Crystallographic and shape orientations of magnetite micro-inclusions in plagioclase

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Abstract
Plagioclase hosted, oriented magnetite micro-inclusions are a frequently observed phenomenon in magmatic and metamorphic rocks. Understanding the orientation relationships between these inclusions and the plagioclase host is highly relevant for interpreting paleomagnetic measurements. The systematics of the shape and crystallographic orientation relationships between needle- and lath-shaped magnetite micro-inclusions and their plagioclase host from oceanic gabbro were investigated using optical microscopy including universal stage measurements, scanning electron microscopy, and crystal orientation analysis by electron backscatter diffraction. The magnetite inclusions show preferred shape orientations following six well-defined directions and with specific crystallographic orientation relationships to the plagioclase host. These relationships are rationalized based on angular and dimensional similarities between the crystal structures of magnetite and plagioclase, which favor the parallel alignment of oxygen layers with similar lattice spacing in both phases. The parallel alignment of oxygen layers in plagioclase and magnetite can be traced back to the oriented nucleation of magnetite, which occurs by the accommodation of FeO$_6$ octahedra in six-membered rings of SiO$_4$ and AlO$_4$ tetrahedra of the plagioclase structure. The orientation systematics of the magnetite micro-inclusions is related to four orientation variants for placing the FeO$_6$ octahedra into the plagioclase structure.

Keywords Plagioclase · Magnetite inclusions · Shape orientation relationships · Crystallographic orientation relationships · Crystal structures · Oxygen layers

Introduction
Oriented micro-inclusions of Fe–Ti oxide minerals such as magnetite, ulvospinel, hematite, and ilmenite hosted in rock-forming silicate minerals are frequently observed in igneous and metamorphic rocks (Poldervaart and Gilkey 1954; Divljan 1960; Neumann and Christie 1962; Armbrustmacher and Banks 1974; Sobolev 1990; Usui et al. 2006; Wenk et al., 2011; Biedermann, et al. 2016; Ageeva et al. 2016, 2017). The Fe–Ti oxide micro-inclusions most likely precipitate within the silicate minerals that originally crystallized with high Fe and Ti contents from evolved melt (Natland et al. 1991) and became supersaturated with respect to Fe–Ti oxide minerals during cooling (Okamura et al. 1976) and/or under changing oxygen fugacity (Doukhan et al. 1990; Ashworth and Chambers 2000). Alternatively, igneous rocks may get metasomatized by interaction with evolved Fe- and Ti–rich melts or fluids during the late magmatic stages, which induces precipitation of Fe–Ti oxide micro-inclusions in the pre-existing silicate minerals (Trindade et al. 1999, 2001; Diot et al. 2003; Bolle et al. 2003; Malpas and Robinson 1997; Grimes et al. 2008; Hekinian 2014).

Among the Fe–Ti oxide minerals, magnetite is of particular interest in the context of paleomagnetism. Magnetite is ferrimagnetic with a Curie temperature of 580 °C, and it is the main carrier of the natural remanent magnetization of rocks (Dunlop and Ozdemir 1997, 2007; Tauxe 2010). In this context, the temperature at which the oriented magnetite inclusions formed is of crucial importance. Considering the
magnetocrystalline anisotropy of magnetite, also the shape and crystallographic orientation relationships between the magnetite micro-inclusions and the plagioclase host are of interest.

In clinopyroxene, magnetite inclusions primarily occur as elongated plates lying parallel to the (010) plane of the clinopyroxene and show two well-defined elongation directions (Bown and Gay 1959; Okamura et al. 1976; Harlow and Klimenitidis 1980; Fleet et al. 1980; Woensdregt et al. 1983; Doukhan et al. 1990; Renne et al. 2002; Feinberg et al. 2004; Hwang et al. 2010), which ensure perfectly coherent magnetite–clinopyroxene interfaces according to the optimum phase boundary model of Bollmann (1970). A geo-thermometer reflecting the temperature of magnetite precipitation was calibrated based on the notion that, due to the difference in thermal expansivity between magnetite and clinopyroxene, the angle between the two elongation directions is temperature dependent (Fleet et al. 1980; Doukhan et al. 1990; Feinberg et al. 2004).

When present as μm- and sub-μm-sized crystals, magnetites behave as single-domain or pseudo single-domain grains, where a primary remanent magnetization is very difficult to change (Dunlop and Ozdemir 1997, 2007; Tauxe 2010). The presence of abundant needle- or lath-shaped magnetite micro-inclusions in plagioclase and pyroxene of anorthosites and gabbros leads to the particularly stable natural remanent magnetization of these rocks (Evans et al. 1968; Sobolev and Faynberg 1990; Renne et al. 2002; Gee and Meurer 2002; Feinberg et al. 2005, 2006a; Tarduno et al. 2006; Ebert et al. 2010; Muxworthy and Evans 2013; Usui et al. 2015; Calvín et al. 2017). In the context of paleomagnetic measurements, understanding the crystallographic and shape orientation relationships between oriented magnetite micro-inclusions and the respective host crystal is important, because in an imposed magnetic field, it is considerably more difficult to saturate the magnetization of a magnetite along the “magnetically hard axes” < 100 > than along the magnetically “easy axes” < 111 > (Dunlop and Ozdemir 1997). Given that the magnetite micro-inclusions show distinct orientations in the plagioclase and pyroxene host crystals, the inherent magnetocrystalline anisotropy of magnetite may lead to anisotropic susceptibility of the entire inclusion–host assemblage and thus put a bias on the preservation of an externally imposed magnetic field. This phenomenon is of particular relevance, if single crystal paleomagnetic measurements are made (Cottrell and Tarduno 1999; Tarduno et al. 2006).

In this communication, we address oriented magnetite micro-inclusions in plagioclase from oceanic gabbros. Needle-shaped magnetite micro-inclusions lying in the (112), (150), and (150) planes of plagioclase were first described for avenurine feldspar by Andersen (1915). Later, Sobolev (1990) discerned five types of orientation of needle-shaped magnetite micro-inclusions and systematized their shape orientation relationships. The study of Sobolev (1990) is based on optical microscopy and gives only limited information on the underlying crystallographic orientation relationships. Wenk et al. (2011) used crystal orientation analysis by electron backscatter diffraction (EBSD) and Laue diffraction to determine the crystallographic orientation relationships between needle- and lath-shaped magnetite micro-inclusions and their plagioclase host. These latter authors focused on needle-shaped magnetite inclusions with their elongation direction parallel to the [001] direction of the plagioclase host and suggested a model relating this orientation to the presence of abundant magnetite nucleation sites along channels in the plagioclase structure running parallel to p[001]. In our study, we combine crystal orientation analysis by EBSD, optical microscopy including U-stage measurements, and scanning electron microscopy (SEM) to complement the observations made by Sobolev (1990) and Wenk et al. (2011). We combine information on the shape and crystallographic orientation relationships of all the orientation types reported by Sobolev (1990) and Wenk et al. (2011) and put these observations into a common framework that is based on the underlying crystallographic relationships.

**Sampling and methods**

**Sampling**

The plagioclases investigated in this study are from oceanic gabbros that were dredged at the Mid Atlantic Ridge between 10°N and 14°N during the 2005–2009 cruises of the R.V. Professor Logachev (Beltenev et al. 2007, 2009; Cipriani et al. 2009; Pertsev et al. 2012). The gabbro samples L2612-41 and L2612-47 were collected from classical oceanic crust of the Vema lithospheric section (Bonatti et al. 2005). Other samples are from gabbro-peridotite Oceanic Core Complexes (OCCs) exhumed in footwalls of large-offset extensional faults (“13°N OCC” and “13°30’N OCC”, Smith et al. 2008). Two groups of gabbros were sampled. One group is represented by rocks with simple geological history including the non-altered sample L30-277–10 and the hydrothermally altered sample L30-277–7. The other group is represented by rocks with more complex petrogenetic history including gabbros intruded by plagiogranite veinlets (Sample L32-101–1) and gabbros with multi-stage late-magmatic and high-temperature hydrothermal alteration (Samples L2612-41 and L2612-47).

**Optical microscopy and universal stage measurements**

Polished thin sections with chemo-mechanical finish were prepared from all samples and investigated by polarization microscopy using both transmitted and reflected light. A

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4-axis universal stage was used for determining the shape orientation of the needle- or lath-shaped magnetite micro-inclusions. In a first step, the microscope table was rotated to put a magnetite needle into the N–S orientation in the microscope image. In a second step, the thin section was tilted around two mutually perpendicular axes of the U-stage to bring the elongation direction of the inclusion into parallel alignment with the microscope axis or into horizontal position, depending on the inclination of the elongation direction with respect to the sample surface. In replicate measurements, the orientation of the elongation directions of individual inclusions could be reproduced within 2°–7°.

**Electron backscatter diffraction (EBSD)**

The crystallographic orientations of plagioclase and magnetite crystals with respect to the sample reference system were determined using EBSD. The EBSD analyses were performed on an FEI Quanta 3D FEG-SEM at the laboratory for scanning electron microscopy and focused ion beam (FIB) applications of the Faculty of Geosciences, Geography and Astronomy at the University of Vienna (Austria). The SEM has a Schottky-type field emission electron source and is equipped with an EDAX Digiview 5 EBSD camera mounted at an elevation angle of 5°. The thin section samples were carbon coated and were at 70° stage tilt and 14–14.5 mm working distance. The EBSD analyses were performed in high vacuum mode. The electron beam was operated at 15 kV accelerating voltage and c. 4 nA probe current in the analytical beam mode. The EBSD camera resolution was set to 4 × 4 binning, yielding a Kikuchi pattern resolution of 215 × 215 pixels. Different camera gain settings were applied for analyzing plagioclase and magnetite to account for the strongly differing signal intensities of the two phases. Static and dynamic background filters were applied along with a grayscale normalization filter to optimize image contrast of the Kikuchi patterns. All crystal orientation data were collected as single points using the software EDAX OIM DC 7.3.1., where the Hough transform settings (binned pattern size, Rho-fraction, minimum peak distance and the maximum number of reflectors used) were adjusted for each analysis point. A minimum number of 3 reflectors were used for indexing, whereas the maximum number of reflectors varied between 13 and 18. Only the band center position was considered for indexing, and the interplanar angle tolerance was set to 2°. Measured band triplets were indexed by automatized comparison with the references structures of plagioclase as triclinic [P-1]: a = 8.152 Å, b = 12.834 Å, c = 7.079 Å; α = 93.49°, β = 116.13 Å, γ = 90.4 Å (AMCS database 762, Wenk et al. 1980), and magnetite as cubic [Fd-3 m]: a = 8.396 Å, α = 90° (TSL Materials Database).

The statistics of each orientation solution (confidence index, Fit value and the total number of band triplets) were individually checked, and only those data that yielded an unambiguous orientation solution were stored. The crystal orientation data were processed using the software EDAX OIM Analysis 7.3.1 and the MatLab MTEX toolbox (Kra-kow et al. 2017). The AutoCAD software was used for 3D visualizations.

**Results**

**Sample petrography**

The mineral content of the gabbros is dominated by primary magmatic coarse-grained (1–15 mm) tabular plagioclase and prismatic and xenomorphic pyroxene, where most pyroxenes are clinopyroxene, and orthopyroxene is rare. In the altered gabbros, the initial grain shape is rarely preserved due to recrystallization and partial replacement by secondary minerals such as amphiboles and fine-grained polyphase mineral aggregates. The Fe–Ti oxides present as large interstitial grains of magnetite and as micron- and sub-micron-sized inclusions in plagioclase and pyroxene. Detailed descriptions of the mineralogy and petrography of the gabbros with complex petrogenetic history (Samples L32-101–1, L2612-41, L2612-47) can be found in Pertsev et al. (2015), Aranovich et al. (2015) and Ageeva et al. (2017).

The plagioclases from the studied gabbros contain abundant micrometer and sub-micrometer-sized needle- or lath-shaped magnetite micro-inclusions (Fig. 1) with preferred shape orientations following distinct directions within the plagioclase host (Fig. 1a, b). The needles are present primarily in the internal portions of the plagioclase grains and are less common or missing in the rim regions and in the vicinity to contacts with plagiogranite veinlets or hydrothermal veins. Within a single inclusion, the magnetite usually has constant crystallographic orientation. It was shown by Ageeva et al. (2016) that in the course of hydrothermal overprint, the magnetite micro-inclusions may recrystallize, coarsen and assume more tabular shape. In addition, oriented sub-micrometer-sized lamellae of ilmenite and/or ulvospinel may be present within individual magnetite inclusion (Fig. 1c, d). The genesis of the ilmenite and ulvospinel lamellae has been discussed by Wenk et al. (2011), Tan et al. (2016), and Ageeva et al. (2016, 2017) and is not further addressed in this communication.

In this study, we focus on the most pristine sample (Sample L30-277–10), where the gabbro is devoid of any indications of hydrothermal alteration. In this sample, the micro-inclusions have pronounced needle shape with diameters of several 100 nm, to about 1 μm and a length of up to several 100 μm (Fig. 1). The inclusions generally have aspect ratios of > 100 and show strong shape preferred orientation with respect to the plagioclase host. The magnetite needles are...
we denote the inclusions with their elongation directions parallel to the pl[001] direction as “pl[001]-mt” (Fig. 2c).

It is seen in the stereographic projection of Fig. 3a that the pl[001]-mt (labeled “F”) and the pl(112)n-mt (“B”) needles lie in the pl(150) plane, the pl[001]-mt (“F”) and the pl(312)n-mt (“C”) needles lie in the pl(150) plane, the pl(112)n-mt (“B”) and the pl(150)n-mt (“E”) needles are closely parallel to the pl(312) plane, and the pl(150)n-mt (“D”) and the pl(312)n-mt (“C”) needles are closely parallel to the pl(112) plane. Finally, the pl(150)n-mt (“D”) and pl(150)n-mt (“E”) needles are parallel to the plane that is perpendicular to the pl[001] direction, which is close to the pl(418) plane, and the less abundant pl(100)n-mt (“A”) needles lie close to the pl(010) and the pl(418) planes.

It is important to note that magnetite needles pertaining to all six shape orientation classes are present in the samples of the oceanic gabbros under study. Among the six orientation classes, the pl(112)n-mt and the pl(312)n-mt needles are the most abundant. The plagioclase from the oceanic gabbro has compositions of labradorite to bytownite with anorthite contents of 60 to 70 mol %. For samples containing plagioclase with andesine composition (Samples L2612-41 and L2612-47), where the anorthite content is comparatively low (42–45 mol %), the pl[001]-mt micro-inclusions are the dominating class representing more than 95% of the observed cases. Albite and oligoclase do not contain any magnetite micro-inclusions.

Crystallographic orientation relationships between the magnetite micro-inclusions and the plagioclase host

It has been shown by Ageeva et al. (2016) and is confirmed by our new measurements that the SORs between the magnetite needles and the plagioclase host are accompanied by systematic crystallographic orientation relationships (CORs). For example, for the pl[001]-mt inclusions, one of the mt < 011 > directions is parallel to the pl[001] direction and, at the same time, one of the mt < 111 > directions is parallel to pl(150)n, and another one of the mt < 011 > directions is sub-parallel to pl(150)n. Thus, the orientation relationships are fixed, and this COR may be referred to as a specific COR (Griffiths et al. 2016; Habler and Griffiths 2017). In some cases, one of the mt < 111 > directions is parallel to pl(150)n or pl(120)n. The latter one corresponds to the COR described by Wenk et al. (2011).

For all shape orientation classes of the plane-normal inclu- sions one of the mt < 111 > directions is parallel to the elongation direction of the inclusion (Fig. 4) and thus to the plane normal of either the pl(112), pl(312), pl(150), or the pl(100) plane, depending on shape orientation class. The orientations of the pl(112)n-mt, pl(312)n-mt, pl(150)n-mt, and the pl(150)n-mt inclusions show rotation around

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Shape orientation relationships between the magnetite micro-inclusions and the plagioclase host

About 90% of the magnetite micro-inclusions show shape-preferred orientations with their elongation directions following several well-defined directions in the plagioclase host (Fig. 2). U-stage measurements confirm the shape orientation relationships (SORs) that were previously identified by Sobolev (1990). The shape orientations of the magnetite needles correlate neither with typical growth facets of plagioclase nor with cleavage- or twinning planes. Five of the inclusion elongation directions are identified as being perpendicular to the pl(112), pl(312), pl(150), pl(150) and pl(100) planes, and one coincides with the pl[001] direction (Fig. 2c). We refer to the different groups of orientations as orientation classes and use the notation “pl(112)n-mt”, “pl(312)n-mt”, “pl(150)n-mt”, “pl(150)n-mt”, and “pl(100)n-mt” for the inclusions with their elongation directions normal to the respective plagioclase planes. These inclusions are categorized as the “plane-normal type”. Furthermore,
their elongation direction, which corresponds to one of the mt < 111 > directions. We refer to those inclusions of the plane-normal type that only have one orientation match with the plagioclase host as being in “general orientation”.

For each shape orientation class of the plane-normal inclusions, a subset of inclusions has additional orientation matches with the plagioclase host, so that a specific COR between the magnetite and the plagioclase host results. For example, a subset of the pl(112)n-mt inclusions show a specific COR with one of the mt{011} planes parallel to the pl(150) plane and another one sub-parallel to the pl(312) plane, in addition to the alignment of one of the mt{111} planes with the pl(112) planes. Similarly, a subset of the pl(312)n-mt inclusions have one of the mt{011} planes parallel to the pl(112) plane and another one of the mt{011} planes parallel to the pl(150) plane, in addition to the alignment of one of the mt{111} planes with the pl(312) plane (Fig. 4b). We refer to those inclusions that have such specific COR with the plagioclase host as being in “main orientation”. Furthermore, for the pl(112)n-mt and the pl(150)n-mt inclusions, an additional specific COR exists, where one of the mt < 001 > directions is parallel to pl[14 10 7] and for the pl(312)n-mt and for the pl(150)n-mt inclusions one of the mt < 001 > directions is parallel to pl[14 10 7]. These CORs are linked to specific orientation variants for placing structural elements of the crystal structure of magnetite into the plagioclase structure and are referred to as the “nucleation orientation”, which is also a specific COR (see further down). Finally, the pl(100)n-mt needles have strong orientation relationships with one of the mt < 111 > directions parallel to the pl(100)n and another one of the mt < 111 > directions parallel to the pl(150)n and one of the mt < 011 > directions parallel to pl[001]. In addition, for the pl(100)n-mt needles, one of the mt < 001 > directions is parallel to pl[14 10 7], which corresponds to a nucleation orientation (Fig. 4a). Note for a particular shape orientation class any general crystallographic orientation is related to the main orientation and to the nucleation orientation by rotations around their elongation direction, which coincides with one of the mt < 111 > directions. The CORs of the most abundant shape orientation classes in general-, main-, and nucleation orientation are listed in Table 1. The shape and
crystallographic orientation relationships for some of these shape orientation classes are illustrated in Fig. 4.

In rare cases, one of the \( \text{mt} < 001 \) directions is parallel to the \( \text{pl}[0 0 1] \), \( \text{pl}[0 0 2] \), \( \text{pl}[1 0 0] \) and \( \text{pl}[0 2 3] \) directions. These arrangements also correspond to possible nucleation positions (see further down).

**Orientations of the magnetite–plagioclase interfaces**

In cross sections of magnetite needles appearing on the polished sample surface, the magnetites are bound by straight interfaces, indicating that the magnetite-plagioclase interfaces are faceted. The orientations of the planar interface segments were determined by combining the orientations of their traces on the polished sample surface as seen on SE images, crystal orientation information as obtained from EBSD, and elongation directions as obtained from U-stage measurements. The rationale underlying the construction is that the needles, which typically have aspect ratios > 100, are bound by prismatic planes containing the elongation direction. Given the high aspect ratios of the needles, the likelihood for the perimeter of a needle cross section appearing on the polished sample surface to be comprised of the traces of these prismatic planes is very high. Assuming that the straight segments of the magnetite-plagioclase interfaces in cross section are contained in prismatic planes, which also contain the elongation direction, the interface plane can be constructed from the direction of the linear segment of the trace of the magnetite-plagioclase interface on the sample surface and the elongation direction. Both these directions can be tied to the crystallographic orientations of the magnetite and plagioclase crystals based on the crystal orientation information from EBSD.

In Fig. 5, the results of this construction are shown for a \( \text{pl}(1 1 2)^n \)-mt inclusion and for a \( \text{pl}[0 0 1] \)-mt inclusion (see also Fig. 3b), both in main orientation. The \( \text{pl}(1 1 2)^n \)-mt inclusion is bound by \( \text{mt}{1 1 1} \) facets, which are aligned parallel to the \( \text{pl}(1 5 0) \) plane, and by \( \text{mt}{0 1 1} \) facets, which are sub-parallel to the \( \text{pl}(3 1 2) \) plane. The \( \text{pl}[0 0 1] \)-mt inclusion is bound by \( \text{mt}{1 1 1} \) facets which are parallel to \( \text{pl}(1 5 0) \), and by \( \text{mt}{0 1 1} \) facets, which are parallel to \( \text{pl}(1 5 0) \). Furthermore, the \( \text{pl}(3 1 2)^n \)-mt inclusions in main orientation were found to be bound by the \( \text{pl}(1 5 0) \) and \( \text{pl}(1 1 2) \) planes, each of which coincides with one of the \( \text{mt}(0 1 1) \) planes. The \( \text{pl}(1 5 0)^n \)-mt inclusions in main orientation were found to be bound by the \( \text{pl}(1 1 2) \) plane, which coincides with one of the \( \text{mt}(0 1 1) \) planes, and the \( \text{pl}(1 5 0)^n \)-mt inclusions in main orientation were found to be bound by the \( \text{pl}(3 1 2) \) plane, which coincides with one of the \( \text{mt}(0 1 1) \) planes.

**Discussion**

The salient features of the plagioclase-hosted magnetite micro-inclusions may be summarized as: (i) the elongation directions of the micro-inclusions correspond to specific
directions in the plagioclase host. In the samples under study, about 90% of the micro-inclusions show this directional coincidence. Based on their orientation relationships with the plagioclase host, they are grouped into six shape orientation classes, five orientation classes are of the plane-normal type with their elongation directions perpendicular to the pl(112), pl(1̅312), pl(1̅50), and pl(150) planes, respectively, and one orientation class is represented by needles with their elongation direction parallel to the pl(100) plane. Each shape orientation class has specific orientation relationships with the plagioclase host. (v) The micro-inclusions of one orientation class that have specific CORs to the plagioclase host are often bound by plagioclase planes, the normal directions of which are parallel to the elongation directions of magnetite micro-inclusions pertaining to the other orientation classes.

According to the theory of interfaces in crystalline materials (Bollmann 1970; Sutton and Balluffi 1995), the shape and the shape orientation of a solid phase precipitate forming in a host crystal are controlled by the similarity between the crystal structures of the precipitate and the host phase. The orientations of the phase boundaries essentially depend on the dimensional fit of the space lattices of the two phases. In the following, we discuss simple geometrical concepts that help to rationalize the systematic SORs and CORs between the magnetite precipitates and the plagioclase host.
In particular, \( \text{pl}(112) \) is nearly perpendicular to \( \text{pl}(150) \). For example, the \( \text{pl}(112) \) and the \( \text{pl}(150) \) planes of the plagioclase are very similar to the d-spacing of \( \text{mt}(222) \).

In addition, the d-spacing of the above-mentioned plagiooclase pairs can be found that are also mutually perpendicular. The two important lattice planes, \( \text{mt}(111) \) and \( \text{mt}(011) \) similarity exists to the magnetite structure, where among the plagioclase lattice planes that are parallel to the two phases. In this context, it is interesting to note that their elongation directions, duplets of pairwise perpendicular or nearly perpendicular lattice planes exist (Table 2).

Table 1 CORs of the six most abundant plagioclase-hosted magnetite micro-inclusions in general and specific (main and nucleation) orientation

| Orientation class | Orientation | \( \text{mt} < 111 > \) | \( \text{mt} < 011 > \) | \( \text{mt} < 001 > \) |
|------------------|-------------|----------------|----------------|----------------|
| \( \text{pl}(112)n\)-mt | General | \( \text{pl}(112)n* \) | | \( \text{pl}(150)n \) |
| | Specific: main | \( \text{pl}(112)n* \) | \( \text{pl}(150)n \) | \( \text{pl}[14 10 7] \) |
| | Specific: nucleation | \( \text{pl}(112)n* \) | \( \text{pl}(150)n \) | \( \text{pl}[14 10 7] \) |
| \( \text{pl}(150)n\)-mt | General | \( \text{pl}(150)n* \) | | \( \text{pl}(112)n \) |
| | Specific: main | \( \text{pl}(150)n* \) | \( \text{pl}(112)n \) | \( \text{pl}[14 10 7] \) |
| | Specific: nucleation | \( \text{pl}(150)n* \) | \( \text{pl}(112)n \) | \( \text{pl}[14 10 7] \) |
| \( \text{pl}(312)n\)-mt | General | \( \text{pl}(312)n* \) | | \( \text{pl}(150)n \) |
| | Specific: main | \( \text{pl}(312)n* \) | \( \text{pl}(150)n \) | \( \text{pl}[14 10 7] \) |
| | Specific: nucleation | \( \text{pl}(312)n* \) | \( \text{pl}(150)n \) | \( \text{pl}[14 10 7] \) |
| \( \text{pl}(150)n\)-mt | General | \( \text{pl}(150)n* \) | | \( \text{pl}(312)n \) |
| | Specific: main | \( \text{pl}(150)n* \) | \( \text{pl}(312)n \) | \( \text{pl}[14 10 7] \) |
| | Specific: nucleation | \( \text{pl}(150)n* \) | \( \text{pl}(312)n \) | \( \text{pl}[14 10 7] \) |
| \( \text{pl}(100)n\)-mt | General | \( \text{pl}(100)n* \) and \( \text{pl}(150)n \) | | \( \text{pl}[001] \) |
| | Specific: nucleation | \( \text{pl}(100)n* \) and \( \text{pl}(150)n \) | \( \text{pl}[001] \) | \( \text{pl}[14 10 7] \) |
| \( \text{pl}(001)\)-mt | General | \( \text{pl}(150)n \) | | \( \text{pl}(001)* \) |
| | Specific: main | \( \text{pl}(150)n \) | \( \text{pl}(001)* \) | | |
| | Specific: nucleation** | \( \text{pl}(150)n \) | \( \text{pl}(001)* \) | \( \text{pl}[14 10 7] \) |

*Directions coinciding with the elongation direction for all orientations of indicated orientation class. Note, for some orientation classes additional specific orientations exist: for the \( \text{pl}(112)n\)-mt inclusions \( \text{mt} < 011 > // \text{pl}[110] \) or \( \text{pl}[021] \); for the \( \text{pl}(312)n\)-mt inclusions \( \text{mt} < 011 > // \text{pl}[112] \); for the \( \text{pl}(100)n\)-mt inclusions \( \text{mt} < 011 > // \text{pl}[001] \); for the \( \text{pl}(001)\)-mt inclusions \( \text{mt} < 011 > // \text{pl}[150] \) or \( \text{pl}[120] \)

**Suggested CORs

Crystal structure basis for the elongation direction of the magnetite inclusions

Given that magnetite has cubic symmetry and plagioclase either has monoclinic or triclinic symmetry, the observation of systematic SORs and CORs between the magnetite micro-inclusions and the plagioclase host is puzzling. The systematic orientation relationships can, however, be understood based on similarities between the crystal structures of the two phases. In this context, it is interesting to note that among the plagioclase lattice planes that are parallel to the basal planes of the plane-normal inclusion types and that form the prismatic planes bounding the inclusions parallel to their elongation directions, duplets of pairwise perpendicular or nearly perpendicular lattice planes exist (Table 2).

In particular, \( \text{pl}(112) \) is nearly perpendicular to \( \text{pl}(150) \), and \( \text{pl}(312) \) is nearly perpendicular to \( \text{pl}(150) \). In this respect a similarity exists to the magnetite structure, where among the two important lattice planes, \( \text{mt}(111) \) and \( \text{mt}(011) \) pairs can be found that are also mutually perpendicular. In addition, the d-spacing of the above-mentioned plagioclase planes is very similar to the d-spacing of \( \text{mt}(222) \). For example, the d-spacing of the \( \text{pl}(112) \) and the \( \text{pl}(150) \) planes are close to perpendicular to one another, and at room temperature the d-spacing of the two lattice planes is nearly identical, \( \text{pl}(150)=2.45 \text{Å} \) and \( \text{pl}(112)=2.46 \text{Å} \), so that their traces show nearly cubic symmetry, when projected in the direction of their line of intersection, which is close to \( \text{pl}[\bar{5}1\bar{3}] \). In Fig. 6, the oxygen atoms of plagioclase and of a \( \text{pl}(112) \)-mt inclusion in main orientation are shown in a projection down the \( \text{pl}[\bar{5}1\bar{3}] \) direction. In this projection one of the \( \text{mt}(111) \) and one of the \( \text{mt}(011) \) planes are parallel to the viewing direction, and the corresponding oxygen atoms appear as mutually perpendicular rows. For a \( \text{pl}(112) \)-mt inclusion in main orientation, one of the \( \text{mt}(111) \) and one of the \( \text{mt}(011) \) oxygen layers are parallel to the \( \text{pl}(112) \) and the \( \text{pl}(150) \) planes, respectively. At room temperature, the d-spacing of the \( \text{mt}(222) \) planes, \( \text{mt}[222]=2.42 \text{Å} \), is nearly identical to the d-spacing of the \( \text{pl}(112) \) planes, \( \text{pl}[112]=2.46 \text{Å} \), ensuring a good match of the corresponding oxygen layers across the prismatic planes bounding the \( \text{pl}(112) \)-mt needles parallel to their elongation direction (Fig. 6a).

The nearly perfect lattice match can also be seen from the coincidence of the respective lattice vectors (Fig. 6c,d). In the projection along the \( \text{pl}[\bar{5}1\bar{3}] \) direction, the \( \text{pl}[150] \) and the \( \text{pl}(112) \) lattice vectors appear in true length. They enclose an angle of ~90°, and with \( \text{pl}[150]=2.45 \text{Å} \) and \( \text{pl}(112)=2.46 \text{Å} \) they have nearly the same length leading to a “cubic” symmetry of the oxygen sublattice. For a \( \text{pl}(112) \)-mt inclusion, the \( \text{mt}[222] \) lattice vector is aligned with and nearly identical to the \( \text{pl}(112) \) lattice vector (Fig. 6d, c), indicating the good match of the lattice planes in the elongation direction of the inclusion. The misfit between the \( \text{mt}(111) \) and the \( \text{pl}(112) \) oxygen layers on either side of a the prismatic
magnetite–plagioclase interfaces is about 1%. This misfit can either be accommodated by introducing misfit dislocations at every about 100th lattice plane or by elastic deformation of both the inclusion and the host crystals. In any case, due to the good lattice match, the prismatic interfaces likely have low interfacial energy and are thus favored.

For a pl(112)n-mt inclusion in main orientation, one of the mt{011} planes is parallel to the pl(112) plane, in addition to the parallel alignment of one of the mt{111} planes and the pl(112) plane. But the d-spacing is rather different for the mt{011}, mt{111} = 2.97 Å, and the pl(150) planes, pl(150) = 2.45 Å, and there is poor lattice match between the {011} oxygen layers of magnetite and the {111} oxygen layers of plagioclase across the basal planes of the inclusions, making them energetically unfavorable so that their formation is suppressed as is actually observed.

Similar structural relationships exist for all shape orientation classes of the plane-normal inclusions. For example, a rotation of the magnetite in Fig. 6b, d by 90° around the normal to the image plane (gray dashed arrow) produces a good match between the pl(150) and one of the mt{111} oxygen layers. This arrangement corresponds to the orientation of the pl(150)n-mt inclusions in main orientation. A similar accordance of the oxygen layers exists for the pl(312)n-mt (pl(312) = 2.50 Å), pl(150)n-mt (pl(150) = 2.40 Å) and pl(100)n-mt (pl(100) = 2.45 Å) inclusions.

From these structural relationships we infer that the SORs and CORs of the magnetite micro-inclusions of the plane-normal type result from the alignment of the densely packed mt{111} oxygen layers with the oxygen layers in the plagioclase that are parallel to the pl(112), pl(1̅312), pl(1̅50), pl(150), and the pl(100) planes, depending on the shape orientation class. The d-spacing of these oxygen layers is very similar to the d-spacing of the mt{222} oxygen layers. As a consequence, the oxygen sublattices of magnetite and plagioclase show a good match across interfaces running perpendicular to these plagioclase planes, which necessarily are interfaces containing the elongation directions of the plane-normal magnetite micro-inclusions. For the inclusions in main orientation, the prismatic interfaces bounding the inclusions in their elongation direction are aligned parallel to the mt{011} and a second important oxygen layer in plagioclase. This orientational coincidence is considered as a secondary effect further contributing to minimizing the interfacial energy, which discriminates

| Table 2 | Angles between magnetite and plagioclase lattice planes |
|---------|---------------------------------------------------------|
|          | mt{011}  | pl(112) | pl(150) | pl(312) | pl(150) | pl(001) |
| mt{011}  | 90°, 35° | –       | 88° (91°) | 85° (85°) | 66° (62°) | 45° (46°) |
| pl(112)  | –       | 88° (91°) | –       | 66° (65°) | 38° (39°) | 90° (90°) |
| pl(150)  | 85° (85°) | 66° (65°) | –       | 92° (91°) | 45° (45°) | – |
| pl(312)  | 66° (62°) | 38° (39°) | –       | 92° (91°) | –       | 90° (90°) |

Entries in bold font indicate pairwise perpendicular lattice planes corresponding to prismatic planes bounding the magnetite inclusions in main orientation parallel to their elongation directions. The angles are given for monoclinic high albite (Winter et al. 1979), the angles for triclinic labradorite (Wenk et al. 1980) are given in brackets.
Oriented nucleation of the magnetite inclusions

The crystal structure of plagioclase is usually rationalized based on crankshaft-like chains running parallel to the pl[100]-direction that comprise interconnected four-membered rings of SiO$_4$ and AlO$_4$ tetrahedra (Ribbe 1984). In their study on plagioclase-hosted magnetite micro-inclusions, Wenk et al. (2011) pointed out that in the context of plagioclase-hosted magnetite, micro-inclusions channels in the plagioclase structure that are formed by six-membered rings of SiO$_4$ and AlO$_4$ tetrahedra and run parallel to the pl[001] direction are of interest. It was shown by Wenk et al. (2011) that these channels are prone to accommodate FeO$_6$ octahedra, which are an important element of the crystal structure of magnetite. It was argued that the edges of the SiO$_4$ and AlO$_4$ tetrahedra forming the channels provide preferred sites for nucleation and growth of magnetite needles parallel to the pl[001] direction. Following the reasoning of Wenk et al. (2011), we explore the crystallographic basis of the preferred nucleation of magnetite in these channels and extend the concept to the plane-normal inclusion types. To account for the possibility that the magnetite micro-inclusions originally formed in a monoclinic plagioclase, which went through the monoclinic–triclinic transition after the formation of the magnetite micro-inclusions, we use the crystal structure of monoclinic high albite (Winter et al. 1979) and of triclinic labradorite (Wenk et al. 1980).

In Fig. 7, the six-membered rings of SiO$_4$ and AlO$_4$ tetrahedra forming the channels parallel to the pl[001] direction in the plagioclase structure are shown schematically in a projection down the pl[001] direction. The distance between the Od and Ob oxygen atoms connecting the SiO$_4$–AlO$_4$ tetrahedra in the six-membered rings is 4.34 Å in high albite (based on Winter et al. 1979) and 4.26 Å and 4.23 Å in labradorite (based on Wenk et al. 1980). This distance is very similar to the distance between the two oxygen atoms in the O$_1$–Fe$_1$–O$_1$ arrangement of the FeO$_6$ octahedra, which is 4.28 Å (based on Fleet 1986). The FeO$_6$ octahedra can thus be easily accommodated in the channels by sharing the Od and Ob oxygen atoms of the tetrahedral rings with the O$_1$ atoms of the FeO$_6$ octahedra. In each six-membered tetrahedral ring, there are two pairs of Od and Ob oxygen atoms, which are aligned with the pl[14 10 7] and with the pl[14 10 7]$^\perp$ directions, respectively. Noting that the line defined by the O$_1$–Fe$_1$–O$_1$ arrangement in the FeO$_6$ octahedra is parallel to one of the mt $<001>$ directions (Fig. 7b), the FeO$_6$ octahedra of magnetite can thus be accommodated in the plagioclase structure so that one...
Projection of the plagioclase structure down its [001] direction showing a six-membered SiO$_4$–AlO$_4$ tetrahedral ring (crystal structural data of high albite from: Winter et al. 1979). b Projection of the magnetite structure down its <011> direction (crystal structural data from: Fleet 1986). The black solid and dashed lines connect the oxygen atoms that are shared by both minerals in case of accommodation of magnetite FeO$_6$ octahedra in the six-membered SiO$_4$–AlO$_4$ tetrahedral rings of the plagioclase structure. The heavy red lines are the traces of the pl([14 10 7]) planes, which are oriented parallel to the viewing direction. Here, the line connecting the O$_1$–Fe$_1$–O$_1$ positions is aligned with the mt[001] direction and with the line connecting the Od–Ob positions that is parallel to the pl([14 10 7]) direction. This arrangement corresponds to the pl([100])n-mt inclusions, where one of the mt<011> directions is parallel to pl[001] and one of the mt{111} planes is parallel to pl[150]. It does not, however, correspond to the main orientation of the pl([150])n-mt inclusions, where one of the mt[011] planes is required to be parallel to pl[112] in addition. The curved arrow indicates the rotational degree of freedom of the FeO$_6$ octahedron of magnetite. In the triclinic labradorite lattice the directions pl[[14 10 7] and pl[[4 10 7]] deviate from the Od–Ob connection lines by an angle of ~5–6° of the mt <001> directions is either parallel to the pl[[14 10 7]] direction or to the pl[[4 10 7]] direction. Given the coincidence of the two O$_1$ oxygen atoms of the FeO$_6$ octahedron with the Od and Ob oxygen atoms of the tetrahedral rings, the FeO$_6$ octahedron has one rotational degree of freedom around the O$_1$–Fe$_1$–O$_1$ axis and thus around one of the mt <001> directions (Fig. 7b).

Figure 7 shows the case where the O$_1$–Fe$_1$–O$_1$ arrangement of the FeO$_6$ octahedron is parallel to the pl[[14 10 7]] direction. Making use of the free rotation of the FeO$_6$ octahedron around the mt[001] direction, an orientation can be found so that one of the mt{111} planes is nearly parallel to pl[150], which corresponds to the CORs of the pl([100])n-mt and the pl([150])n-mt inclusions. Applying a different rotation angle around the same rotation axis, a second orientation of the magnetite FeO$_6$ octahedron can be found, where one of the mt{111} planes is parallel to the pl([112]) plane, which corresponds to the COR of the pl([112])n-mt inclusions. Similarly, when the O$_1$–Fe$_1$–O$_1$ arrangement of the FeO$_6$ octahedron of magnetite is aligned with the pl[[14 10 7]] direction, two orientation relationships may be produced by rotation of the FeO$_6$ octahedron around the mt[001] direction, which correspond to the orientations of the pl([312])n-mt and the pl([150])n-mt inclusions, where one of the mt{111} planes is parallel to the pl([312]) and to the pl([150]) planes, respectively.

The shape orientation classes pl([112])n-mt, pl([312])n-mt, pl([150])n-mt, pl([150])n-mt, and pl([100])n-mt of the plane-normal inclusions are linked with the four orientation variants of the FeO$_6$ octahedra of magnetite in the six-membered tetrahedral rings shown in a projection down the pl[[001]] direction in Fig. 8. It should be noted that besides the pairs of suitably spaced oxygen atoms defining the pl[[14 10 7]] and pl[[4 10 7]] directions, other pairs of oxygen atoms pertaining to the six-membered rings of SiO$_4$ and AlO$_4$ tetrahedra forming the channels parallel to plagioclase [001] exist, which have suitable distances between the oxygen atoms (4.10–4.40 Å) for accommodating magnetite FeO$_6$ octahedra in the plagioclase structure. These pairs of oxygen atoms define several additional directions including pl[[0 2 3]], pl[[0 2 3]], pl[[4 69]], and pl[[2 90]], which one of the mt<001> directions could be aligned to. But only those orientation variants that allow for the parallel alignment of important oxygen layers in plagioclase and magnetite were identified in the CORs of the needle-shaped (elongated) magnetite micro-inclusions. We infer that out of the numerous suitable nucleation orientations only those that are accompanied by parallel alignment of oxygen layers and d-spacing match form needles. If the alignment and match do not apply, the magnetite crystals attain an isometric shape and form dust-like micro-inclusions.

For the pl[[001]]-mt inclusions, one of the mt<011> directions is parallel to the needle elongation direction. Their elongation direction cannot be argued based on good match of oxygen layers between the magnetite inclusions and the plagioclase host. According to Wenk et al. (2011), formation of the pl[[001]]-mt inclusions should rather be ascribed to the high concentration of nucleation sites along the pl[[001]] channels and the supposed enhanced diffusion along these channels, which both foster the formation of magnetite needles parallel to the pl[[001]] direction. It was first described by Sobolev (1990) and is confirmed by our observations that the pl[[001]]-mt inclusions are generally thicker and shorter than the inclusions pertaining to the other orientation classes. Moreover, whereas both the pl[[001]]-mt inclusions and all types of the plane-normal inclusions are observed in plagioclase of labradorite to bytownite compositions with anorthite contents of 50–70 mol %, the pl[[001]]-mt inclusions are also observed in plagioclase of oligoclase to andesine compositions with anorthite contents of 30–40 mol % in which no other types of micro-inclusions are found. It is inferred that the pl[[001]]-mt inclusions form by another mechanism than
Finally, the question arises, how the main crystallographic orientations of the micro-inclusions relate to the orientation of the FeO₆ octahedra in the plagioclase structure. The orientations of the FeO₆ octahedra where the two O₁ atoms of the O₁–Fe₁–O₁ arrangement are shared with the Ob and Od oxygen atoms of the six-membered tetrahedral rings and one of the mt{111} planes is parallel to pl(112), pl(150), pl(312), pl(150), or pl(100) are the respective nucleation orientations of the FeO₆ octahedra and corresponding plagioclase lattice planes for the four orientation variants. In orientation variant I, one of the mt{111} planes is parallel to the pl(112) plane; in orientation variant II, one of the mt{111} planes is parallel to the pl(150) plane and another one of the mt{111} planes is parallel to the pl(100) plane; in orientation variant III, one of the mt{111} planes is parallel to the pl(312) plane; and in orientation variant IV, one of the mt{111} planes is parallel to the pl(150) plane. The elongation directions of the micro-inclusions are indicated by the dashed gray lines, and the small arrows indicate the corresponding plane-normal directions.

Fig. 8 a Structural model of high albite (Winter et al. 1979) in [001]-projection showing the six-membered rings of SiO₄ and AlO₄ tetrahedra forming the channels parallel to the pl[001] direction. Magnetite FeO₆ octahedra (yellow polyhedra) are accommodated in the channels in four different orientation variants. The Od and Ob oxygen positions that are shared between the plagioclase and the FeO₆ octahedra are marked by gray arrows. The planes that are aligned in the magnetite and plagioclase structures are colored in red. The orientation variants of the FeO₆ octahedra are in accordance with the CORs between the pl(112)n-mt, pl(150)n-mt, pl(100)n-mt, pl(312)n-mt, and pl(150)n-mt inclusions and the plagioclase host. b The inclusions of the plane-normal type, and they occur over a larger range of conditions.
Oxygen layers in the plagioclase. The latter is considered as the prime control of the SOR and COR of the plane-normal inclusions.

For example, the main orientation of the pl(112)n-mt inclusions is characterized by one of the mt{111} planes being parallel to the pl(112) plane and one of the mt{011} planes being parallel to the pl(150) plane. This COR can be reached from the nucleation orientation by a rotation of about 15º around the mt <111> direction that is perpendicular to pl(112). The pl(112)n-mt inclusions show indeed a rotational dispersion of their COR corresponding to this rotation (Ageeva et al. 2016). Similarly a statistical COR corresponding to a rotation around the pl(150)n direction was shown for the pl(150)n-mt inclusions by the same authors. It must be noted that the coincidence of the OI atoms of the FeO₆ octahedra with the Ob and Od oxygen atoms of the tetrahedral rings, which is ensured in the nucleation orientation, is incompatible with a rotation around any one of the mt <111> directions and is thus lost for any other general orientation and for the main orientation. In Fig. 9, the rotation from the nucleation orientation to the main orientation is shown for a pl(112)n-mt inclusion.

The pl(100)n-mt inclusions represent a particular case, because besides the match of the d-spacing match and alignment of the oxygen layers in elongation direction, these inclusions show parallel orientation of one of the mt{111} with pl(150) providing an additional alignment of oxygen layers exactly in the position of nucleation (Fig. 4a, left). No rotation around the needle elongation direction was found for the micro-inclusions of this orientation class.

**Fig. 9** Orientation of the FeO₆-octahedron (yellow) in a six-membered ring of SiO₄ and AlO₄ tetrahedra (grey) in a projection that ensures that mt{111} and pl(112) are parallel to the plane of view. a Nucleation orientation of the FeO₆-octahedron in orientation variant I corresponding to the pl(112)n-mt inclusions. b Orientation of the FeO₆-octahedra after 15º rotation around the normal to the pl(112) plane into the main orientation of the pl(112)n-mt needles with one of the mt{111} planes parallel to the pl(112) and one of the mt{011} planes parallel to the pl(150). The red triangle (in both images) represents the pl(112) plane.

**Processes underlying the formation of oriented magnetite inclusions in plagioclase**

The typical order of crystallization of oceanic gabbro is olivine → plagioclase → clinopyroxene → orthopyroxene as expected for the crystallization sequence of MORB-type melt at low pressure (e.g., Villiger et al. 2007; Suhr et al. 2008). In drilled sections of oceanic gabbro, indeed the corresponding sequence from olivine-rich depleted lithologies to gabbro and gabbronorite and finally to highly evolved oxide gabbros enriched in incompatible elements (Goddard et al. 2009; Dick et al. 2017, 2019) is observed. Plagioclase-hosted Fe–Ti oxide micro-inclusions are common in both, highly evolved oxide gabbros and gabbros without cumulus or intercumulus oxide grains. They are typical in middle- to coarse-grained gabbro and usually occur in the central portions of big plagioclase grains and are less frequent or missing in the rims. These features suggest that three factors underlay the appearance of magnetite micro-inclusions in plagioclase of oceanic gabbros: (i) early crystallization of plagioclase, preceding the appearance of pyroxene and individual Fe–Ti oxide grains in the matrix. This implies high concentration of Fe in the melt and crystallization of relatively Fe-rich plagioclase; (ii) increase of O₂ providing oxygen supply required for the nucleation of Fe–Ti oxides in the plagioclase host; such conditions may accompany an enrichment of plagioclase by iron (under magmatic or sub-solidus conditions), or contribute to the precipitation of Fe-Ti oxides from relatively Fe-rich plagioclase during cooling; (iii) slow cooling providing the time needed for nucleation and growth of the micro-inclusions.

Neither the mechanism nor the exact temperature of precipitation is known, and it is uncertain whether the magnetite precipitates have formed in a monoclinic or in a triclinic structure. In paleomagnetic studies (Ebert et al. 2010; Evans et al. 1968; Sobolev and Faynberg 1990; Feinberg et al. 2005; Biedermann et al. 2016; Calvin et al. 2017), it is generally found that magnetite inclusions in the rock forming silicate minerals carry a very stable primary thermoremanence indicating that the magnetite needles formed by high-temperature exsolution above the Curie temperature of 580 °C of magnetite (Ebert et al. 2010). Once the plagioclase has become supersaturated with respect to magnetite, this mineral nucleated in the channels running parallel to pl[001] of the plagioclase structure. Oriented nucleation of magnetite was favored by the perfect match between the oxygen atoms pertaining to the FeO₆ octahedra of the magnetite structure and specific oxygen atoms of the six-membered tetrahedral rings forming the channels in the plagioclase structure. The ideal nucleation orientation with one of the mt{001} directions parallel or closely parallel to pl[14 10 7] or pl[14 10 7] allows for the parallel alignment of one of the densely packed mt{111} oxygen layers with oxygen layers.
in plagioclase that are parallel to pl(112), pl(150), pl(312), pl(150) and pl(100). The nucleation orientation does not, however, allow for the additional parallel alignment of one of the mt<011> oxygen layers with another one of the important oxygen layers in the plagioclase host. The alignment of a second oxygen layer drives rotation around the mt<111> direction, which is parallel to the needle elongation direction, towards or into the main orientation. It is not known whether this rotation is linked to recrystallization or is a primary feature that was already attained during nucleation. Formation of the magnetite inclusions with their elongation direction parallel to the pl[001] direction cannot be rationalized based on the alignment of important oxygen layers in magnetite and plagioclase. Following Wenk et al. (2011), their formation is ascribed to the presence of abundant magnetite nucleation sites along the channels running parallel to the pl[001] direction. In addition, growth of magnetite inclusions parallel to pl[001] is enhanced by the supposed fast diffusion along these channels.

Conclusions

Plagioclase from anorthosites and gabbros often contain needle- or lath-shaped magnetite micro-inclusions with clear shape orientation following several well-defined directions in the plagioclase host. The shape orientation relationships are accompanied by systematic crystallographic orientation relationships. The links between the shape- and crystallographic orientation relationships can be understood based on the dimensional and angular match between the magnetite and plagioclase crystal structures. In the studied plagioclase crystals, 90% of the magnetite micro-inclusions pertain to six-shape orientation classes. One orientation class has its elongation direction and one of the mt<011> directions parallel to the pl[001] direction, and the other five orientation classes are of the plane-normal type, in which inclusion elongation direction coincides with one of the mt<111> directions and with either the pl(112), the pl(150), the pl(312), the pl(150), or the pl(100) plane normal, respectively. The preferred direction of growth (shape orientation) is determined by the alignment of the close-packed mt<111> oxygen layers with the corresponding oxygen layers in plagioclase, which have nearly identical d-spacing. These orientation relations may be traced back to the nucleation stage, where FeO6 octahedra of the magnetite crystal structure are accommodated in an oriented manner in channels running parallel to pl[001] in the plagioclase structure.

The magnetite inclusions with their elongation direction parallel to the pl[001] direction do not follow the same pattern of lattice match as the plane-normal types. These inclusions rather reflect the availability of abundant magnetite nucleation sites in the channels parallel to the pl[001] direction.

In many gabbros and anorthosites magnetite micro-inclusions pertaining to different orientation classes are present within the plagioclase crystals. The magnetite micro-inclusions are often the main carriers of the natural magnetic remanence and endow their diamagnetic plagioclase host with a magnetic moment. In view of the magnetocrystalline anisotropy of magnetite, understanding the systematics of the shape and crystallographic orientation relationships of magnetite micro-inclusions in plagioclase is highly relevant for interpreting paleomagnetic data, in particular, when single grain measurements are made.

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References

Ageeva O, Habler G, Topa D, Waitz T, Li C, Pertsev A, Zhilicheva O, Abart R (2016) Plagioclase hosted Fe-Ti-oxide micro-inclusions in an oceanic gabbro-plagiogranite association from the Mid Atlantic Ridge at 13° 34’ N. Am Journ Sci 316:85–109
Ageeva O, Habler G, Pertsev A, Abart R (2017) Fe-Ti oxide micro-inclusions in clinopyroxene of oceanic gabbro: phase content, orientation relations and petrogenetic implication. Lithos 290–291:104–115
Andersen O (1915) On aventurine feldspar. Am J Sci 238:351–399
Aranovich LY, Prokofiev VY, Pertsev AN, Bortnikov NS, Ageeva OA, Bel’tenev VE, Simakin, SG, (2015) Composition and origin of a K2O rich granite melt in the mid atlantic ridge, 13 34’ N: evidence from the analysis of melt inclusions and minerals of the gabbro-plagiogranite association. Dold Earth Sci 460(2):174–178
Armbrustmacher TJ, Banks NG (1974) Clouded plagioclase in metadolerite dikes, Southeastern Bighorn Mountains. Wyom Am Mineral 59(7):656–665
Dunlop DJ, Ivanov V, Rozhdestvenskaya I, Cherkashov G, Stepanova T, Shilov V, Pertsev A, Davydov M, Egorov I, Melekestseva I, Narkevsky E, Ignatov V (2007) A new hydrothermal field at 13°30′ N on the Mid-Atlantic Ridge. InterRidge News 16:9–10

Beltenev V, Ivanov V, Rozhdestvenskaya I, Cherkashov G, Stepanova T, Shilov V, Davydov M, Laiba A, Kayloio V, Narkevsky E, Pertsev A, Dobretsova I, Gustatys A, Popova Y, Amplieva E, Evrard C, Moskalev, Gebruk A, Pertsev AN, Bortnikov NS, Vlasov EA, Dobretsova I, Gustatys A, Popova Y, Amplieva E, Evrard C, Moskalev, Gebruk A (2009) New data about hydrothermal fields on the Mid-tlantic Ridge between 11°–14° N: 32nd cruise of R/V professor Logatchev. InterRidge News 18:13–17

Biedermann AR, Pettte K, Angel RJ, Hirt AM (2016) Anisotropy of magnetic susceptibility in alkaline feldspar and plagioclase. Geophys Suppl Royal Astron Soc 205(1):479–489

Bolle O, Diet H, Trindade RI (2003) Magnetic fabrics in the Holom granite (Vest-Agder, southernmost Norway): implications for the late evolution of the Sveconorwegian (Grenvillian) orogen of SW Scandinavia. Precamb Res 121(3):221–249

Bollmann W (1970) Crystal defects and crystalline interfaces. Springer, Heidelberg-Berlin

Bonatti A, Bonatti E, Ligi BD (2005) Flexural uplift of a lithospheric slab near the Vema transform (Central Atlantic): timing and mechanisms. Earth Planet Sci Lett 240(3–4):642–655

Bown MG, Gay P (1959) The identification of oriented inclusions in pyroxene crystals. Am Miner 44(5–6):592–602

Calvin P, Ruiz-Martinez VC, Villalain JJ, Casas-Sainz AM, Mous S aid B (2017) Emplacement and deformation of Mesozoic gabbros of the High Atlas (Morocco): paleomagnetism and magnetic fabrics. Tectonics 36(12):3012–3027

Cipriani A, Bonatti E, Ligi BD (2009) 26 million years of mantle upwelling below a segment of the Mid Atlantic Ridge: the Vema Lithospheric section revisited. Earth Planet Sci Lett 285(1–2):87–95

Cottrell RD, Tarduno JA (1999) Geomorphic paleointensity derived from single plagioclase crystals. Earth Planet Sci Lett 169:1–5

Dick HJB, MacLeod CJ, Blum P, Abe N, Blackman DK, Bowles JA, Cheadle MJ, Cho K, Cigàela J, Deans JR, Edgcomb VP, Ferrando C, France L, Ghosh B, Ildefonse BM, Kendrick MA, Koepeke JH, Leon JAM, Liu C, Ma Q, Morishita T, Morris A, Natland JH, Nizaka T, Pliemperer O, Sanfilippo A, Sylvan JB, Tveary MA, Tribuzio R, Viegas LGF (2017) Expedition 360 Summaries of ODP Leg 360 Scientists, Southwest Indian Ridge Lower Crust and Moho. Proceedings of the Inter-national Ocean Discovery Program, 360: College Station, TX(International Ocean Discovery Program). 10,14379/i0dp.proc.360.101.2017

Dick HJB, MacLeod CJ, Blum P, Abe N, Blackman DK, Bowles JA et al (1473A) Dynamic accretion below a slow-spreading ridge segment: IODP Hole 1473A and the Atlantis Bank Oceanic Core Complex. J Geophys Res Earth. https://doi.org/10.1029/2013JB016858

Diet H, Bolle O, Lambert JM, Laureneau P, Duchesne JC (2003) The Tellnes ilmenite deposit (Rogaland, South Norway): magnetic and petrofabric evidence for emplacement of a Ti-enriched nor- itic crystal mush in a fracture zone. J Struct Geol 25(4):481–501

Divjiljan S, (1960) The results of field and laboratory studies of aven- turing plagioclases from some Norwegian pegmatites. Proceedings of the 21st International Geological Congress, Norden 17:94–101

Doukhan N, Ingrin J, Doukhan JC, Latrous K (1990) Coercipitation of magnetite and amphibole in black star diopsides; a TEM study. Am Miner 75(7–8):840–846

Dunlop DJ, Ozdemir O (1997) Rock Magnetism. Cambridge University Press, Cambridge

Dunlop DJ, Ozdemir O, Kono M (2007) Magnetizations of rocks and minerals. Treatise Geophys 5:277–336

Ebert Y, Kessel R, Shaar R, Agnon A, Ron H (2010) Petrology and rock magnetism of the gabbro of Troodos ophiolite. Phys Earth Planet Inter 183(3–4):413–420

Evans ME, McElhinny MW, Gifford AC (1968) Single domain magnetite and high coercivities in a gabbroic intrusion. Earth Planet Sci Lett 4(2):142–146

Feinberg JM, Wenk HR, Renne PR, Scott GR (2004) Epitaxial relationships of clinopyroxene-hosted magnetite determined using electron backscatter diffraction (EBSD) technique. Am Miner 89(2–3):462–466

Feinberg JM, Scott GR, Renne PR, Wenk HR (2005) Exsolved magnetite inclusions in silicates: features determining their rema-nence behavior. Geology 33(6):513–516

Feinberg JM, Wenk HR, Scott GR, Renne PR (2006) Preferred ori-entation and anisotropy of seismic and magnetic properties in gabbroanorites from the Bushveld layered intrusion. Tectono-physics 420(3–4):345–356

Fleet ME (1986) The structure of magnetite: symmetry of cubic spinels. J Solid State Chem 62(1):75–82

Fleet ME, Gregory AB, Robert L (1980) Oriented magnetite inclu-sions in pyroxenes from the Grenville Province. Can Mineral 18(1):89–99

Gee J, Meurer WP (2002) Slow cooling of middle and lower oceanic crust inferred from multicomponent magnetizations of gabbroic rocks from the Mid-Atlantic ridge South of the Kane fracture zone (MARK) area. J Geophys Res Solid Earth 107(7):3

Godard M, Awaji S, Hansen H, Bellerbrand E, Brunelli D, Johnson K, Yamasaki T, Maeda J, Abratis M, Christie D, Kato Y (2009) Geochemistry of a long in-situ section of intrusive slow-spread oceanic lithosphere: results from IODP Site U1309 (Atlantis Massif, 30 N Mid-Atlantic-Ridge). Earth Planet Sci Lett 279(1–2):110–122

Griffiths TA, Habler G, Abart R (2016) Crystallographic orientation relationships in host–inclusion systems: new insights from large EBSD data sets. Am Miner 101(3):690–705

Grimes CB (2008) Duration, rates, and patterns of crustal growth at slow-spreadinmg mid-ocean ridges: using zircon to investigate the evolution of in situ ocean crust Dissertation. University of Wyoming, Wyoming

Harlow GE, Klimenutidis R (1980) Clouding of Pyroxenes and Plagioclases in Eucrites: Implications for Post-Crystallization Processing. Lunar and Planetary Science Conference.

Hekimian R (2014) Earth’s Mantle Melting and Volcanism. Sea Floor Exploration 1:109–143

Hwang SL, Shen P, Chu YTF, HT, (2010) On the coherency-controlled growth habit of precipitates in minerals. J Appl Cryst 43:417–428

Krakov R, Bennett RJ, Johnstone DN, Vukmanovic Z, Solano-Alvarez W, Lainé SJ, Einsle JF, Midgley PA, Rae CMF, Hielsher R (2017) On three-dimensional misorientation spaces. Royal Soc Mathe Phys Eng Sci 473(2206):20170274

Malpas JG, Oberk W, Lainé SJ, Einsle JF, Midgley PA, Rae CMF, Hielsher R (2017) On three-dimensional misorientation spaces. Royal Soc Mathe Phys Eng Sci 473(2206):20170274

Okamura FP, McCallum IS, Stroh JM, Ghose S (1976) Pyroxene-spinel intergrowths in lunar and terrestrial pyroxenes. Lunar Planet Sci Conf Proc 7:1889–1899

Pertsev AN, Bortnikov NS, Vlasov EA, Beltenev VE, Dobretsova IG, Ageeva OA (2012) Recent massive sulfide deposits of the
Semenov ore district, Mid-Atlantic Ridge, 13° 31′ N: associated rocks of the oceanic core complex and their hydrothermal alteration. Geol Ore Deposits 54(5):334–346
Pertsev AN, Aranovich LY, Prokofiev VV, Bortnikov NS, Cipriani A, Simakin SS, Borisovskiy SE (2015) Signatures of residual melts, magmatic and seawater-derived fluids in oceanic lower-crust gabbro from the Vema lithospheric section, Central Atlantic. J Petrol 56(6):1069–1088
Poldervaart A, Gilkey AK (1954) On clouded feldspars. Am Miner 39:75–91
Renne PR, Scott GR, Glen JM, Feinberg JM (2002) Oriented inclusions of magnetite in clinopyroxene: source of stable remanent magnetization in gabbros of the Messum Complex, Namibia. Geochem Geophys Geosyst 3(12):1–11
Ribbe PH (1984) Average structures of alkali and plagioclase feldspars: systematics and applications. Feldspars and Feldspathoids. Springer, Dordrecht, pp 1–54
Smith DK, Escartín J, Cann SH, JR, (2008) Fault rotation and core complex formation: significant processes in seafloor formation at slow-spreading mid-ocean ridges (Mid-Atlantic Ridge, 13–15 N). Geochem Geophys Geosyst 9(3):9
Sobolev PO (1990) Orientation of acicular iron-ore mineral inclusions in plagioclase. Internat Geol Rev 32(6):616–628
Sobolev PO, Faynberg FS (1990) Causes of remanent magnetization in the gabbronorite of the Burakovskiy pluton. Trans (Dokl) USSR Acad Sci Earth Sci Sect 314(5):92–96
Suhr G, Hellebrand E, Johnson K, Brunelli D (2008) Stacked gabbro units and intervening mantle: a detailed look at a section of IODP Leg 305, Hole U1309D. Geochem Geophys Geosyst 9(10):7
Sutton A, Balluffi R (1995) Interfaces in crystalline materials. Oxford Scientific Publications, Oxford
Tan W, He H, Wang CY, Dong H, Liang X, Zhu J (2016) Magnetite exsolution in ilmenite from the Fe-Ti oxide gabbro in the Xinjie intrusion (SW China) and sources of unusually strong remnant magnetization. Am Miner 101(12):2759–2767
Tarduno JA, Cottrell RD, Smirnov AV (2006) The paleomagnetism of single silicate crystals: Recording geomagnetic field strength during mixed polarity intervals, superchrons, and inner core growth. Rev Geophys 44(1):98
Tauxe L (2010) Essentials of paleomagnetism. University of California Press, Berkeley

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