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#### **Key Points:**

- We present a robust procedure for determining the anisotropy of magnetic susceptibility (AMS) carriers (ferro, para, and diamagnetic phases)
- Mean susceptibility at room and low temperatures defines the respective contributions of the magnetic phases to the rock's susceptibility
- A novel scenario table, coupling respective contributions and associated magnetic fabrics, allows reliable interpretation of AMS data

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## A Practical Approach for Identification of Magnetic Fabric Carriers in Rocks

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**Abstract** Magnetic fabric analyses of rocks by anisotropy of magnetic susceptibility (AMS) are a robust petrofabric tool that has been used in varied geological environments and tectonic settings. A fundamental difficulty of this method is to define the dominant magnetic phases and their resulting geological interpretation. We study the magnetic behavior of rocks by simulating data of mixed magnetic phases (i.e., diamagnetic, paramagnetic, and ferromagnetic). We show that it is possible to recognize the dominant magnetic phases by measuring the mean susceptibility at room temperature ( $k_m^{\text{RT}}$ ) and at low temperature ( $k_m^{\text{LT}}$ ). Distinct regions of magnetic phase dominancy are demonstrated in  $k_m^{\text{LT}}/k_m^{\text{RT}}$  versus  $k_m^{\text{RT}}$  and  $k_m^{\text{LT}}$  versus  $k_m^{\text{RT}}$  plots. We present a comprehensive approach by coupling the magnetic phase dominancy with possible magnetic fabrics, which are obtained from AMS measured at room and low temperatures (RT-AMS and LT-AMS) and anisotropy of anhysteretic remanent magnetization, into a scenario table. Application of this table allows a robust procedure for determining which magnetic phases are dominant, and permits a fast and reliable geological interpretation in complex settings.

### 1. Introduction

The analysis of the anisotropy of magnetic susceptibility (AMS) has been proven as a robust petrofabric tool that is used to decipher depositional, tectonic, and flow processes; hence, further interpret the deformation history of rocks (Borradaile, 1988; Hrouda, 1982; Levi & Weinberger, 2011; Levi et al., 2006, 2014, 2018; Parés, 2015; Tarling & Hrouda, 1993; Weinberger et al., 2017). AMS is commonly measured at room temperature (RT-AMS) and evolves due to the contribution of all minerals in the rock, allowing a fast and easy method of describing the net magnetic fabric (Borradaile & Jackson, 2010). The contribution of different minerals to the AMS of a rock is dependent upon their abundance, orientation, and intrinsic anisotropy (Aubourg et al., 1995). It may be influenced by the different responses of minerals to an applied magnetic field during measurement (Richter & van der Pluijm, 1994; Rochette, 1987). The RT-AMS is often controlled by different magnetic phases, that is, diamagnetic, paramagnetic, and ferromagnetic (s.l.), which may result in a composite fabric (Aubourg et al., 1995; Borradaile & Tarling, 1981). Consequently, in some cases, one specific magnetic phase may dominate the RT-AMS although its relative mineral content in the rock is minor. In other cases, the RT-AMS may represent a composite fabric, in which two or more magnetic phases dominate the RT-AMS, not allowing for a coherent geological interpretation. This is especially true when a specific magnetic phase holds information pertaining to the deformation history of the rock, which is obscured in the composite RT-AMS fabric. Furthermore, there are cases in which the main carriers of the mean susceptibility and the anisotropy are different (Borradaile, 1987; Borradaile et al., 1986, 1993; Borradaile & Gauthier, 2003; Hirt et al., 1995; Hounslow, 1985; Rochette, 1987; Rochette & Vialon, 1984; Rochette et al., 1992). Therefore, it is challenging to recognize which minerals and associated magnetic phases are the carriers of the AMS based solely on RT-AMS measurements.

Different approaches have been undertaken to overcome these difficulties. Early attempts to differentiate the contribution of paramagnetic minerals to the matrix of the rock relied, for example, on measurement of the bulk magnetic susceptibility (Rochette, 1987). Various magnetic tests were developed to supplement the RT-AMS method by measuring the magnetic fabrics of specific minerals and magnetic phases. One attractive measurement is based on the low-temperature AMS (LT-AMS) method (e.g., Cifelli et al., 2004, 2005; García-Lasanta et al., 2013, 2014; Issachar et al., 2016, 2018; Issachar, Levi, et al., 2019; Issachar, Weinberger, et al., 2019; Lüneburg et al., 1999; Oliva-Urcia et al., 2011, 2012, 2013; Oliva-Urcia, Rahl, et al., 2010; Oliva-Urcia, Román-Berdiel, et al., 2010; Parés & Van Der Pluijm, 2002; Parés & van der Pluijm, 2014; Schmidt et al., 2007; Soto et al., 2012, 2014), in which specimens are cooled down to liquid nitrogen temperature



(77 K), amplifying the paramagnetic susceptibility (see details in Section 2). Recent improvements in laboratory techniques enable to integrate LT-AMS measurements in routine magnetic fabric studies (Issachar et al., 2016, and references therein), and decipher the contribution of paramagnetic minerals to the bulk magnetic susceptibility (Jover et al., 1989; Richter & van der Pluijm, 1994; Schultz-Krutisch & Heller, 1985) and to the magnetic fabric (Hirt & Gehring, 1991; Ihmlé et al., 1989; Lüneburg et al., 1999; Parés & Van Der Pluijm, 2002; Richter & van der Pluijm, 1994). However, some ferromagnetic minerals may also display susceptibility variations at low temperature, which must be taken into account (Martín-Hernández & Ferré, 2007).

The magnetic anisotropy of minerals that retain a remanent magnetization (i.e., the ferromagnetic [s.l.] phase) can be estimated using different methods. Among them are anisotropy of anhysteretic remanent magnetization (AARM) and anisotropy of isothermal remanence (AIRM). AARM is achieved by subjecting specimens to a decaying alternating magnetic (AF) field, and at the same time to a weak direct magnetic (DC) field. The evolved magnetization can be measured in different directions and the anisotropy of the remanence is determined (Jackson, 1991; McCabe et al., 1985). AIRM is attained by first magnetizing a specimen with a DC field, measuring the remanence, and then cleaning the remanence with an equally strong AC field (Martín-Hernández & Ferré, 2007). Repeated measurements in different directions allow determining the anisotropy. When using higher DC fields, this technique may be useful to elucidate the role played by certain high coercivity minerals by applying the DC field in opposite directions successively (Daly & Zinsser, 1973; Fuller, 1963; Hrouda, 2002; Stephenson et al., 1986; Tauxe et al., 1990). Other methods include high-field torque measurements (Hrouda & Jelínek, 1990; Martín-Hernández and Hirt, 2001, 2004), and measurements of the magnetization in different fields and temperatures (Kelso et al., 2002; Martín-Hernández & Hirt, 2001; Rochette & Fillion, 1988; Schmidt et al., 2007). These methods have been applied in many studies, aiming to recognize the contribution of the different magnetic phases to the net magnetic susceptibility (e.g., Aubourg et al., 1995; Borradaile et al., 1993; García-Lasanta et al., 2013, 2014; Issachar et al., 2018; Jover et al., 1989; Martín-Hernández & Hirt, 2001; Oliva-Urcia et al., 2011, 2013; Parés et al., 1999; Soto et al., 2014; Tokiwa & Yamamoto, 2012).

The use of the aforementioned laboratory methods and supplementary mathematical calculations allow, in some cases, to separate the net magnetic fabric into its diamagnetic, paramagnetic, and ferromagnetic (s.l.) phases (e.g., Cifelli et al., 2005; Issachar et al., 2018; Martín-Hernández & Ferré, 2007; Parés & van der Pluijm, 2014; Schmidt et al., 2007; Soto et al., 2014). While these methods can be used to isolate the magnetic fabric of specific minerals, they are time-consuming and do not directly solve the problem of recognizing the carries of the bulk AMS. In this study, we provide a practical approach to identify the AMS carriers, aiming to strengthen the interpretation of magnetic fabrics for geological applications. Based on theoretical considerations and numerical simulations, we present a straightforward guide that defines specific AMS parameters and their resulting geological interpretation. We show how to identify the dominant magnetic phases that carry the AMS solely by mean susceptibility measurements at room and low temperatures, accompanied by LT-AMS and AARM measurements. We highlight circumstances in which the AMS represents a composite magnetic fabric, which may lack a forthright geological interpretation. We point out in which cases time-consuming magnetic laboratory work may be less important for the identification of the AMS carriers. To conclude, we support our findings by analyzing AMS data from various published studies.

## 2. Mathematical Background

The AMS describes the magnetic susceptibility tensor (**K**) of a rock specimen, measured at low magnetic fields, in the order of  $10^2$  (A/m). The magnetic susceptibility is a second-rank symmetrical tensor with eigenvectors  $K_1$ ,  $K_2$ , and  $K_3$  (maximum, intermediate, and minimum), which correspond to  $k_1$ ,  $k_2$ , and  $k_3$  eigenvalues. The mean susceptibility is defined as  $k_m = \frac{k_1 + k_2 + k_3}{3}$ . In this study, we explore the possibilities to identify and quantify the contribution of different magnetic phases to the mean susceptibility of a specimen measured at room and low temperatures. The Curie-Weiss law (e.g., Cullity & Graham, 2008) describes the relation between temperature and magnetic susceptibility for paramagnetic and ferromagnetic minerals (s.l., as long as they are above their respective Curie temperature):



$$k = \frac{C}{T - \theta_c} \tag{1}$$

where *C* is the material Curie constant, *T* is the temperature, and  $\theta_c$  the paramagnetic Curie temperature (Richter & van der Pluijm, 1994).

For the purpose of this study, we focus only on natural paramagnetic minerals whose characteristic Curie temperatures are much lower than that of natural ferromagnetic (s.l.) minerals. For these minerals, the Curie temperature is much lower than the 77 K of liquid nitrogen, and is therefore omitted ( $\theta_c \approx 0$ ). For paramagnetic minerals characterized by non-zero Curie temperature, these equations may not be strictly valid (See Section 5). This allows us to derive the following equations for paramagnetic minerals measured in both room temperature (superscript, <sup>RT</sup>) and low temperature (superscript, <sup>LT</sup>):

$$k_m^{\rm RT} = \frac{C}{T^{\rm RT}} \tag{2}$$

$$k_m^{\rm LT} = \frac{C}{T^{\rm LT}} \tag{3}$$

Combining Equations 2 and 3 enables to express the paramagnetic amplification factor ( $\alpha$ ):

$$\alpha = \frac{k_m^{\rm LT}}{k_m^{\rm RT}} = \frac{T^{\rm RT}}{T^{\rm LT}},\tag{4}$$

which is the ratio between room temperature (293 K) and the temperature of liquid nitrogen (77 K, which is the lowest temperature reached in LT-AMS during cooling), setting  $\alpha$  to the theoretical value of 3.8. However, practically this value is lower than the theoretical value, as during measurement, the temperature of a specimen is usually higher, due to gradual warming after exposure to air at room temperature (Issachar et al., 2016).

The mean susceptibility measured at room-temperature,  $k_m^{\text{RT}}$ , is described as the sum of the respective contributions of the diamagnetic, paramagnetic, and ferromagnetic mean susceptibilities:

$$k_m^{\rm RT} = k_{md} + k_{mp} + k_{mf} \tag{5}$$

Assuming that the change of ferromagnetic (s.l.) susceptibility with temperature is negligible (see Section 5) compared to that of the paramagnetic susceptibility, the mean susceptibility measured in low temperature,  $k_m^{\text{LT}}$ , is defined as:

$$k_m^{\rm LT} = k_{md} + \alpha \cdot k_{mp} + k_{mf} \tag{6}$$

Subtracting Equation 5 from Equation 6 gives:

$$k_m^{\rm LT} - k_m^{\rm RT} = k_{mp} \left( \alpha - 1 \right) \tag{7}$$

Dividing Equation 7 by  $k_m^{LT} - k_m^{RT}$  and substituting the term for  $k_{mp}$  from Equation 5 into the result, allows calculating the contribution of the diamagnetic and ferromagnetic phases relative to the paramagnetic phase, by measuring the  $k_m^{RT}$  and  $k_m^{LT}$  of a specimen:

$$\frac{k_{md} + k_{mf}}{k_{mp}} = \frac{k_m^{\rm RT} \left(\alpha - 1\right)}{k_m^{\rm LT} - k_m^{\rm RT}} - 1$$
(8)

The above equations allow the calculation of  $k_{mp}$  and the ratio of  $k_{md} + k_{mf}$  to  $k_{mp}$ . To fully calculate the respective contribution of each magnetic phase to the specimen's mean susceptibility, either  $k_{md}$  or  $k_{mf}$  must





**Figure 1.**  $k_m^{\text{LT}}/k_m^{\text{RT}}$  versus  $k_m^{\text{RT}}$  plot. Distinct end cases of pure diamagnetic, pure paramagnetic, pure ferromagnetic, and equal contribution of these phases are distinguishable. In the low  $k_m^{\text{RT}}$  region (<~50 × 10<sup>-6</sup> SI), diamagnetic contribution is also evident. The  $k_m^{\text{KI}}$  axis is limited by the highest susceptibility of natural occurring minerals. An undefined value at  $k_m^{\text{RT}} = 0$  is marked with a white dot.

be estimated. Ferromagnetic (s.l.) susceptibility is always positive, whereas, diamagnetic susceptibility is always negative and in the range of -10to  $-15 \times 10^{-6}$  SI) for rocks (Butler, 1992; Hrouda, 2004). It is therefore possible to estimate  $k_{md}$  by approximating the volumetric percentage of diamagnetic minerals in the rock, and multiplying by the mean susceptibility of the diamagnetic mineral (Elhanati et al., 2020). While the exact percentage and specific diamagnetic minerals are not always known, a rough estimate would give very similar results because of the weak magnetic response of diamagnetic minerals. A further mathematical description for the separation of the magnetic phase tensors is provided by Issachar et al. (2016) (see Appendix A).

## 3. Numerical Simulation and Analysis

To study the characteristics of the AMS at room and low temperatures for different lithologies and magnetic phase compositions, we have numerically simulated specimens with varying ferromagnetic, paramagnetic, and diamagnetic respective contributions. We have tested seven cases of dominant phases (15 specimens per case) as follows: three cases for one dominant magnetic phase, three cases for two dominant magnetic phases, and one case for three dominant magnetic phases.

For each case, we have examined the following characteristics:

- The  $k_m^{\text{LT}}$ ,  $k_m^{\text{RT}}$ , and  $k_m^{\text{LT}}/k_m^{\text{RT}}$  values of each specimen The  $k_m^{\text{LT}}/k_m^{\text{RT}}$  versus  $k_m^{\text{RT}}$  and  $k_m^{\text{LT}}$  versus  $k_m^{\text{RT}}$  curve for the 15 specimens, their slope, and intersection with the axes

We discuss the differences in the resulting curves of the seven cases as presented by  $k_m^{\text{LT}}/k_m^{\text{RT}}$  versus  $k_m^{\text{RT}}$ (hereafter LT/RT vs. RT plot) and  $k_m^{\text{LT}}$  versus  $k_m^{\text{RT}}$  (hereafter LT vs. RT plot) plots. By coupling the dominant magnetic phases with theoretical orientation distributions of AMS axes, determined by RT-AMS, LT-AMS, and AARM measurements, we further discuss the interpretation of which phases control the RT-AMS in different scenarios.

The discussion is limited to two well-known types of magnetic fabrics: deposition (also known as "sedimentary") and tectonic. The deposition fabric represents the magnetic fabric acquired by sedimentary rocks during deposition, and is usually characterized by well-grouped vertical  $K_3$  axes perpendicular to the bedding plane and scattered K<sub>1</sub> and K<sub>2</sub> axes, which lie on the bedding plane (Borradaile & Jackson, 2004). The tectonic fabric represents deformation environments and may exhibit different fabrics depending on the type of deformation. In many cases, the three principal AMS axes are well-grouped and coaxial with the directions of the three principal strain axes (Borradaile & Jackson, 2010). An isotropic fabric (i.e., interchangeable  $K_1$ ,  $K_2$  and  $K_3$ ) may represent weak deformation (Rochette et al., 1992), but is more often the result of an undeformed rock composed of isotropic crystals (Hrouda, 2004). Hence, for the purpose of fabric comparison, isotropic fabrics are considered primary fabrics, akin to deposition fabrics (See Section 5). We rely on the cases presented alongside the fabric type combinations to cover the main possible cases one may encounter in different geological environments and tectonic settings. We demonstrate our results on sedimentary rocks, as they are the most common in fabric separation studies. However, the same comparative principles may be applied to igneous and metamorphic rocks possessing primary and secondary fabrics.

## 4. Results and Interpretation

#### 4.1. Respective Contribution to Mean Susceptibility

Figure 1 shows the LT/RT versus LT plot with the distinct end cases, wherein the specimens are purely single phase. Pure paramagnetic specimens show a constant  $k_m^{\text{LT}}/k_m^{\text{RT}}$  value of 3.8, which is the paramagnetic amplification factor at 77 K (see Section 2), while pure ferromagnetic or pure diamagnetic specimens show a value of 1, which corresponds to no amplification, as theoretically expected for  $k_m^{LT} = k_m^{RT}$ . When the





**Figure 2.**  $k_m^{\text{LT}}$  versus  $k_m^{\text{RT}}$  plot. Distinct end cases of pure diamagnetic, pure paramagnetic, pure ferromagnetic and equal contribution of these phases are distinguishable. In the low  $k_m^{\text{RT}}$  region ( $< 50 \times 10^{-6}$  SI), the diamagnetic phase has dominant contribution. Inset: zoom-in of the purely diamagnetic region.

paramagnetic and ferromagnetic phases both equally contribute to the mean susceptibility, the  $k_m^{\text{LT}}/k_m^{\text{RT}}$  value is 2.4 (i.e., the average of the two end cases). Any combination of non-equal paramagnetic and ferromagnetic respective contributions to mean susceptibility will drive the  $k_m^{LT}$  $k_m^{\text{RT}}$  value toward the more dominant phase. It is therefore possible to obtain, from this data alone, the ratio of paramagnetic to ferromagnetic respective contributions. When the negative diamagnetic contribution is equal to the positive ferromagnetic and paramagnetic contribution,  $k_m^{\text{RT}}$  is equal to zero, forming an asymptotic behavior. At low  $k_m^{\text{RT}}$  values, the  $k_m^{\text{LT}}/k_m^{\text{RT}}$  values form an asymptotic curve that goes to infinity, while at high  $k_m^{\text{RT}}$  values, the  $k_m^{\text{LT}}/k_m^{\text{RT}}$  values are asymptotic to a specification. ic value (as described above). Hence, diamagnetic dominancy is directly recognizable in this plot by the asymptotic behavior at low  $k_m^{RT}$  values. It should be noted that specimens that consist of only diamagnetic and ferromagnetic minerals will have a constant  $k_m^{\text{LT}}/k_m^{\text{RT}}$  value of 1, as there will be no low-temperature amplification. Such specimens will have an undefined  $k_m^{\text{LT}}/k_m^{\text{RT}}$  value at the point where both phases have an equal contribution to the mean susceptibility, as  $k_m^{\text{LT}} = k_m^{\text{RT}} = 0$ . While the low  $k_m^{\text{RT}}$  region is defined as a diamagnetic dominant region, the asymptotic behavior is the result of the combination of the negative diamagnetic phase with the low temperature amplified paramagnetic phase. Small variations of paramagnetic or diamagnetic contribution may radically affect the  $k_m^{\text{LT}}/k_m^{\text{RT}}$  plot at low susceptibilities. This sensitivity of the plot, coupled with the asymptotic limit at  $k_m^{RT} = 0$  renders the LT/RT versus LT plot non-applicable for distinguishing the respective contribution of the magnetic phases to the mean susceptibility in low  $k_m^{\text{RT}}$  values. In the

high  $k_m^{\text{RT}}$  region, the LT versus RT plot is more useful (see Section 4.2). The transition between the diamagnetic-dominant low  $k_m^{\text{RT}}$  region, and the paramagnetic/ferromagnetic-dominant high  $k_m^{\text{RT}}$  region does not have a defined value, and is better described as a gradual transition zone. The simulations suggest that different combinations of the three magnetic phases, will result in the asymptotic behavior occurring at different  $k_m^{\text{RT}}$  values, whereas above ~50 × 10<sup>-6</sup> SI the values lie on common linear correlation curves.

The analysis by the LT versus RT plot is based on a linear correlation curve obtained for a group of specimens that typically have a lithological affinity. Our simulations yield a high linear correlation for specimens (i.e.,  $R^2 < 0.9$ ), in which the ratio of paramagnetic to non-paramagnetic contribution to the mean susceptibility is constant. When a group of specimens yields a low linear correlation, they do not represent a specific rock type and therefore should not be analyzed as a group on the LT versus RT plot. The LT versus RT plot (Figure 2) shows the distinct end cases, wherein the specimens are either purely single phase, or contain two phases with an equal contribution to the mean susceptibility. All possible combinations of different magnetic phases manifest gradually between the end cases. For high  $k_m^{RT}$  values (>~50 × 10<sup>-6</sup> SI) pure paramagnetic and ferromagnetic specimens are expected to align along a slope line of 3.8 and 1, respectively. When both phases equally contribute to the mean susceptibility, the specimens align along a slope line of 2.4. Other combinations of paramagnetic and ferromagnetic phases will drive the slope toward the more dominant phase. While the low  $k_m^{\text{RT}}$  region (< ~50 × 10<sup>-6</sup> SI) implies the existence of a dominant diamagnetic phase, specimens plotted in this region follow the same general behavior outlined above, namely, the more dominant the paramagnetic phase-the closer the slope will get to 3.8, while a more dominant ferromagnetic and/or diamagnetic phases will result in a slope closer to 1. When the diamagnetic phase is the only dominant phase,  $k_m^{\text{RT}}$  values are negative and the slope is 1. Minor amounts of paramagnetic minerals slightly increase the slope in the negative  $k_m^{\text{RT}}$  region. Notably, in Figure 2, the theoretical slopes intersect the Y-axis at zero or above (in the presence of paramagnetic minerals). Consequently, specimens that have a similar intersection point as the corresponding theoretical slope may better fit the slope compared to other specimens, which have the same slope with a different intersection point. Nevertheless, this bias is more relevant at the low  $k_m^{\text{RT}}$  region (for more details, see Appendix B).



In summary, the two plots presented in Figures 1 and 2 indicate that mean susceptibility measurements at room and low temperatures allow distinguishing the respective contribution of the different magnetic phases to the specimen mean susceptibility. The use of the LT/RT versus RT plot is generally preferable as actual measured  $k_m^{\text{RT}}$  values are used, compared to the calculated linear correlation curve used in the LT versus RT plot. Moreover, the LT versus RT plot requires a large sampling (~>10 specimens) for a robust linear correlation, while the LT/RT versus RT plot can be used even for a single specimen. Nevertheless, the LT/RT versus RT plot is less applicable at low  $k_m^{\text{RT}}$  values ( $k_m^{\text{RT}} < \sim 50 \times 10^{-6}$  SI), and in this region, the LT versus RT plot is generally preferable.

#### 4.2. AMS Carriers

Knowledge of the magnetic phase's contribution to the mean susceptibility, as assessed by the analyses of mean susceptibilities at room and low temperatures, is not sufficient for interpreting the RT-AMS fabric. The different phases may have different sub-fabrics, resulting in a complex composite fabric. Hence, there is need to interpret the RT-AMS fabric alongside the LT-AMS and AARM fabrics. This examination allows the identification of the magnetic phases that carry and govern the RT-AMS fabric as well as the recognition of sub-fabrics, which may be obscured in the RT-AMS. In Table 1, we summarize the eight possible scenarios of fabric combinations by considering RT-AMS, LT-AMS, and AARM fabrics (their axis orientations, represented on the left side of Table 1), and the magnetic phase's respective contributions to the mean susceptibility. For each scenario, we consider seven cases of dominant phases (single phase: ferromagnetic, paramagnetic, or diamagnetic; two phases: ferromagnetic & paramagnetic, ferromagnetic & diamagnetic, paramagnetic & diamagnetic; all phases: ferromagnetic & paramagnetic & diamagnetic), based on the analysis of  $k_m^{\text{RT}}$  and  $k_m^{\text{LT}}$  (Section 4.1). Table 1 offers a practical guide for interpretation of the AMS data, by identifying the magnetic phases that govern the RT-AMS fabric for each of the 56 resulting cases. Notably, some complex cases (see below) may have dominant phases with different tectonic sub-fabrics. In such cases, the RT-AMS fabric is an average of the sub-fabrics and therefore bears no straightforward geological interpretation. In addition, we highlight in Table 1 some fabric combinations, which are "unlikely." For example, a case of ferromagnetic dominancy in which RT-AMS and AARM fabrics are essentially different. In unlikely fabric combinations, measuring issues are to be suspected (Table 1, Cases II.3, III.1, IV.1, IV.2, IV.3, VI.1, VII.3, VIII.1, VIII.2, and VIII.3).

We consider the AARM and LT-AMS fabrics as a proxy for the ferromagnetic and paramagnetic fabrics, respectively (hereafter "proxy fabrics"). Notably, in the absence of paramagnetic minerals, the LT-AMS fabric will be identical to the RT-AMS fabric; in the absence of ferromagnetic minerals, the AARM fabric will be meaningless. The diamagnetic fabric cannot be measured directly and thus has no proxy fabric, but in some cases, it could be isolated by analytical calculation (see Appendix A for more details).

#### 4.2.1. Single Dominant Phase

In cases where only one magnetic phase has a dominant contribution to the mean susceptibility, the RT-AMS is expected to reflect that phase (Table 1, Cases x.1, x.3, and x.4, where "x" is used for brevity for all fabric combinations). Thus, the single-phase cases are fairly simple to diagnose, as the magnetic phase that dominates the mean susceptibility governs the RT-AMS fabric.

If the ferromagnetic phase dominates the mean susceptibility, then the RT-AMS fabric is expected to be similar to the AARM fabric (Table 1, Cases I.3, III.3, V.3, and VI.3). However, there are many cases in which the RT-AMS fabric is different from the AARM fabric in spite of the ferromagnetic dominancy (see Section 5 below). In cases where the LT-AMS shows a different fabric, then it probably reflects a paramagnetic sub-fabric that is obscured by the ferromagnetic phase in the RT-AMS fabric (Table 1, Cases III.3 and VI.3). Likewise, if the paramagnetic phase dominates the mean susceptibility, then the RT-AMS fabric is expected to be similar to the LT-AMS fabric (Table 1, Cases I.1, II.1, V.1, and VII.1). In cases where the AARM shows a different fabric, then it probably reflects a ferromagnetic sub-fabric with a minor content of ferromagnetic minerals that is obscured by the paramagnetic phase in the RT-AMS fabric (Table 1, Cases II.1 and VII.1). If the diamagnetic phase dominates the mean susceptibility, then the RT-AMS fabric is probably governed by the diamagnetic phase and the AARM and LT-AMS fabrics may show different distribution-orientations



## Table 1

Coupling the Phase Dominancy With the Mean Susceptibility (Based on  $k_m^{LT}$  and  $k_m^{RT}$  Values) and RT-AMS, LT-AMS, and AARM Fabrics

	Fabrics							
RT- AMS	LT-AMS	AARM	$k_m^{\text{RT}}$ [x 10 <sup>-6</sup> SI]	Case #	LT/RT values	LT versus RT slope	Dominate phases (in $k_m^{\text{RT}}$ )	RT-AMS carriers
TECTONIC			>~50	I.1	~3.8	~3.8	Para	Para
			<~50	I.2	~2.4	~2.4	Para and Ferro	Ferro and/or para/no interpretation
	$(\mathbf{\cdot} \mathbf{\cdot})$			I.3	~1	~1	Ferro	Ferro
	TECTO	TEC		I.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
		TOP		I.5	Asymptotical	~3.8	Para and Dia	Para and/or dia/no interpretation
	NIC	AIC.		I.6	Asymptotical	~2.4	Para, Ferro, and Dia	Para and/or dia/Ferro and/or dia/ All phases/no interpretation
TECTONIC			>~50	I.7	Asymptotical	~1	Ferro and Dia	Ferro and/or dia/no interpretation
				II.1	~3.2	~3.8	Para	Para
	$(\cdot)$			II.2	~2.1	~2.1	Para and Ferro	Para/no interpretation
	TE	D		II.3	~1	$\sim 1$	Ferro	Unlikely fabric
	сто	EPO	<~50	II.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
	NIC	SITIC		II.5	Asymptotical	~3.8	Para and Dia	Para and/or dia/no interpretation
		Ň		II.6	Asymptotical	~2.4	Para, Ferro, and Dia	Para and/or dia/no interpretation
				II.7	Asymptotical	~1	Ferro and Dia	Dia/no interpretation
			>~50	III.1	~3.2	~3.8	Para	Unlikely fabric
			<~50	III.2	~2.1	$\sim 2.1$	Para and Ferro	Ferro/no interpretation
		TE		III.3	~1	$\sim 1$	Ferro	Ferro
CTO		СТО		III.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
NIC		NIC		III.5	Asymptotical	~3.8	Para and Dia	Dia/no interpretation
	ž			III.6	Asymptotical	~2.4	Para, Ferro, and Dia	Ferro and/or dia/no interpretation
			> ~50 < ~50	III.7	Asymptotical	~1	Ferro and Dia	Ferro and/or dia/no interpretation
		DEPOSITION		IV.1	~3.2	~3.8	Para	Unlikely fabric
				IV.2	~2.1	$\sim 2.1$	Para and Ferro	Unlikely fabric
TE	DEPOSITION			IV.3	~1	~1	Ferro	Unlikely fabric
СТО				IV.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
NIC				IV.5	Asymptotical	~3.8	Para and Dia	Dia/no interpretation
				IV.6	Asymptotical	~2.4	Para, Ferro, and Dia	Dia
				IV.7	Asymptotical	~1	Ferro and Dia	Dia/no interpretation
			>~50	V.1	~3.2	~3.8	Para	Para
				V.2	~2.1	$\sim 2.1$	Para and Ferro	Ferro and/or Para/no interpretation
				V.3	~1	~1	Ferro	Ferro
DEPO	DEPO	DEPC	<~50	V.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
OSITI	SILL	OSITE		V.5	Asymptotical	~3.8	Para and Dia	Para and/or dia/no interpretation
NOI	NO	Î N		V.6	Asymptotical	~2.4	Para, Ferro, and Dia	Para and/or dia/Ferro and/or dia/ All phases/no interpretation
				V.7	Asymptotical	~1	Ferro and Dia	Ferro and/or dia/no interpretation



Table 1

	Fabrics							
RT- AMS	LT-AMS	AARM	$k_m^{\mathrm{RT}}$ $[x  10^{-6}  \mathrm{SI}]$	Case #	LT/RT values	LT versus RT slope	Dominate phases (in $k_m^{\text{RT}}$ )	RT-AMS carriers
			>~50	VI.1	~3.2	~3.8	Para	Unlikely fabric
				VI.2	~2.1	~2.1	Para and Ferro	Ferro/no interpretation
D	T	D		VI.3	~1	~1	Ferro	Ferro
EPO	ECTO	EPO	<~50	VI.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
SITIO	NIC	SITIC		VI.5	Asymptotical	~3.8	Para and Dia	Dia
N		ž		VI.6	Asymptotical	~2.4	Para, Ferro, and Dia	Ferro and/or dia/no interpretation
				VI.7	Asymptotical	$\sim 1$	Ferro and Dia	Ferro and/or dia/no interpretation
			>~50	VII.1	~3.2	~3.8	Para	Para
				VII.2	~2.1	~2.1	Para and Ferro	Para/no interpretation
				VII.3	~1	$\sim 1$	Ferro	Unlikely fabric
EPO	EPO	CTO	<~50	VII.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
SITIC	SITIC	NIC		VII.5	Asymptotical	~3.8	Para and Dia	Para and/or dia/no interpretation
NO	Ň			VII.6	Asymptotical	~2.4	Para, Ferro, and Dia	Para and/or dia/no interpretation
				VII.7	Asymptotical	$\sim 1$	Ferro and Dia	Dia
			>~50	VIII.1	~3.2	~3.8	Para	Unlikely fabric
		TE		VIII.2	~2.1	$\sim 2.1$	Para and Ferro	Unlikely fabric
	TE			VIII.3	~1	$\sim 1$	Ferro	Unlikely fabric
EPO	ECTO	ECTO	<~50	VIII.4	$\sim 0$ to 1	${\sim}1$ to 1.5	Dia	Dia
SITIO	NIC	NIC		VIII.5	Asymptotical	~3.8	Para and Dia	Dia
N				VIII.6	Asymptotical	~2.4	Para, Ferro, and Dia	Dia
				VIII.7	Asymptotical	~1	Ferro and Dia	Dia

*Note.* The coupling yields the actual carriers of the RT-AMS fabric, which may be different than the contributor to the mean susceptibility. The model demonstrates applications on sedimentary rocks; however, the same comparative principles may be applied to igneous and metamorphic rocks possessing primary and secondary fabrics.

of AMS axes than that of the RT-AMS fabric, reflecting the ferromagnetic and paramagnetic sub-fabrics, respectively (Table 1, Cases x.4).

#### 4.2.2. Two Dominant Phases

Cases in which two magnetic phases have a dominant contribution to the mean susceptibility are more complicated as the interpretation of the RT-AMS also depends on how the phase-related minerals are oriented relative to each other. When both the ferromagnetic and paramagnetic phases dominate the mean susceptibility (Table 1, Case x.2), a comparison between AARM and LT-AMS fabrics reveals which phase governs the RT-AMS fabric. If the RT-AMS fabric is similar to both AARM and LT-AMS fabrics, then the RT-AMS fabric is probably a composite of these similar fabrics (Table 1, Case I.2). If RT-AMS, AARM, and LT-AMS fabrics are essentially different, then the RT-AMS is a combination of two different fabrics, and therefore has no straightforward geological interpretation (Table 1, Case V.2). If only one of the proxy fabrics is similar to the RT-AMS fabric, the former governs the RT-AMS fabric and the latter reflects a sub-fabric, which is obscured in the RT-AMS fabric (Table 1, Cases II.2, III.2, VI.2, and VII.2).

In cases where the diamagnetic phase is one of the two dominant phases (Table 1, Cases x.5 and x.7), a similar behavior is expected to the aforementioned scenarios for ferromagnetic and paramagnetic phases, but it is much more complex to identify the magnetic phase that governs the RT-AMS fabric, as there is no diamagnetic proxy fabric for comparison. If the RT-AMS is similar to the proxy fabric (i.e., AARM or LT-AMS), then the RT-AMS fabric might be solely governed by that phase (i.e., ferromagnetic or paramagnetic) or by



the diamagnetic phase as well (Table 1, Cases I.5, I.7, II.5. III.7, V.5, V.7, VI.7, and VII.5). In cases where the RT-AMS fabric is different than the proxy fabric, the RT-AMS fabric might be solely governed by the diamagnetic phase or represent a combination of two different fabrics and therefore has no straightforward geological interpretation (Table 1, Cases II.7, III.5, IV.5, IV.7, VI.5, VII.7, VIII.5, and VIII.7). In such cases, it is not possible to distinguish between these possibilities, using the obtained fabrics.

#### 4.2.3. Three Dominant Phases

In cases where all three magnetic phases have dominant contributions to the mean susceptibility (Table 1, Case x.6), the RT-AMS fabric is probably a composite of different fabrics and bears no straightforward geological interpretation. In special cases, where the RT-AMS is similar to one specific proxy fabric (Table 1, Cases II.6, III.6, VI.6, and VII.6), then the RT-AMS is mostly governed by the equivalent phase. Akin to the two-phase case, the diamagnetic phase may or may not govern the RT-AMS as well.

## 5. Limitations of the Practical Approach

The present study suggests a practical and time-efficient approach for identification of the AMS carriers in rocks. However, there are cases in which this approach disregards complexities that evolve due to (1) susceptibility temperature-dependence of specific ferromagnetic minerals; (2) difference in the temperature-dependence of mean susceptibility and anisotropy, and varying Curie temperatures of paramagnetic minerals; (3) applying the AARM fabric as a proxy of the ferromagnetic (s.l.) fabric; and (4) fabric classification assumptions. These complexities are briefly discussed below.

### 5.1. Ferromagnetic Temperature-Dependent Susceptibility

Generally, the susceptibility and anisotropy of ferromagnetic (s.l.) minerals are temperature independent. However, there are a few exceptions, and difficulties may arise in certain cases. The Verwey transition in magnetite/titanomagnetite and the Morin transition in hematite are the most important in geological specimens. The Verwey transition is a crystallographic change that occurs near 125 K and influences the magnetic properties of minerals of the Fe<sub>3</sub>O<sub>4</sub> system (Walz, 2002 and references therein). Below the Verwey transition temperature, the susceptibility of magnetite/titanomagnetite shows temperature dependency and is generally increasing with temperature decrease. Richter and van der Pluijm (1994) measure LT/RT ratios of 4–8 for separated magnetite grains. The effect of the Verwey transition on the anisotropy properties of rocks is not well understood yet.

The Morin transition is related to changes in the isotropic point of hematite as spin orientations become antiparallel below temperatures near 260 K (Özdemir et al., 2008 and references therein). The transition influences both susceptibility and anisotropy. In general, below the Morin transition temperature, the susceptibility of hematite is expected to decrease and the direction of  $K_1$  axes is expected to switch from the basal plane to the hexagonal *c*-axis (Boer de & Dekkers, 2001 and references therein). Oliva-Urica et al. (2016) measured samples of red beds from the western Atlas, which showed susceptibility decrease at 77 K with LT/RT rations of 0.7 (TT5 samples) and even 0.5 (AG36 samples), and, accordingly, inferred the dominancy of hematite grains.

The abundance of magnetite/titanomagnetite and hematite grains may introduce errors in the identification of the magnetic fabric carriers using the approach presented in this study. The magnitude of susceptibility and anisotropy changes due to Verwey and Morin transitions, as well as their specific temperature, is dependent on grain sizes and impurities, and thus, no rule of thumb could be stated regarding their influence on the rock susceptibility and anisotropy. Fortunately, it is relatively simple to discover these transitions due to the narrow range of temperatures in which they occur. We therefore suggest that in cases where a significant susceptibility change is detected near 125 K or 260 K, the identification criteria presented in this study should be regarded with caution. Otherwise, the temperature independence of ferromagnetic minerals (s.l.) can be assumed as a first-order approximation, in accordance with previous magnetic fabric separation studies (e.g., Biedermann, 2018; Martín-Hernández & Ferré, 2007; Parés & van der Pluijm, 2014).





**Figure 3.** Expected error  $\alpha_e$  (in %) for different Curie temperatures and paramagnetic contents.

#### 5.2. Paramagnetic Temperature-Dependent Magnetic Properties

Different rock-forming paramagnetic minerals have shown variations in the Curie temperature  $\theta_c$ , mainly controlled by the applied field direction (Biedermann, Bender Koch, et al., 2014). For example, the range of  $\theta_c$  for biotite is -24 to 44 K (Ballet & Coey, 1982; Beausoleil et al., 1983; Biedermann, Bender Koch, et al., 2014), and for muscovite -24 to 5 K (Ballet & Coey, 1982; Biedermann, Bender Koch, et al., 2014) Furthermore, different crystals (e.g., biotite, olivine and some amphiboles, see Biedermann et al., 2015; Biedermann, Pettke, et al., 2014) exhibit a change of susceptibility owing to local onset of ferromagnetic interactions at temperatures as high as 100 K (above the expected temperature of LT measurements). Therefore, the chemical composition of minerals and oxidation degree cause variations of  $k_m$  between RT and LT measurements for certain grain populations. Based on this, we estimate the expected error  $\alpha_e$  (i.e., fraction of change from  $\alpha = 3.8$ ) as a function of  $\theta_c$  and the mineral abundance in the specimen:

$$\alpha_e = \sum_{i=1}^n \frac{\left|\alpha - \alpha_i\right|}{\alpha} C_i,\tag{9}$$

where for a rock composed of n minerals  $\alpha$  is the expected paramagnetic amplification factor (see Equation 4):  $\alpha = 3.8$ ,  $\alpha_i$  is the paramagnetic amplification factor for a mineral with a specific Curie temperature:  $\alpha_i = \frac{T_{\text{RT}} - \theta_c}{T_{\text{LT}} - \theta_c}$ , and  $C_i$  is the fraction of the mineral that comprises the specimen.

The expected error depends on the amount of paramagnetic minerals in the rock and their Curie temperatures. Figure 3 shows  $\alpha_e$  for different Curie temperatures that may be encountered in paramagnetic minerals. The content (in %) of the paramagnetic minerals in the rock is of paramount importance. For 5% paramagnetic content, the error is expected to be small (i.e.,  $\alpha_e < 10\%$ ) even for high Curie temperatures (i.e., ~50 K). For rocks that are composed entirely of paramagnetic minerals, an error of  $\alpha_e = 20\%$  is expected at Curie temperatures of 17 K and above. We demonstrate the use of the estimated error on chalk samples (Issachar et al., 2016), which contain 95% of calcite and 5% of paramagnetic minerals (palygorskite and smectite). Calcite is a diamagnetic mineral and does not affect  $\alpha_e$ . The highest Curie temperature of the paramagnetic minerals is in the range of 11–55 K (i.e., for ferrous nontronites; see Schuette et al., 2000). Using Equation 9, the maximum expected error on the paramagnetic amplification factor by neglecting the Curie temperature is ~0.091 (i.e., 9.1%).

While the identification of AMS carriers relies on the measurement and comparison of the mean susceptibilities (RT and LT), the relationship between the mean susceptibility and anisotropy under changing temperatures is not always direct (Biedermann, Bender Koch, et al., 2014). Various paramagnetic minerals show a different increase in anisotropy degree in response to cooling (compared to room temperature). For example, the increase of anisotropy degree at 77 K for biotite, is almost double the increase found for muscovite, chlorite, and pholgopite (Biedermann, 2018).

### 5.3. AARM as a Ferromagnetic Proxy Fabric

Another limitation arises due to the application of AARM as a proxy of the ferromagnetic fabric (eigenvectors only) due to: (1) the sensitivity of AARM to ferromagnetic minerals of specific coercivity; (2) different grain size populations with different sub-fabrics; and (3) Ferromagnetic minerals that exhibit inverse AMS fabrics. AARM only portrays the fabric of the minerals whose coercivity is lower than the applied AF field. While it is possible to apply the DC field under different AF ranges, thereby targeting specific ferromagnetic minerals, the usually applied AF ranges are between 0–100 mT and 0–60 mT (Biedermann et al., 2020). These fields usually fit the coercivity of stable single-domain (SSD) and pseudosingle-domain (PSD) ferromagnetic minerals. While in many cases, the magnetic remanence is carried mostly by these



minerals, ferromagnetic grains such as MD magnetite or hematite are usually not detected by the AARM measurements (Biedermann et al., 2017; Bilardello & Jackson, 2014; Jackson, 1991; Jackson & Tauxe, 1991; McCabe et al., 1985). Furthermore, the anisotropies of the different ferromagnetic grain populations may combine or subtract from each other (Biedermann et al., 2020), which may affect the total AARM as well as the RT-AMS (Lanci & Zanella, 2016).

Other complexities may also arise from the choice of DC field which affects the AARM degree (Bilardello & Jackson, 2014), as well as the choice of AARM magnetization orientations, and AF field frequencies and decay rates (Biedermann et al., 2020). Some of the ferromagnetic minerals (e.g., prolate SD magnetite) may display inverse fabric (i.e., minimum susceptibility parallel to the long axis of the grain) under the influence of an induced magnetic field. As the SSD grains are magnetically saturated, the applied magnetic field has no effect on the net magnetization, but only on its direction. In the absence of an induced magnetic field (i.e., during AARM measurement), these grains will not display an inverse fabric, which must be taken into account when comparing tensors of susceptibility and remanence (Jackson, 1991).

Susceptibility versus temperature curves, as well as ARM and IRM step demagnetization, can help inferring which ferromagnetic minerals are present, and deduce the optimal coercivity range for AARM (Martín-Hernández & Ferré, 2007). Taking into account the aforementioned complexities, in some cases (e.g., in the presence of hematite) alternative methods and techniques, like AIRM or A(p)ARM (partial AARM), should be applied in order to better approximate the ferromagnetic fabric. These methods can be used to target and isolate high coercivity fractions such as those associated with hematite (e.g., Biedermann et al., 2020; Bilardello & Jackson, 2014; Jackson, 1991; Jackson & Tauxe, 1991; Martín-Hernández & Ferré, 2007, and references therein).

#### 5.4. Coaxial and Primary Fabrics

The comparison of RT-AMS, LT-AMS, and AARM fabrics (Table 1) relies on the assumption that deformation fabrics are coaxial. This approximation holds true for many cases. For example, Weinberger et al. (2017) studied the deformation fabrics of earthquake-triggered slump sheets in soft rocks and showed that the RT-AMS and AARM fabrics are almost coaxial. Keeping in mind the above limitations, we analyze several published case studies, aiming to demonstrate the practical approach for identification of the AMS carriers. When deformation fabrics of different magnetic phases are non-coaxial, they cannot be assumed to be the result of the same deformation process without specific mineralogical considerations. Finally, for the purpose of fabric comparison, we also consider both deposition and isotropic fabrics as primary fabrics, representing an initial undeformed state of the studied rock. In practice, however, a rock may show an isotropic fabric when it is composed of isotropic minerals, even when the crystals acquired a preferential alignment due to deformation. Isotropic fabrics may also be the result of very weak anisotropy (i.e., below the instrument detection level), or the result of different anisotropies that cancel each other out.

## 6. Published Case Studies

Several studies published both room and low temperature susceptibility values of rocks (Casas-Sainz et al., 2018; Cifelli et al., 2005; Issachar et al., 2018, Issachar, Weinberger, et al., 2019; Oliva-Urcia et al., 2016; Soto et al., 2014). We present these data for different rock types on the LT/RT versus RT and LT versus RT plots (Figure 4), showing cases of a single and multiple dominant magnetic phases. In the LT/RT versus RT plots high  $k_m^{\text{RT}}$  region (>~50 × 10<sup>-6</sup> SI, Figure 4a), the different rocks show constant  $k_m^{\text{LT}}/k_m^{\text{RT}}$  values, suggesting that the relative contribution of the magnetic phases is also constant, even though  $k_m^{\text{RT}}$  values are dispersed. The plot reveals paramagnetic contribution (e.g., Clay group A;  $k_m^{\text{LT}}/k_m^{\text{RT}} = 3.8$ ), ferromagnetic contribution (e.g., Detrital Sediments TT5;  $k_m^{\text{LT}}/k_m^{\text{RT}} = 1$ ) and equal contribution of paramagnetic and ferromagnetic phases (e.g., Lutite QB18;  $k_m^{\text{LT}}/k_m^{\text{RT}} = 2.4$ ). Other rocks show different contributions of magnetic phases that lie between these cases (e.g., Fault Rock, Detrital Sediments AG28, Detrital Sediments TT7). In the low  $k_m^{\text{RT}}$  region (< ~50 × 10<sup>-6</sup> SI), the asymptotic behavior of the chalk specimens is evident, indicating the dominancy of the diamagnetic phase. In comparison, the clastics, which also possess low





**Figure 4.** RT-AMS and LT-AMS data of published studies (references indicated on plot) presented on: (a)  $k_m^{LT}/k_m^{RT}$  versus  $k_m^{RT}$  plot and (b) a  $k_m^{LT}$  versus  $k_m^{RT}$  plot. Inset: zoom-in of the purely diamagnetic region.

 $k_m^{\text{RT}}$  values, do not show a similar asymptotic behavior. This behavior demonstrates the lack of reliability of the LT/RT versus RT plot in the low  $k_m^{\text{RT}}$  region.

In the LT versus RT plot (Figure 4b), the rocks fit distinct linear slopes, allowing to distinguish between different phase contributions and indicating consistent and robust results when coupled with the LT/RT versus RT plot. Notably, the efficiency of this plot in the low  $k_m^{\text{RT}}$  region is evident. For example, the chalk specimens show an equal contribution of the paramagnetic and diamagnetic phases, but do not show the asymptotic behavior near  $k_m^{\text{RT}} = 0$  observed in the LT/RT versus LT plot (see Appendix B for more details). The pure diamagnetic specimens (limestone and rocksalt) fit the  $k_m^{\text{RT}} = k_m^{\text{LT}}$  slope line in the negative quadrant, as expected.

Figure 5 presents the RT-AMS, LT-AMS, and AARM fabrics of four case studies. By considering the associated fabrics and the susceptibility values at room and low temperatures, plausible interpretations for the carriers of the RT-AMS can be outlined. These case studies correspond to specific scenarios presented in Table 1.

In the Lutite specimens (QB18, Soto et al., 2014), the susceptibility values indicate contribution mainly from paramagnetic and ferromagnetic phases. The magnetic fabrics show quite similar tectonic fabrics. Hence, the RT-AMS is governed by both paramagnetic and ferromagnetic phases (Table 1, Case I.2). This is in agreement with the findings of Soto et al. (2014), who have concluded that the ferromagnetic phase has a similar sub-fabric to that of the paramagnetic minerals.

In the lacustrine (on-land) sediments (Elhanati et al., 2020), the susceptibility values indicate contribution mainly from paramagnetic and ferromagnetic phases. The RT-AMS and LT-AMS fabrics show similar tectonic fabrics and the AARM fabric is dissimilar. Hence, the RT-AMS is governed by the paramagnetic phase and the ferromagnetic sub-fabric is obscured in the RT-AMS (Table 1, Case I.2).

In the clastics specimens (Issachar, Weinberger, et al., 2019), the susceptibility values indicate contribution mainly from the paramagnetic phase. The RT-AMS, LT-AMS, and AARM show similar tectonic fabrics. Hence, the RT-AMS is governed by the paramagnetic phase and the ferromagnetic fabric is quite similar, yet, it is obscured in the RT-AMS as indicated by the  $k_m^{LT}/k_m^{RT}$  ratios of the specimens (Table 1, Case I.1).

In the chalk specimens (Issachar et al., 2018), the susceptibility values and  $k_m^{\text{LT}}/k_m^{\text{RT}}$  ratios indicate contribution mainly from paramagnetic and diamagnetic phases. The RT-AMS shows tectonic fabric, whereas





Figure 5. Comparison of RT-AMS, LT-AMS, and AARM fabrics of rock samples from four case studies (references indicated on plot).

the LT-AMS shows a different tectonic fabric and the AARM shows an isotropic fabric. Hence, the RT-AMS represents a combination of paramagnetic and diamagnetic dissimilar sub-fabrics, and therefore has no straightforward geological interpretation (Table 1, Case II.5).

## 7. Summary of the Practical Approach

Based on the numerical simulation and analysis presented, we highlight the following steps, which should be taken to identify the magnetic fabric carriers:

- 1. Measure the mean susceptibility of the specimens at low and room temperature
- 2. Plot the specimens on LT/RT versus RT and LT versus RT plots, and find the dominant magnetic phases by analyzing the resulting plots. A flowchart that summarizes the identification of the dominant magnetic phases based on the plots is presented in Figure 6
- 3. Compare LT-AMS and AARM measurements to that of the RT-AMS to fully characterize the carriers of the AMS, using the scenario table (Table 1)

In most cases, one can deduce which magnetic phases are dominant in a given specimen-based solely on the mean susceptibility measured in both room and low temperatures (steps 1 and 2). The relative contributions of the magnetic phases to the mean susceptibility are distinguishable on LT/RT versus RT and LT versus RT plots, as the specimens align along the lines of known slopes. The presence of a diamagnetic dominant phase can be deduced by considering if the specimens are plotted in the low  $k_m^{\text{RT}}$  region (<  $\sim 50 \times 10^{-6}$  SI).



k <sub>m</sub> <sup>RT</sup>	$k_m^{LT}/k_m^{RT}$ values	k <sub>m</sub> <sup>LT</sup> vs k <sub>m</sub> <sup>RT</sup> slope	Dominant phases in $k_m^{RT}$
*	~3.8 (asymptotical) ,	~3.8	] → Para
>50 ×10 <sup>-6</sup> SI	~2.4 (asymptotical) ,	~2.4	Para & Ferro
	~1 (asymptotical) ,	~1	Ferro
1	~0 to 1 ,	~1 to 1.5	]→ Dia
<50 ×10 <sup>-6</sup> SI	∞ (asymptotical) ,	~3.8	Para & Dia
	$\sim$ (asymptotical) ,	~2.4	Para, Ferro & Dia
	~1 , [	~1	─→ Ferro & Dia

**Figure 6.** Flowchart illustrating which are the dominant phases contributing to the mean susceptibility at room temperature of a specimen, based on the  $k_m^{LT}/k_m^{RT}$  values and  $k_m^{LT}$  versus  $k_m^{RT}$  linear slope.

The LT/RT versus RT plot is generally preferable than the LT versus RT plot, as it uses the measured LT/RT values of a specimen and does not rely on calculated linear correlation curves. Moreover, a linear correlation requires a minimum number of specimens to show robust results, while the LT/RT versus RT plot can be used for even a single specimen. However, at the low  $k_m^{\text{RT}}$  region, the asymptotic behavior of the LT/RT versus RT plot preferable.

While the analysis of dominant magnetic phases is usually satisfied by using mean susceptibility measurements alone, they are not sufficient in order to distinguish between the carriers of the AMS and study the magnetic anisotropy of the specimen. As outlined in step 3, the results obtained from the dominant phase analysis need to be coupled with the magnetic fabrics obtained by RT-AMS, LT-AMS, and AARM. Doing so allows the recognition of the RT-AMS carriers and identification of composite fabrics and obscured sub-fabrics. Nevertheless, in some cases (e.g., a single dominant phase), the RT and LT mean susceptibility measurements are sufficient to distinguish the full carriers of the AMS, thereby omitting the need for LT-AMS and AARM measurements.

## 8. Concluding Remarks

We present a comprehensive approach that integrates the results of RT-AMS, LT-AMS, and AARM measurements for studying the contribution of different magnetic phases and carriers to the anisotropies and net magnetic fabrics.

The present approach disregards complexities such as non-zero paramagnetic Curie temperature, temperature-dependence of specific ferromagnetic minerals, and high coercivity ferromagnetic minerals. However, with the aid of a flowchart and scenario table that serves as guides to help researchers find specific cases, we demonstrate how to decipher the AMS carriers and achieve a robust and reliable geological interpretation.

## Appendix A: Full Susceptibility Tensor Separation

Measuring  $k_m^{\text{RT}}$  and  $k_m^{\text{LT}}$  of a specimen allows to calculate the contribution of the paramagnetic phase relative to the diamagnetic and ferromagnetic phases:



$$\frac{k_{md} + k_{mf}}{k_{mp}} = \frac{k_m^{\rm RT} \left(\alpha - 1\right)}{k_m^{\rm LT} - k_m^{\rm RT}} - 1$$
(A1)

By also assuming the diamagnetic susceptibility (usually the diamagnetic contribution is easy to estimate by the rock type), one could calculate all three phase's susceptibilities.

The full susceptibility tensor measured at room temperature is described as:

$$\boldsymbol{K}^{\text{RT}} = \boldsymbol{k}_d + \boldsymbol{k}_p + \boldsymbol{k}_f = c_d \boldsymbol{K}_d + c_p \boldsymbol{K}_p + c_f \boldsymbol{K}_f \tag{A2}$$

where  $\mathbf{k}_d$ ,  $\mathbf{k}_p$ , and  $\mathbf{k}_f$  are the respective susceptibility contribution tensors, which are simply the result of multiplying the diamagnetic, paramagnetic, and ferromagnetic susceptibility tensors (i.e.,  $\mathbf{K}_d$ ,  $\mathbf{K}_p$ , and  $\mathbf{K}_f$ , respectively), with their respective percentages in the rock ( $c_d$ ,  $c_p$ , and  $c_i$ ). A contribution tensor is the product of mean susceptibility ( $k_m$ ) and a normalized contribution tensor ( $\mathbf{k}$ ), so Equation A2 can be re-written as:

$$k_m^{\text{RT}} \cdot \overset{\overset{\overset{}}{k}}{\overset{}{k}}^{\text{rT}} = k_{md} \cdot \overset{\overset{}}{k}_{d} + k_{mp} \cdot \overset{\overset{}}{k}_{p} + k_{mf} \cdot \overset{\overset{}}{k}_{f}$$
(A3)

The low-temperature equation can be written similarly as:

$$k_m^{\text{LT}} \cdot \overset{\mathbf{k}}{\overset{\mathbf{k}}{k}} = k_{md} \cdot \overset{\mathbf{k}}{\overset{\mathbf{k}}{k}} + \alpha \cdot k_{mp} \cdot \overset{\mathbf{k}}{\overset{\mathbf{k}}{p}} + k_{mf} \cdot \overset{\mathbf{k}}{\overset{\mathbf{k}}{k}}_f$$
(A4)

By measuring the RT-AMS and LT-AMS,  $k_m^{\text{RT}} \cdot \check{k}^{\text{RT}}$  and  $k_m^{\text{LT}} \cdot \check{k}^{\text{LT}}$  are derived directly.  $k_{md}$ ,  $k_{mp}$ , and  $k_{mf}$  can be calculated as described in the main article. The AARM measurement supplies the  $\check{k}_f$  tensor, leaving only two unknown variables:  $\check{k}_d$  and  $\check{k}_p$ , which can be then solved with a set of two equations (Equations A3 and A4), to yield the full diamagnetic and paramagnetic susceptibility tensors for a single specimen.

## Appendix B: Intersection Points With the $k_m^{LT}$ Axis in the LT Versus RT Plot

The LT versus RT plot is based on using the slope of a linear correlation for a group of specimens. While different groups of specimens with the same dominant phases are expected to have a similar slope (e.g., a slope of ~3.8 and ~1 for pure paramagnetic and ferromagnetic dominance, respectively), the same does not hold true for their intersection point with the axes. The intersection point with the  $k_m^{LT}$  axis, as well as the point in which  $k_m^{LT} = k_m^{RT}$ , can vary between different paramagnetic minerals. Therefore, when comparing different samples on the LT versus RT plot using pre-drawn theoretical lines, it is important to note that the lines can be pre-drawn somewhat arbitrarily, with regards to the intersection point with the  $k_m^{LT}$  axis. This emphasizes the importance of the linear LT/RT slope in the plot, as this parameter is not biased by the determining theoretical intersection points. Figure B1 shows chalk specimens (orange circles) that display a very good fit to a linear regression line, with  $R^2 = 0.98$ . The slope of the linear curve is 3.35, indicating mainly dominancy of the paramagnetic phase. The diamagnetic phase is also dominant, as inferred from the low  $k_m^{RT}$  values. While the specimens also fit with the pre-determined theoretical lines, a different choice of intersection point for the theoretical lines could have invalidated the fit to the theoretical line.







#### Data Availability Statement

All the data used for this study are accessible by contacting the authors at dan.elhanati@gmail.com and are available online at https://data.mendeley.com/datasets/9cs2rsrt3s/2.

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