle (Figures 3a and 3b).

In sum, regardless of which orientation classes dominates, for 70%–80% of the magnetite inclusions in plagioclase, the elongation direction closely parallels the pl(010) plane. The plagioclase grains in oceanic gabbro are typically twinned, and for understanding the potential influence of inclusion orientation anisotropy on the bulk magnetic properties of a magnetite bearing plagioclase grain, the orientation distribution of the magnetite needles needs to be considered in twinned plagioclase grains.

#### 3.6. Shape Orientation Distribution of the Magnetite Inclusions in Twinned Plagioclase

Plagioclase grains in oceanic gabbro show complex twinning. Large grains typically follow a Manebach twin law (twin plane pl(001); twin axis pl(001)n) and less frequently a Carlsbad law (twin plane  $\perp pl[001]$ ; twin axis pl[001]). All grains show polysynthetic twinning after the Albite-law (twin plane pl(010); twin axis pl(010) n) or Albite and Pericline twins (twin plane  $\perp pl[010]$ ; twin axis pl[010]) (Deer et al., 2001; Xu et al., 2016). Within a single plagioclase grain, the combination of the different twins leads to the formation of domains with





**Figure 4.** Schematic plots of inclusion orientation distributions showing simulated statistical distributions (halfwidth  $30^\circ$ , upper hemisphere) of the magnetite needle orientations in plagioclase with different combinations of twinning (Ab—Albite, Pe—Pericline, Cb—Carlsbad, Mb—Manebach, Un—untwinned). In row (a), only magnetite inclusions of the plane-normal type, among which the pl(112)n-mt are the most abundant, are considered. In row (b), both, the plane-normal and the pl[001]-mt inclusion types are considered. In row (c) only the pl[001]-mt inclusions are considered. Table 1 lists the proportion of the inclusions pertaining to the different orientation classes. The  $30^\circ$  girdle parallel to the pl(010) plane (dashed black lines) comprises the inclusions oriented perpendicular to pl(112), pl( $\overline{3}12$ ), pl( $\overline{10}$ ), pl( $\overline{112}$ ), pl( $\overline{312}$ ), and pl(100) planes and parallel to pl[001]. All plots have the same viewing direction along pl[001]. The poles of selected plagioclase planes and directions are shown for untwinned plagioclase in column (i) The pole and the projection of the pl(010) plane are indicated by the large black circles and the thick black line, respectively; the pl[001] and pl(112)n directions are indicated by the white square and the black double circle, respectively; the black dots mark the poles of the plane corresponding to the elongation directions of the other orientation classes. Combining pericline and albite twins hardly affects the orientation distribution of the magnetite inclusions. Cases III and IV consider combined albite and pericline twinning in Carlsbad and Manebach twin individuals. The twinning operations and plotting were performed with the MatLab MTEX software package (Krakow et al., 2017).

different crystallographic orientations, which are related through the symmetry operations underlying the twinning. The dominance of some inclusion orientation classes in different twin individuals of plagioclase increases the observed dispersion of magnetite elongation directions inside a twinned plagioclase grain (Figure 3c).

Based on the shape orientation distribution of the needle-shaped magnetite inclusions in untwinned plagioclase (Figures 3a and 3b), the shape orientation distribution of the magnetite needles in twinned plagioclase was simulated for plagioclase grains with the most common twin combinations. The results are illustrated in Figure 4 and Figure S3 in Supporting Information S1. The pl(010) plane orientation is barely affected by the twinning of plagioclase, and most of the inclusions contained in the twin individuals remain oriented closely parallel to the pl(010) plane so that the girdle distribution parallel to pl(010) persists even after multiple twinning.





**Figure 5.** EBSD data (upper hemisphere) of L30-277-10 showing the poles of the plagioclase planes corresponding to the elongation directions of the needle-shaped magnetite inclusions of all eight orientation classes, and orientation maps corresponding to these projections. The plagioclase grains are twinned after (a) Manebach and Albite laws and (b) the Albite law. Models that schematically represent the mutual orientation relationships of the twins in plagioclase grains are shown. The 30° girdle containing the elongation directions of the majority of the needle shaped magnetite inclusions is shaded in gray. Black circles indicate the poles of the pl(010) planes. Figure S4 in Supporting Information S1 gives more examples of crystallographic orientation relationships in twinned plagioclase. Note that the pole figures only show the inclusion elongation directions in grains of twinned plagioclase and do not include data on the statistical distribution of the inclusions.

In plagioclase that underwent high-temperature hydrothermal processing, the majority of the inclusions are oriented along the pl[001] direction (Figure 4, row C). It is worth noting that, since the pl[001] direction lies in the pl(010) plane, the magnetite inclusions are also elongated parallel to pl(010) in hydrothermally overprinted plagioclase. In cases with moderate (Figure 4, row B) or low (Figure 4, row A) concentrations of pl[001]-mt inclusions, all types of twinning show higher dispersion of the plane-normal-type inclusion orientations, yet have higher concentrations of pl[001]-mt inclusions. An additional maximum of pl[001]-mt orientations only results from Manebach twinning (Figure 4, column IV, row C).

EBSD data from plagioclase domains with Manebach and Albite twinning (Figure 5a and Figures S4a and S4b in Supporting Information S1), Carlsbad and Albite twinning (Figure 5b and Figure S4c in Supporting Information S1), exclusive polysynthetic Albite twinning (Figure 5b), and Albite and Pericline polysynthetic twinning (Figure S4d in Supporting Information S1) follow the simulated orientation relationships of the inclusions in untwinned and twinned plagioclase (Figures 3a, 3b, 4). The combined evidence reveals an anisotropy in the shape orientations of the magnetite inclusions in twinned plagioclase, which may be described in terms of two end-member distribution types. First, in samples where the plane-normal type inclusions dominate, the orientation distribution of the inclusions' elongation directions shows a minimum perpendicular to the (010) plane and a  $\sim$ 30° wide girdle parallel to pl(010) that is relatively densely populated with needle elongation directions (row A in Figure 4). The second end-member case occurs when the magnetite inclusions oriented parallel to the pl[001] direction (row C in Figure 4).

#### 3.7. Anisotropy of Magnetic Remanence (AMR)

Figure 6 shows the AF demagnetization and anisotropy of magnetic remanence (AMR) of a plagioclase grain from sample L30-277-7 that is twinned after the albite law. The lattice orientations of the plagioclase and the magnetite inclusions were observed with polarized light (Figures 6a and 6b) and identified by EBSD (Figures 6c and 6d). AF demagnetization removed a very small fraction of the remanence, which we interpret as due to highly anisotropic magnetite (Figure 6e). It is interesting to note that the maximum AMR axis lies subparallel to the pl[001]-direction and the minimum AMR axis coincides with the pole to the pl(010) plane, while the intermediate axis lies in the pl(010) plane (Figure 6d). The anisotropy parameters define a triaxial prolate ellipsoid with





**Figure 6.** Confrontation of microscopy and magnetic measurements. Transmitted light optical images of sample L30-277-7 under crossed polarizers: (a) black and white, (b) real color - showing the magnetite inclusions in plagioclase. In (a) the different inclusion orientation classes are indicated as follows: pl(112)n-mt (red);  $pl(\overline{3}12)n-mt$  (blue); pl(150)n-mt and  $pl(1\overline{50})n-mt$  (cyan) (this pair cannot be discerned due to a coincidence of their projections into the plane of the thin section);  $pl(\overline{11}2)n-mt$  (white); the latter two pairs cannot be discerned due to a coincidence of their projections in this thin section; pl(100)n-mt (black): pl[001]-mt (yellow) (c) Pole figure (lower hemisphere) showing the shape orientations of the needles pertaining to the different orientation classes using the same color code as in (a) except for  $pl(1\overline{12})n-mt$  and  $pl(\overline{312})n-mt$ , which are shown by dotted lines, and for  $pl(1\overline{50})n-mt$  which is shown in green. The poles of the pl[001] and pl[001] directions are shown by open circles; the 30°-girdle parallel pl(010) is shaded in gray. (d) Stereographic projection (lower hemisphere) of the pl[001] direction and the pl(010) pole of the plagioclase together with the maximum (max), intermediate (int), and minimum (min) AMR axes (the three symbols correspond to three repeated measurements, Table 2). The stereographic projection shows a good correlation between the minimum AMR axis with the pl(010) pole and the maximum AMR axis with the pl[001] direction, while the AMR intermediate axis lies within the girdle of the poles defined by the magnetiz encloses or coincide well with the maximum AMR axis and the pl[001] direction. Open and filled circles represent poles in the upper and lower hemisphere, respectively. (e) Zijderveld plot showing the resistance to demagnetization (only ca. 30% of the total magnetization removed by 90 mT) and high coercivity of the grain. The +*X*, -*Y*, and -*Z* axes are parallel to the A1, A2, and A3 axes, respectively

a high degree of anisotropy (P = 1.9; Table 2). The data reveal a good correspondence between the anisotropy of magnetic remanence and the distribution of the shape orientations of the needle-shaped magnetite inclusions. Stepwise demagnetization of the natural remanent magnetization shows that the magnetic remanence lies near the maximum AMR axis in the pl(010) plane (Figure 6d), thereby indicating substantial control of the plagioclase host on the magnetite inclusions, and hence on the bulk-rock remanent magnetization.

A similar correspondence between the shape orientation distribution of the magnetite with respect to the plagioclase host and the anisotropy of magnetic remanence is observed for samples 1514–17 and 1491–10 (Figure 7, Figure S5 in Supporting Information S1). The anisotropy parameters indicate triaxial prolate (Sample 1514–17) and triaxial oblate (Sample 1491–10) ellipsoids with anisotropy degrees of 1.7 and 4.3, respectively (Table 2). The minimum AMR axes and the pl(010) poles correlate well in both samples. The maximum AMR axes closely parallel the pl[001] direction in the plagioclase grain in 1514–17 (Figures 7a–7c), represented by Albite twins and lies between the pl[001] directions of two Manebach twins in 1491–10 (Figures 7d–7f). The natural remanent



### Table 2

Magnetic Anisotropy Parameters of Plagioclase Grains From Samples L30-277-7, 1514-17, and 1491-10

	L	F	Р							
Run	$\overline{M_{\rm max}/M_{\rm int}}$	$\overline{M_{\rm int}/M_{\rm min}}$	$\overline{M_{\rm max}/M_{\rm min}}$	Pj	Т					
Sample L30-277-7										
1	1.63	1.14	1.86	1.92	-0.57					
2	1.66	1.15	1.90	1.97	-0.57					
3	1.52	1.19	1.81	1.84	-0.41					
Sample 1514-17										
1	1.47	1.19	1.75	1.77	-0.38					
2	1.38	1.21	1.67	1.68	-0.25					
3	1.40	1.19	1.67	1.68	-0.31					
Sample 1491-10										
1	1.80	2.35	4.24	4.28	0.18					
2	1.77	2.42	4.29	4.34	0.22					
3	1.68	2.60	4.37	4.47	0.29					

*Note.* M—magnetization; L—degree of magnetic lineation; F—degree of magnetic foliation; P—degree of anisotropy; Pj—corrected degree of anisotropy; T—shape parameter (Tarling & Hrouda, 1993).

magnetization directions of these magnetite-bearing plagioclase grains again lie close to the maximum AMR axes.

#### 4. Discussion

## 4.1. Inclusion Origin

The plagioclase hosted magnetite inclusions of the studied samples most likely formed by exsolution from iron bearing plagioclase during the sub-solidus evolution of the gabbro (Bian et al., 2021; Usui et al., 2006). Based on the notion that the ilmenite lamellae that are frequently observed in the magnetite inclusions either formed by direct exsolution from Ti-magnetite at temperatures of about 900°C (Lattard, 1995; Lattard et al., 2005; Tan et al., 2016) or by high-temperature oxidation at temperatures in excess of 600°C (Tan et al., 2016), the formation temperature of the magnetite inclusions were above the Curie temperature of magnetite (575°C-580°C, Akimoto, 1962). The magnetic record of the magnetite inclusions and of the magnetite bearing plagioclase grains are thus considered as a thermoremanent magnetization. The ulvospinel lamellae present in the magnetite inclusions of samples L-2612-41, L-2612-49 indicate re-crystallization of these rocks at temperatures below about 600°C, which was probably linked to hydrothermal processes (Ageeva, Pilipenko, et al., 2020). In the following, we focus on the overall magnetic anisotropy of magnetite-bearing plagioclase. In particular, we address the relationship between SOR and COR of the magnetite inclusions with the plagioclase host and the anisotropy of magnetic remanence of a magnetite-bearing plagioclase grain.

#### 4.2. Orientation Distribution of the Inclusions in Plagioclase

More than 95% of the needle-shaped magnetite inclusions belong to one of eight orientation classes including the seven plane-normal classes (pl(112)n-mt, pl( $\overline{3}$ 12)n-mt, pl( $\overline{1}$ 2)n-mt, pl( $\overline{3}$ 12)n-mt, pl(100)n-mt, pl(150)n-mt, pl(1 $\overline{5}$ 0)n-mt), and the pl[001]-mt needles (Figures 1, 3 and 4). Six of these orientation classes, including the pl(112)n-mt inclusions, which are the most abundant, and the pl( $\overline{112}$ )n-mt and pl( $\overline{312}$ )n-mt inclusions, which are the least common (Table 1 and Figures 3 and 4), are elongated parallel or nearly parallel to the pl(010) plane and form a 30°-wide girdle parallel to the pl(010) plane (Figures 3a and 3b). Only the needles pertaining to the pl(150)n-mt and pl( $\overline{150}$ )n-mt plane-normal classes, which together constitute less than about 20% of the inclusions, have elongation directions at high angles to the pl(010) plane. Thus, more than 75% of the needle and lathshaped magnetite inclusions pertain to the 30°-wide girdle parallel to the pl(010) plane (Figure 4 and Table 1). The pl[001]-mt needles show independent behavior (Table 1) and represent the dominant or sole inclusion type in metamorphically and hydrothermally modified samples.

Thus, the inclusions show a nearly planar orientation distribution parallel to the pl(010) plane with a maximum between the pl(112) pole and the pl[001] direction (Figure 4, column I, rows A, B) or they show preferential alignment parallel to the pl[001] direction (Figure 4, column I, row C). A similar orientation distribution was reported from gabbro-norites by Sobolev (1990), where pl(112)n-mt or pl[001]-mt needles dominate.

#### 4.3. Effect of Plagioclase Twinning

Four types of twins were identified in the plagioclase grains of the investigated gabbro (Figures 3–5 and Figures S3-S5 in Supporting Information S1). The Manebach and Carlsbad twins all show signs of growth twinning (Seifert, 1964): the twinned plagioclase grains consist of two twin individuals of approximately similar size and shape and only occur in grains that are substantially larger than grains without such twinning.

The albite and pericline twins are polysynthetic and are regarded as transformation or deformation twins. Bian et al. (2021) argued that the magnetite inclusions formed during or after transformation twinning. As a consequence, several shape orientation variants of the eight orientation classes may occur within a twinned plagioclase





**Figure 7.** Crystallographic and magnetic orientation data for plagioclase grains from samples 1514-17 (a–c) and 1491-10 (d–f). (a, d) Stereographic projection showing the pl[001] direction and the pl(010) pole of the twinned plagioclase together with the maximum (max), intermediate (int), and minimum (min) AMR axes (the three symbols correspond to the three repeat measurements, Table 2). A good correlation exists between the minimum AMR axis with the pl(010) pole and the maximum AMR axis with the pl[001] direction in (a) and between the pl[001] directions of two Manebach twins labeled mb1 and mb2 in (d). The intermediate axes lie within or close to the 30°-girdle. The pink circles indicate the directions from the AF demagnetization experiment. (b, e) Zijderveld plots showing the demagnetization trajectory from 0 to 90 mT. For the correspondence between sample coordinate system and EBSD reference system see Figure 6e. (c, f) Transmitted light optical images (crossed polarizers) of the plagioclase grains with Albite (c) and Manebach combined with Pericline and Albite twinning (f). The orientations of the magnetic inclusions of the different orientation classes are indicated by colored lines: pl(112)n-mt (red); pl( $\overline{3}$ 12)n-mt (blue); pl(150)n-mt (cyan); pl( $\overline{150}$ )n-mt (green); pl[001]-mt (yellow). The length of the lines is inversely proportional to the tilt of the inclusions relative to the surface of the thin section. Additional crystallographic orientation relationships data are presented in Figure S5 in Supporting Information S1. The colored bar in (f) indicates the position of the orientation distribution map shown in Figure S5 in Supporting Information S1.

grain. The orientation distribution resulting from combining the different variants shows an increased dispersion of the SORs of the inclusions (Figure S3 in Supporting Information S1), but for all combinations of twins the six orientation classes belonging to the 30°-girdle along the pl(010) plane remain within this girdle. The crystal orientation maps of the twinned plagioclase grains (Figure 5, Figure S4 in Supporting Information S1) clearly reveal the girdle with high concentrations of inclusion elongation directions. The anisotropic distribution of needle-shaped magnetite inclusions with the preferred alignment of the inclusions parallel or sub-parallel to the pl(010) plane thus does not only exist in individual twin domains, but is also present in multiply twinned plagioclase grains. In addition, the orientation of the pl[001]-mt class of inclusions is invariant with respect to twinning after the Albite, Pericline and Carlsbad laws. This twinning thus increases the concentration of the pl[001]-mt inclusions relative to the needles of all other orientation classes the orientations of which become more dispersed through the twinning (Figure S3 in Supporting Information S1). As a consequence, in twinned plagioclase the anisotropy in the orientation distribution of the inclusions still has its minimum normal to the pl(010) plane and its maximum close to parallel to the pl[001] direction, or between the pl[001] direction and normal to the pl(112) plane (Figure 4 row A, columns II-IV).

The most important characteristics of the inhomogeneous distribution of needle elongation directions are the minimum density of orientations sub-perpendicular to the pl(010) plane and the maximum density of orientations sub-parallel to pl[001] direction, which is typical for the grains with moderate and high concentrations of

pl[001]-mt inclusions. In cases where the plane normal type magnetite inclusions dominate, the maximum is shifted toward the normal of pl(112) plane, which is  $45^{\circ}$  away from the pl[001] direction, but still lies within the pl(010)-girdle.

#### 4.4. Magnetic Anisotropy of Magnetite-Bearing Plagioclase

Figures 6d, 7a, and 7d show that the maximum AMR axis directions and the remanent magnetization directions are nearly parallel to the pl[001] direction. Thus, the orientation of the AMR ellipsoid is well aligned with the anisotropy of the inclusion orientation distribution, which has its maximum directed along pl[001] and its minimum perpendicular to the pl(010) plane. Moreover, the NRM vector directions lie close to the axis of maximum magnetization of the AMR ellipsoid (Figures 6d, 7a, and 7d); hence, the magnetic anisotropy controls the remanent magnetization recording. Usui et al. (2015) found a similar effect in plagioclase from Paleoarchean granitoids.

For oceanic gabbro, it is thus well established that the anisotropy of remanence of individual needle-shaped magnetite inclusions is imprinted on the entire plagioclase-host grain through the anisotropic orientation distribution of the needle elongation directions. The plagioclase grains in mafic intrusive rocks are typically tabular parallel to pl(010) with their longest direction parallel to the pl[001] or pl[100] directions (Gee et al., 2004; Higgins, 2006). In foliated gabbro, the pl(010) plane is usually aligned parallel to the foliation plane (Feinberg, Wenk, et al., 2006) and the pl[001] may coincide with the lineation direction (Gee et al., 2004). This gives rise to a *normal magnetic fabric*, which is characterized by a correspondence between the long and the short axes of the magnetic anisotropy ellipsoid and the directions of silicate petrofabric lineation and foliation, respectively (Chadima et al., 2009; Cheadle & Gee, 2017; Gee et al., 2004; Higgins, 2006; Rochette et al., 1992; Selkin et al., 2014). The observed orientation distribution of the magnetiz inclusions in twinned plagioclase grains is in accordance with a magnetic fabric with the minimum magnetization normal to pl(010) and the maximum magnetization sub-parallel to pl[001] (Figure S6 in Supporting Information S1).

Alignment of minerals is typical for oceanic gabbros of fast spreading ridges, where the pl(010) plane is parallel to the foliation plane (Cheadle & Gee, 2017; Seront et al., 1993). Our gabbro samples come from a slow-spreading zone of the Mid Atlantic ridge and the studied material shows no clear bulk mineral alignment. Given the magnetic anisotropy of the magnetite bearing plagioclase grains, a normal magnetic fabric would be expected to arise if mineral alignment occurred in foliated or lineated varieties of the oceanic gabbros. The plagioclase-hosted micro-inclusions may represent the single or the dominant carrier of magnetization, or alternatively, they may constitute the bulk rock magnetic fabric together with the magnetic fabric formed by micro-inclusion bearing pyroxene (Biederman et al., 2020; Selkin et al., 2014) and by the interstitial magnetite grains in the rock matrix (Feinberg, Wenk, et al., 2006; Mattsson et al., 2021; Stephenson, 1994; Suhr et al., 2008; Uyeda et al., 1963).

Although EBSD, AMR and AF-demagnetization measurements were carried out for relatively few samples (Table S1 in Supporting Information S1), the relation between SOR of plagioclase hosted magnetite micro-inclusions and the magnetic anisotropy of the magnetite bearing plagioclase is expected to be a widespread phenomenon. This view is corroborated by the fact that systematic SORs of plagioclase hosted magnetite inclusions were observed for several tens of oceanic gabbros from slow spreading ridge segments screened using optical microscopy in this study. Moreover, similar SOR of plagioclase hosted magnetite inclusions have been described from different geological settings (e.g., Sobolev, 1990; Wenk et al., 2011). In detail, the relations between SOR and magnetic anisotropy may, however, deviate from those established in this study, depending on geological history.

The possible contribution of the plagioclase-hosted inclusions to the magnetic anisotropy may be estimated from routine petrographic observations with an optical microscope. The magnetite needles constituting the pl(010) girdle can be discerned from those that pertain to the orientation classes with the needle elongation directions at a high angle to the pl(010) plane by conventional polarization microscopy (Figure S1 in Supporting Information S1). The relative abundances of the needles belonging to the two groups allows one to estimate the degree of anisotropy in their orientation distribution and to predict the AMR of the magnetite in a plagioclase grain. This method may be used to plagioclase with twinning according to the Albite law, which is typical in mafic rocks.

#### 4.5. Effect of Hydrothermal Processing

In samples L-2612-41 and L-2612-49, all plagioclase-hosted magnetite inclusions are aligned parallel to the pl[001] direction and thus pertain to the single pl[001]-mt orientation class. These samples were affected by high-temperature hydrothermal processes (Pertsev et al., 2015). Domains containing pl[001]-mt inclusions are typical for the rim zones of plagioclase grains or around cracks. A similar prevalence of pl[001]-mt inclusions was described from anorthositic gneisses by Wenk et al. (2011). We infer that magnetite inclusions of the pl[001]-mt type form over a wide range of conditions (late magmatic, metamorphic, hydrothermal), whereas the magnetite inclusions in the plane-normal types appear to be restricted to late magmatic stages.

It should be noted that the inclusions of the plane-normal orientation classes are elongated parallel to one of their mt[111] directions, which are the easy axes of magnetization (Ageeva, Bian, et al., 2020; Bian et al., 2021). In contrast, the pl[001]-mt inclusions are elongated parallel to one of their mt[011] directions. Due to the fact that shape has a stronger influence on magnetic anisotropy than crystallographic direction (Rochette et al., 1992), this difference supposedly only plays a subordinate role.

In plagioclase domains with only pl[001]-mt inclusions, a rotational prolate shape is expected for the ellipsoid of the magnetic remanence anisotropy with the long axis parallel to the pl[001] direction for Carlsbad, Albite and Pericline twins (Figure 4, row C, columns I-III) or sub-parallel to the pl[001] direction for Manebach twins (Figure 4, row C, columns IV). As the pl[001] direction lies in the pl(010) plane, such magnetite-bearing plagioclase will form or contribute to a normal magnetic fabric, which is characterized by a correspondence between the long and the short axes of AMS ellipsoids to the lineation direction and the normal to the foliation plane of the silicate petrofabric, respectively (Cheadle & Gee, 2017; Gee et al., 2004; Higgins, 2006; Rochette et al., 1992; Selkin et al., 2014).

The exclusive presence of pl[001]-mt inclusions may be related to high temperature hydrothermal processing or metamorphic overprint. It is expected, that when the proportion of pl[001]-mt inclusions increases relative to the inclusions of the plane-normal type, the shape of the AMR ellipsoid of magnetite bearing plagioclase grains changes from predominantly oblate to predominantly prolate. In foliated gabbro, the exclusive presence of pl[001]-mt inclusions may contribute to an oblate magnetic anisotropy, and in lineated gabbro, a prolate magnetic anisotropy will arise when the pl[001] direction is aligned parallel to the lineation.

#### 4.6. Dust-Like Inclusions

The equant, so-called *dust-like* magnetite inclusions often accompany needle-shaped inclusions or may be present as the only type of inclusions in some plagioclase domains. In plagioclase domains where dust-like and needleshaped inclusions occur together, they show a multitude of CORs with respect to the plagioclase host, but one COR is usually dominant. In such domains, about 50% of the dust-like inclusions show mt(111) parallel to pl(120; Figure 2d) and usually have short prismatic shapes. The pl(120) planes have d-spacings of  $d_{(120)*2} = 2.37$  Å, which is only slightly lower than the d-spacing of the pl lattice planes that are aligned with one of the mt(111) planes of the plane-normal type inclusions (d = 2.40-2.50 Å). They may thus form by the same mechanism as the inclusions of the plane-normal types, but the poorer match in d-spacing between mt(111) and pl(120) leads to more isometric shapes. In addition, two of the mt[001] directions are aligned with the plagioclase pl[023] and pl[023]directions (Figure 2f) - a feature which is reminiscent of the magnetite inclusions of the plane-normal classes. These directions are parallel to lines connecting pairs of oxygen atoms in channels of the plagioclase crystal structure running parallel to pl[001] which are separated by a distance that is similar to the spacing between oxygen atoms along the mt[001] direction and correspond to the orientation of the apexes of FeO<sub>c</sub>-octahedra of</sub> the magnetite crystal structures (4.12-4.36 Å). Analogous alignments between the mt[001] directions and the pl[14 10 7] and pl[14 10 7] directions were identified for needle-shaped magnetite inclusions of the plane-normal types and interpreted as suitable modes for the accommodation of FeO<sub>6</sub>-octahedra in the crystal structure of plagioclase. The corresponding COR was thus referred to as the nucleation orientation of the magnetite inclusions in plagioclase (Ageeva, Bian, et al., 2020).

#### 5. Conclusions

Plagioclase grains from oceanic gabbro dredged at the Mid Atlantic Ridge (11°-17°N) were analyzed with respect to the relationships between the shape orientation distribution of needle and lath shaped magnetite inclusions and the anisotropy of magnetic remanence. The magnetite inclusions are single to pseudo single domainsized and show systematic shape and crystallographic orientation relationships with the plagioclase host. In plagioclase from pristine gabbro the needle elongation directions form a 30° wide girdle distribution parallel to the pl(010) plane. This distribution gives rise to a triaxial anisotropy ellipsoid with the direction of the minimum axis sub-perpendicular to the pl(010) plane and the maximum axis sub-parallel to the pl(010) plane, which corresponds to the most abundant needle orientations. The natural remanent magnetization vector is subparallel to the direction of the maximum AMR axis indicating that the anisotropy generated by the fabric of the needle shaped magnetite inclusions controls the paleomagnetic signal. In hydrothermally modified samples, most magnetite needles are oriented parallel to the pl[001] direction and the overall texture of the magnetite inclusions changes so that the resulting ellipsoid of remanent magnetization is expected to attain a rotational prolate shape with the maximum remanent magnetization parallel to pl[001]. The magnetic anisotropy of magnetite bearing plagioclase contributes to a normal magnetic fabric in foliated or lineated gabbro, where the plagioclase (010) plane is parallel to the foliation and the pl[001] direction is parallel to the lineation. Plagioclase hosted magnetite inclusions are particularly stable recorders of the paleomagnetic filed. For paleomagnetic reconstructions it is, however, essential that the potential anisotropy effects resulting from the needle and lath-shaped magnetite inclusions are adequately accounted for. The distribution anisotropy can be estimated based on standard petrographic analyses.

#### **Data Availability Statement**

Supporting Information is available at: https://zenodo.org/record/6046994#.YhU5vujMIjg.

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