Part 2 Interpretation

Room temperature susceptibility

How do we interpret a value of magnetic susceptibility measured at room temperature? Magnetic susceptibility gives us information about the mineralogy and geochemistry of environmental materials. From mineralogy we can often deduce additional information about the material, such as its origin or the chemistry of its environment. Information about the origin may give us further information about the environmental conditions which gave rise to the minerals. An infinite number of environmental conditions gives rise to a very wide range of mineralogies and magnetic susceptibility values, as shown in Figure 2.1. It shows that virtually all types of environmental materials have been measured with values ranging from <0.001 to >30 x 10^{-6} m^3 kg^{-1} encompassing five to six orders of magnitude.

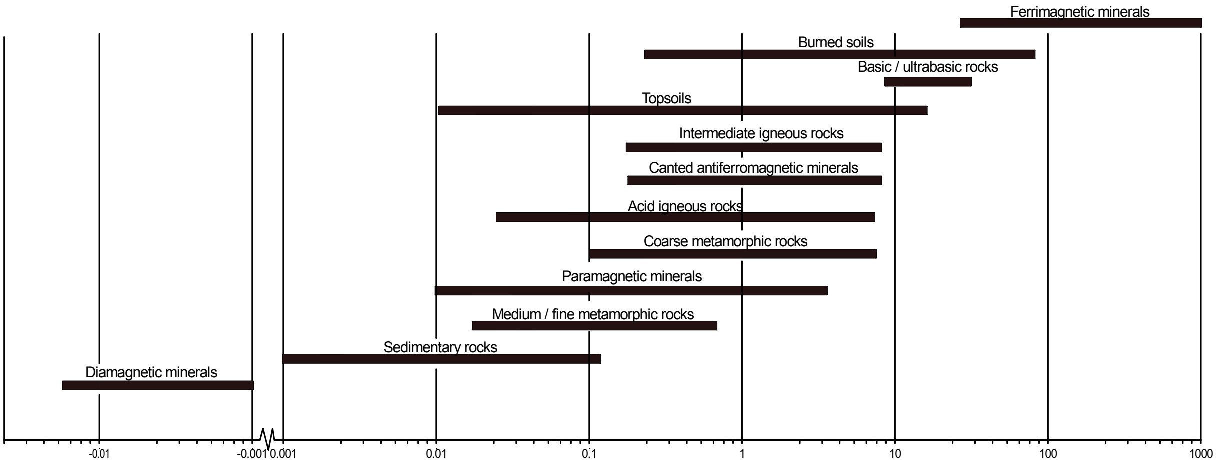

Figure 2.1 Typical ranges of room temperature magnetic susceptibility values measured for environmental materials and minerals

One kind of interpretation procedure is shown in Figure 2.2. Not all measurements can or need to be interpreted strictly in this way. Whilst representing a useful approach, the procedure followed in conjunction with the sections below acts as a tutorial in the subject for users who are unacquainted with magnetic and environmental theories. More experienced users may wish to move directly to certain other sections or to tables of data in order to make comparisons with their own results. It begins by making the assumption that the magnetic susceptibility of most environmental materials is controlled by the mixture of minerals present. Minerals are naturally occurring chemical compounds which are usually in the form of crystals. Their internal structure is determined by the arrangement of atoms of chemical elements into a three-dimensional pattern termed a lattice. The magnetic behaviour of a mineral is controlled both by the particular atoms making up the lattice and the way in which the lattice is structured. In some minerals the same atoms give rise to different magnetic states because they can form alternative lattice structures. The minerals which show strong magnetic responses tend to contain atoms of iron (Fe) in their lattice.

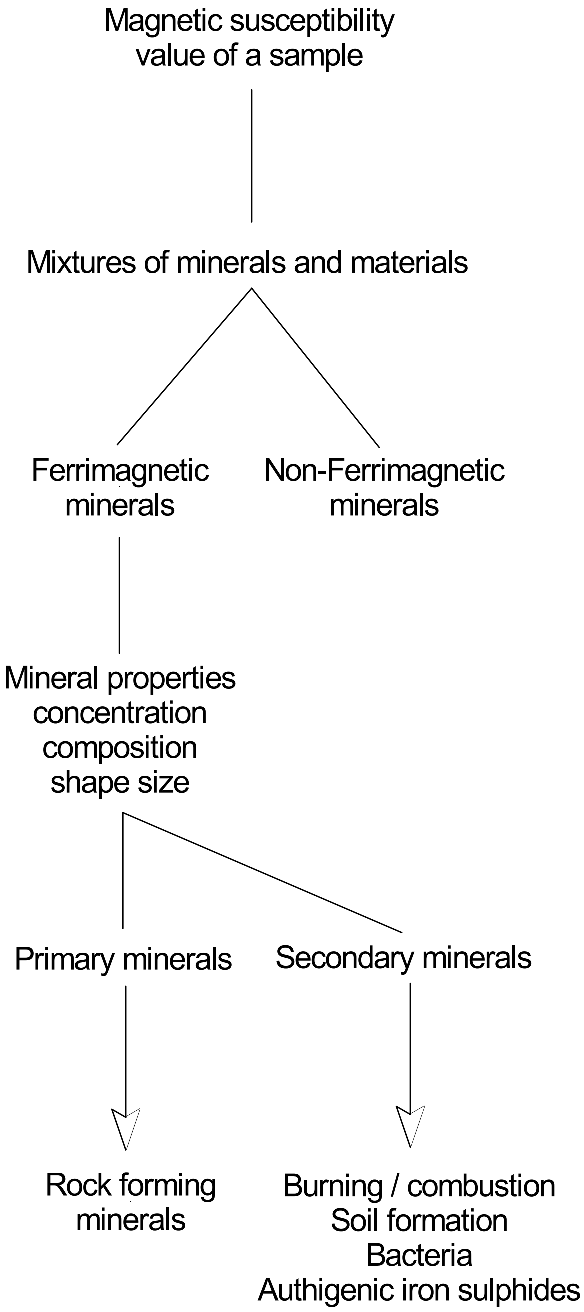

Figure 2.2 A procedure for interpreting magnetic susceptibility

Table 2.1 Magnetic behaviour and magnetic susceptibility

Ferromagnetic	Strong positive susceptibility *e.g. pure iron, nickel, chromium*
Ferrimagnetic	Strong positive susceptibility *Some iron oxides and sulphides, e.g. magnetite, maghemite, pyrrhotite, greigite*
Canted antiferromagnetic	Moderate positive susceptibility *Some iron oxides, e.g. hematite, goethite*
Paramagnetic	Weak positive susceptibility *Many Fe-containing minerals and salts, e.g. biotite, olivine, ferrous sulphate*
Diamagnetic	Weak negative susceptibility *e.g. water, organic matter, plastics, quartz, feldspars, calcium carbonate*

The idea of minerals and materials having different magnetic status was introduced in Part 1. There are five categories of magnetic behaviour, shown in Table 2.1 ranked in decreasing order of typical magnetic susceptibility. From this information and the previous discussion of magnetic susceptibility theory (Figure 1.1) it can be presumed that a sample of rock or soil containing predominantly ferrimagnetic minerals will have a higher susceptibility than one containing, say, all paramagnetic minerals. And this is certainly a good guide to explaining the relative magnitude of susceptibilities in samples of pure minerals. However, it is uncommon for a natural sample to contain only one category of magnetic minerals.

It is therefore necessary to consider virtually all samples as a mixture of minerals often falling into two or three categories of magnetic behaviour and each having a different magnetic susceptibility value. Therefore, we need to know the magnetic susceptibility values of individual minerals in order to interpret the magnetic susceptibility values of bulk samples. A list of individual magnetic susceptibilities of minerals and materials is given in Table 2.2.

There are exceptions to a mineral basis for environmental magnetism. The weakest diamagnetic group (Table 2.1) of materials contains non-crystalline forms like wood, water and plastic. The strongly magnetic ferromagnetic group (Table 2.1) comprises ‘pure’ particles of the elements iron, nickel and chromium, members of the transition element range or Group 8 of the Periodic Table.

Mixtures of minerals

In theory, we can explain or predict the magnetic susceptibility of a sample in terms of the sum of the magnetic susceptibility values of the individual minerals and materials shown in Table 2.2. The idea of interpreting each measurement in terms of many different minerals sounds a fairly daunting task. But in practice we can simplify matters by making some assumptions about which minerals are significant in a sample.

Samples which are not contaminated by ferrous metal do not usually contain ferromagnetic materials. In their absence, the susceptibility of a sample is most likely to be controlled by the ferrimagnetic component, and less likely by the other categories of minerals present, shown in Table 2.1. Magnetite, for instance, is about 1000 times more magnetic than the strongest canted antiferromagnetic or paramagnetic mineral, and about 10000 times stronger than the weakest clay mineral. Ferrimagnetic iron oxides, like magnetite, are found in virtually all environments.

In igneous rocks, magnetite may represent about 1-2% of the minerals. But even in these relatively small proportions, its high susceptibility will often mean that it contributes more to the susceptibility of the whole sample than does the combined effect of all the other minerals. The dominating effect of magnetite can be seen by considering a hypothetical soil. Imagine a soil composed of organic matter, water, quartz sand, clay and iron oxides (Table 2.3). With the information about the concentration or proportion of the different materials and minerals present (column 1), and their individual susceptibilities taken from Table 2.2, we can see how the total susceptibility value is produced. By multiplying the fraction or concentration (column 2) by the specific susceptibility (column 3) we obtain the susceptibility (column 4) of each mineral/material component in this soil. The total susceptibility of the soil, 0.5855×10^{-6} m^3 kg^{-1} is obtained by summing the susceptibility values of the components. Column 5 shows calculations of the fraction of the total susceptibility held by each type of mineral/material. Note that a very small concentration (0.1%) of magnetite provides 85.4% of the sample's susceptibility, and the largest fractions, the paramagnetic minerals, organic matter, sand and water (90% of the soil) provide only 6% or so of the total sample susceptibility.

Table 2.2 Minerals and magnetic susceptibility

Mineral/Material	**Formula**	**Iron (%)**	**Mass specific magnetic susceptibility (10^{-6} m^3 Kg^{-1})**
Ferromagnetic metals			
Iron	αFe	100	276000
Cobalt	Co		204000
Nickel	Ni		68850
Ferrimagnetic			
Magnetite	Fe_3O_4	72	
(0.012-0.069 μm)			513-1116
			500-1000
(0.09-2000 μm)			596 ± 77
(1-250μm)			440-716
			390-580
Maghemite	γFe_2O_3	70	410, 440
			286-371
Titanomagnetite	Fe_3O_4-Fe_2TiO_4		169-290
Titanohaematite	Fe_2O_3-$FeTiO_3$		281-315
Pyrrhotite	Fe_7S_8		50, 53
Greigite	Fe_3S_4		
(Canted) antiferromagnetic			
Hematite	αFe_2O_3	70	1.19-1.69
			0.58-0.78
			0.49-0.65
			0.27, 0.31, 0.6, <0.63
Goethite	αFeOOH	63	0.35, 0.38, 0.7, <1.26
Paramagnetic (20 °C)			
Ilmenite	$FeTiO_3$	37	1.7, 2
Ulvospinel	Fe_2TiO_4		
Olivine	$4[(Mg,Fe)_2SiO_4]$	<55	0.01-1.3
Siderite	$FeCO_3$	48	1.0
Biotite	Mg,Fe,Al silicate	31	0.05-0.95
Pyroxene	$(Mg,Fe)_2Si_2O_6$	<12	0.04-0.94
Chamosite	oxidised chlorite		0.9
Nontronite	Fe-rich clay		0.863
Amphibole	Mg,Fe,Al silicate		0.16-0.69
Epidote	Ca,Fe,Al silicate	31	0.25-0.31
Pyrite	FeS_2	47	0.3
Lepidocrocite	γFeOOH	63	0.5-0.75, 0.69
Prochlorite	mica-like mineral		0.157

Vermiculite	complex silicate		0.152
Illite	$K1Al_4(Si,Al)_8O_2O(OH)_4$		0.15
Bentonite	complex silicate		0.058
Smectite	complex silicate		0.05, 0.027
Chalcopyrite	$CuFeS_2$	30	0.03
Attapulgite	complex silicate		0.02
Dolomite	$CaMg(CO_3)_2$		0.011
Diamagnetic			
Calcite	$CaCO_3$		-0.0048
Alkali-feldspar	Ca,Na,K,Al silicate		-0.005
Plastic			-0.005
Quartz	SiO_2		-0.0058
Organic matter			-0.009
Water	H_2O		-0.009
Halite	NaCl		-0.009
Kaolinite	$Al4Si_4O_{10}(OH)_8$		-0.019

Data from published and unpublished sources, showing ranges and individual measurements of susceptibility values and iron content.

Table 2.3 Magnetic susceptibility of soil components

1	**2**	**3**	**4**	**5**
Mineral/material	**Fraction**	χ_{lf} **10^{-6} m^3 kg^{-1}**	**Component χ_{lf} 10^{-6} m^3 kg^{-1}**	**% Fraction total χ_{lf}**
Magnetite	0.001	500	0.5	85.4
Goethite	0.099	0.5	0.0495	8.5
Paramagnetic minerals	0.75	0.05	0.0375	6.4
Organics, quartz, sand and water	0.15	-0.01	-0.0015	-0.3
Total	1.0	500.54	0.5855	100.0

Samples of rocks and soils showing purely paramagnetic behaviour rarely show χ_{lf} values exceeding 0.1 x 10^{-6} m^3 kg^{-1}. Therefore, as a rule-of-thumb, the χ_{lf} of any sample with a value less than this is probably controlled by the concentration of paramagnetic minerals and for values greater than this by ferrimagnetic minerals. There are exceptions to this rule, especially in some weak samples where the susceptibility may be controlled by minute concentrations of ferrimagnetic minerals (see Weak samples).

Ferrimagnetic minerals

Most environmental materials have room temperature magnetic susceptibility values controlled by ferrimagnetic minerals. The iron oxides, magnetite, maghemite, titanomagnetite, titanomaghemite are the dominant ferrimagnetic minerals in many soils, rocks, sediments and dusts. Ferrimagnetic iron sulphides are much less common, and are usually found in a narrow range of environments; greigite in some sediments and waterlogged soils, and pyrrhotite in some metamorphic and basic igneous rocks. The next sections focus on ferrimagnetic iron oxides.

Table 2.4 Magnetic susceptibility of magnetite

Titanomagnetite	**Single domain**	**Ultrafine**	**Fraction**	
10^{-6} m^3 kg^{-1}	**10^{-6} m^3 kg^{-1}**	**10^{-6} m^3 kg^{-1}**	**%**	**ppm**
20	60	100	10	100000
2	6	10	1	10000
0.2	0.6	1	0.1	1000
0.02	0.06	0.1	0.01	100
0.002	0.006	0.01	0.001	10
0.0002	0.0006	0.001	0.0001	1
0.00002	0.00006	0.0001	0.00001	0.1

Magnetic susceptibility of samples with different fractions of pure titanomagnetite (200 x 10^{-6} m^3 kg^{-1}), stable single domain magnetite (600 x 10^{-6} m^3 kg^{-1}) and ultrafine superparamagnetic magnetite (1000 x 10^{-6} m^3 kg^{-1}) in a matrix of zero susceptibility. Fractions defined in mass percentages, parts per million (ppm). Find the nearest χ_{lf} of a sample in columns 1, 2 and 3 (or recalculate for intermediate values of χ_{lf}) and read across for equivalent fractions of minerals in sample. Thus, a sample with χ_{lf} of 20 x 10^{-6} m^3 kg^{-1} could represent either ~ 10% coarse titanomagnetite (reading across top line from column 1), ~3.3% stable single domain magnetite or ~2% ultrafine magnetite (based on recalculations of top values in columns 2 and 3).

Mineral concentration

The range of susceptibilities where it is thought that ferrimagnetic minerals dominate, that is greater than 0.1 x 10^{-6} m^3 kg^{-1} covers three to four orders of magnitude (Figure 2.2). Natural samples lying at either end of this susceptibility range vary in their concentration of ferrimagnetic minerals by a factor of about 300. Therefore the major factor controlling the susceptibility of samples in this range will be the concentration of ferrimagnetic minerals; in other words the total number or volume of ferrimagnetic crystals. The concentration of magnetite in a sample is estimated by dividing the bulk susceptibility value of the sample by the susceptibility of the assumed or known magnetite type or size (Table 2.2 and Figure 2.3). Table 2.4 can be used to estimate concentrations of ultrafine superparamagnetic magnetite, stable single domain magnetite and coarse titanomagnetite minerals (see Crystal size and domains below). As Figure 2.2 shows, concentration is only one of four factors controlling magnetic susceptibility. Magnetic susceptibility also depends on the mineral composition, crystal size and crystal shape.

Mineral composition

The composition of ferrimagnetic iron oxides varies from the 'pure' oxides of magnetite and maghemite, to 'impure' oxides such as titanomagnetite and titanomaghemite, in which the Fe atoms are partially substituted by atoms of titanium (Ti). There are continuous sequences or solid solutions of minerals between these two sets which have varying titanium contents. Titanium substitution reduces the Fe content and magnetic moment of the mineral, and hence lowers the magnetic susceptibility. This is confirmed in Table 2.2, which shows titanomagnetite with susceptibility values as low as 15% of the highest values for magnetite. Where titanium substitution has progressed beyond a certain point the minerals lose ferrimagnetic status and become transformed into the paramagnetic titanium oxides ilmenite and ulvospinel.

The type of iron oxides which occur in specimens of igneous rock depends upon the chemical composition of the liquid magma and the mode of crystallisation. The main oxide is titanomagnetite and the proportion of titanium tends to be higher in basic rather than acid rocks. Oxidation at high temperatures (>600 °C) during cooling will result in conversion to magnetite, whilst at low temperatures (<400 °C) oxidation produces titanomaghemite. Titanomagnetites tend to form during rapid rather than slow cooling of the magma. The iron oxides will have a range of crystal dimensions from <1 μm to several millimetres, and the crystal shape can vary from spheres to rods. Weathering of igneous rocks can alter crystal structure and chemical composition, and has the crucial effect of releasing minerals into soils and sediments. The iron oxides in sedimentary rocks will in part be inherited from igneous rocks.

Crystal size and domains

Ferrimagnetic grains are divided up into different regions or cells of magnetisation, known as **domains**. Above diameters of ~110 μm, magnetite grains are referred to as **multidomain** (MD) because energetically it is favourable to have more than one domain. In small grains <0.2 μm, the restricted volume allows only one domain to form, and these are termed **single domain** (SD) grains. Grains in the interval 0.2 - 110 μm are large enough to favour more than one domain but show the magnetic properties of single domain grains; these are termed **pseudo-single domain** (PSD). Ultrafine grains <0.03 μm are SD but display unique properties. The magnetisation is strong but unstable due to thermal energies counteracting induced magnetisation very quickly after a magnetic field is removed. This behaviour is similar to paramagnetism, but with a much greater susceptibility. Hence it is termed **superparamagnetic** (SP) behaviour. Measurements on natural and synthetically produced magnetites of known sizes (Table 2.2) have helped to define the major changes in susceptibility with crystal size and domain, and these are shown in Figure 2.3. Recent measurements suggest that the variations of χ_{lf} with crystal size are smaller than previously thought and may be considered to have a constant mean of 3.1 SI (± 0.4 SI) equivalent to a χlf value of ~596 x 10^{-6} m^3 kg^{-1} (± 77 x 10^{-6} m^3 kg^{-1}) over a very wide range (0.09 - 6000 μm) of crystal sizes. This range includes all the MD, PSD and stable SD domain states (SSD). In crystal diameters less than 0.03 μm, the domain state is essentially SP and values of χ_{lf} are higher and may exceed 1000 x 10^{-6} m^3 kg^{-1}. The SP crystals are also characterised by their response to susceptibilities measured at different frequencies and are detected by frequency dependent measurements (see below).

Crystal shape

The crystal shape of the ferrimagnetic mineral assemblage influences magnetic susceptibility values. Longer crystals have the effect of shifting the boundaries between the domain states towards coarser crystal sizes. For example, rod-shaped crystals might exhibit SP behaviour in crystals as long as 0.05 μm. However, without other magnetic measurements or direct observations by transmission electron microscope, evaluation of the effects of crystal shape on susceptibility is difficult. In summary, where ferrimagnetic minerals dominate the magnetic mineral assemblage (i.e. κ_{lf} >0.1 x 10^{-6} m^3 kg^{-1}), magnetic susceptibility is controlled by the following factors in order of decreasing importance:

mineral concentration	*(χ_{lf} varies by factor of 200-300)*
mineral composition	*(χ_{lf} varies by factor of 3-4)*
crystal size	*(χ_{lf} varies by factor of <2)*
crystal shape	*(χ_{lf} varies by factor of <2)*

Primary and secondary minerals

Ferrimagnetic minerals which were formed within igneous rocks and which retain all or virtually all of their magnetic properties are referred to in this text as **primary minerals**. Other ferrimagnetic iron oxides and sulphides are referred to as **secondary minerals**; that is, they have formed by other processes that include burning, fossil fuel combustion, bacteria, soil formation, diagenesis and authigenesis. The crystal size or domain state provides a clue as to the processes of formation of magnetite. Table 2.5 shows that primary rock minerals and products of fossil fuel combustion tend to fall into MD, PSD and SSD ranges, while burning, pedogenic processes and bacterial action tend to produce fine secondary crystals of SSD or SP behaviour. Therefore, in some situations the ability to distinguish between domain and grain sizes will help to identify the process of crystal formation. However, room temperature measurements of magnetic susceptibility cannot alone distinguish between secondary or ferrimagnetic minerals and domains. The next sections therefore deal with how further measurements of frequency-dependent susceptibility, and low and high temperature susceptibility may help to identify minerals and domains.