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Preferred mineral orientation of a chloritoid-bearing slate in relation to its magnetic fabric

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ABSTRACT

A regional analysis of the anisotropy of the magnetic susceptibility on low-grade metamorphic, chloritoid-bearing slates of the Paleozoic in Central Armorica (Brittany, France) revealed very high values for the degree of anisotropy (up to 1.43). Nonetheless, high-field torque magnetometry indicates that the magnetic fabric is dominantly paramagnetic. Chloritoid's intrinsic degree of anisotropy of 1.47 ± 0.06, suggests that chloritoid-bearing slates can have a high degree of anisotropy without the need of invoking a significant contribution of strongly anisotropic ferromagnetic (*s.l.*) minerals. To validate this assumption we performed a texture analysis on a representative sample of the chloritoid-bearing slates using hard X-ray synchrotron diffraction. The preferred orientation patterns of both muscovite and chloritoid are extremely strong (~38.6 m.r.d. for muscovite, 20.9 m.r.d. for chloritoid) and display roughly axial symmetry about the minimum magnetic susceptibility axis, indeed suggesting that chloritoid may have a profound impact on the magnetic fabric of chloritoid-bearing rocks. However, modeling the anisotropy of magnetic susceptibility by averaging single crystal properties indicates that the CPO of chloritoid only partially explains the slate's anisotropy.

1. Introduction

The anisotropy of magnetic susceptibility (AMS) of a rock depends on the orientation distribution of the rock-forming minerals and their intrinsic magnetic properties (shape or magnetocrystalline anisotropy). Commonly, several magnetic carriers, with ferromagnetic (*sensu lato* – *s.l.*, i.e. a combining term for ferromagnetic *sensu stricto*, ferrimagnetic and antiferromagnetic), paramagnetic and/or diamagnetic behavior, contribute to the magnetic fabric. The diamagnetic fabric will only be important when the other contributions are very weak, such as in the case of pure sandstones and limestones (Borradaile et al., 1999; de Wall et al., 2000). While the ferromagnetic (*s.l.*) contribution to the magnetic fabric primarily depends on domain state, grain size and interaction between particles, the paramagnetic contribution results from intrinsic crystal lattice anisotropy of the paramagnetic minerals and their degree of preferred orientation (Borradaile and Jackson, 2010). Therefore, the paramagnetic fabric is more likely to serve as a proxy for the petrofabric related to the deformation of the rock in slates.

Although many pioneering magnetic fabric studies assumed ferromagnetic (*s.l.*) minerals to be the primary cause for the observed magnetic fabrics in fine-grained siliciclastic metasedimentary rocks (Graham, 1954; Rees, 1961; Fuller, 1964), Fe-bearing phyllosilicates often are the main magnetic carriers contributing to the magnetic fabric (e.g. Coward and Whalley, 1979; Borradaile et al., 1986; Rochette, 1987). For Fe-bearing phyllosilicates, it was found that the degree of intrinsic magnetocrystalline anisotropy (P_J) does not exceed 1.35 (Beausoleil et al., 1983; Borradaile et al., 1987; Zapletal, 1990; Borradaile and Werner, 1994; Martín-Hernández and Hirt, 2003) (see Table 1 for definition of the AMS parameters used in this work). Consequently, the P_J value of 1.35 has been used as the upper limit for the paramagnetic contribution to the AMS of siliciclastic metasedimentary rocks and higher P_J values are systematically attributed to a ferromagnetic (*s.l.*) contribution (Rochette, 1987; Rochette et al., 1992).

A regional magnetic fabric study of chloritoid-bearing slates of the Paleozoic Plougastel formation in the low-grade metamorphic

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Table 1
AMS parameters used in this work.

Property/Parameter	Equation	Reference
Bulk susceptibility (K_m)	$K_m = \frac{K_1+K_2+K_3}{3}$	Nagata, 1961
Corrected degree of anisotropy (P_J)	$P_J = \exp\sqrt{\{2[(\eta_1-\eta_m)^2+(\eta_2-\eta_m)^2+(\eta_3-\eta_m)^2]\}}$ with $\eta_1 = \ln K_1$; $\eta_2 = \ln K_2$; $\eta_3 = \ln K_3$; $\eta_m = \sqrt[3]{K_1\ K_2\ K_3}$	Jelinek, 1981
Shape parameter (T)	$T = \frac{2\eta_2-\eta_1-\eta_3}{\eta_1-\eta_3}$	Jelinek, 1981

(epizone) Monts d'Arrée slate belt (MASB) in Central Armorica (Brittany, France) (Fig. 1), revealed a dominantly paramagnetic fabric with P_J values up to 1.43. In contrast, the stratigraphically equivalent slates free of chloritoid, in the very low-grade (anchizone) Crozon fold-and-thrust belt, showed P_J values only up to 1.27 (Haerinck et al., 2013a). In order to assess the possible paramagnetic contribution of monoclinic chloritoid, its magnetocrystalline anisotropy has been determined on a collection of chloritoid crystals, collected from different tectonometamorphic settings worldwide (Haerinck et al., 2013b). The magnetocrystalline degree of anisotropy of chloritoid was found to be 1.47 ± 0.06, which is significantly higher than the magnetocrystalline degree of anisotropy of most paramagnetic phyllosilicates (1.35, references above). Furthermore, a new analysis of the magnetocrystalline anisotropy of muscovite single crystals by Biedermann et al. (2014) revealed a P_J value of 1.44 ± 0.02, much higher than previously supposed (1.15 ± 0.05; Martín-Hernández and Hirt, 2003).

These very high magnetocrystalline degrees of anisotropy suggest that the very strong paramagnetic anisotropy of the chloritoid-bearing slates of the MASB may be due to a (very) strong alignment of the chloritoid and potentially also muscovite crystals. To our knowledge, there are no examples of a quantitative texture analysis on chloritoid-bearing slates, making it impossible to check the validity of our basic assumption. Therefore, the presumed strong chloritoid alignment in the slates of the MASB was the incentive to study the preferred orientation of the rock-forming minerals in a representative sample of these slates.

The preferred orientation of phyllosilicates in argillaceous metasedimentary rocks has been studied primarily by X-ray pole figure goniometry (e.g. Wood and Oertel, 1980; Oertel, 1983; Sintubin, 1993; van der Pluijm et al., 1994). Since then, new methods have been developed to obtain quantitative information from diffraction images produced by high energy synchrotron X-rays (e.g. Wenk et al., 2010). A major advantage of the synchrotron X-ray method is that information is obtained about the full crystal preferred orientation (CPO) of all minerals composing a bulk sample. Here we present the preferred orientation of the constituting minerals muscovite, chloritoid, chlorite and quartz of a representative sample of the chloritoid-bearing slate of the MASB to explore whether the pronounced magnetic anisotropy in this chloritoid-bearing slate can indeed be attributed to a strong alignment of chloritoid crystals. Note that such a link between mineral preferred orientations and magnetic properties is well established for slates in which the magnetic properties are dominated by the paramagnetic phyllosilicate minerals (e.g. Richter et al., 1993; Siegesmund et al., 1995; Chadima et al., 2004; Hansen et al., 2004; Martín-Hernández et al., 2005; Cifelli et al., 2009; Oliva-Urcia et al., 2010).

2. Sample characterization and magnetic properties

We investigated a representative sample of chloritoid-bearing slates typical for the low-grade (epizone) metamorphic MASB, a particular Variscan tectonostratigraphic segment of the Central Armorica Domain (CAD) in Brittany (France) (Fig. 1). The CAD represents a part of the Perigondwanan microcontinent Armorica and consists of a Neoproterozoic, Cadomian cratonic basement, reflecting Pan-African geodynamics (Ballèvre et al., 2001; Chantraine et al., 2001), and its late Proterozoic to Paleozoic metasedimentary cover (Guillocheau and Rolet, 1982; Guerrot et al., 1992). The MASB is primarily composed of rocks of the Pridolian to Lochkovian Plougastel Formation and is characterized by a high-strain deformation that occurred during a single, progressive, NW–SE oriented, contractional deformation event in low-grade metamorphic conditions (Sintubin et al., 2008). This coaxial, homogeneous shortening is accommodated by both cylindrical folding and cogenetic cleavage development, and is estimated to be in the order of 50–60 %, which reflects the bulk regional strain (van Noorden et al., 2007). The sample location (coordinates: N48° 24′ 22.970″ – W03° 54′ 42.579″) is an outcrop with an NW–SE oriented outcrop face of approximately 20 m long and 10 m high, located 100 m west of Roc'h Trévézel (Figs. 1–2). The outcrop displays a multimeter-scale antiform and consists of a multilayer sequence with relatively thin quartzitic and pelitic layers, a few competent quartzitic sandstone beds and two homogeneous siltstone beds (HSB). The sample (sample BR09TH131C3) has been taken from the HSB in the core of the antiform (Fig. 2a–b).

The HSBs of the Roc'h Trévézel outcrop area show a strongly developed cleavage fabric and lack any macroscopically visible bedding fabric or grain-size variation. An intersection lineation is often visible on the cleavage planes, having a subhorizontal NE–SW trending orientation. Microscopic fabric analysis shows that the strongly developed tectonic cleavage is a spaced foliation, consisting of cleavage domains with micaceous material and chloritoid minerals and microlithons containing primarily quartz (Fig. 2c). Mineralogical analysis of the HSBs of the Roc'h Trévézel outcrop area shows that they are dominated by quartz (42 ± 9 vol%) and white mica (37 ± 10 vol%), with a significant fraction of chloritoid (18 ± 5 vol%) and a minor amount of chlorite (2 ± 2 vol%) (Haerinck et al., 2013a).

The low-field and high-field AMS is measured on a cubic sample of 8 cm^3 cut from an in situ oriented homogeneous siltstone sample with one face parallel to the cleavage plane (Fig. 2b insert). It is defined by a Cartesian sample coordinate system with A along the cleavage's strike, B along the cleavage's dip and C along the pole to the cleavage. The low-field AMS analysis, using an AGICO KLYS3 kappabridge (Jelínek and Pokorný, 1997) at the KU Leuven, shows a bulk magnetic susceptibility (K_m) of 389×10^{-6} [SI]. The magnetic susceptibility ellipsoid is strongly oblate, as evidenced by a shape parameter (T) of 0.76, and has an extremely strong eccentricity, evidenced by a corrected degree of anisotropy (P_J) of 1.40. The minimum magnetic susceptibility axis (K_3) shows a close angular relationship with both the pole to bedding and the pole to cleavage (sample's C axis), (Fig. 3): both poles are oriented at an angle of 6° with respect to K_3, which is roughly equal to the accuracy of the sampling and preparation procedure. However, a regional analysis