Mineral Magnetism: Providing New Insights into Geoscience Processes

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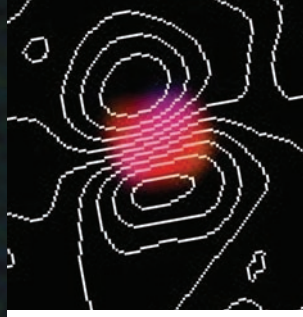

ABOVE: Single-domain grain (50 nm) of magnetite from a magnetotactic bacteria displaying a dipole-like external magnetic field and a uniformally magnetized interior

Magnetic minerals are ubiquitous in the natural environment, and they are also present in a wide range of biological organisms, from bacteria to human beings. The last ten years have seen a striking improvement in our ability to detect and image the magnetization of minerals in geological and biological samples. These minerals carry a wealth of information encoded in their magnetic properties. Mineral magnetism (together with the related disciplines of rock magnetism, paleomagnetism, environmental magnetism, and biomagnetism) decodes this information and applies it to an ever increasing range of geoscience problems, from the origin of magnetic anomalies on Mars to quantifying variations in Earth's paleoclimate.

KEYWORDS: magnetism, magnetic minerals, magnetism theory, electron holography

MAGNETIC MINERALS ARE EVERYWHERE!

Look closely enough at any geological sample and you will find traces of magnetic minerals. From rocks, sediments, and soils, to meteorites, polar ice, and speleothems, detectable quantities of magnetic mineral grains are found virtually everywhere in the natural environment. The magnetic properties of rocks and sediments are highly sensitive to variations in the concentration, grain size, chemical composition, and microstructure of the magnetic minerals within them. Often these minerals retain a memory of the geomagnetic field that was present during the rock's formation, yielding paleomagnetic information that can be used to map the movements of the continental and oceanic plates—one of the most powerful tools we have for reconstructing the tectonic history of the Earth and other planets (McEnroe et al. 2009 this issue). The variation in intensity of the geomagnetic field, as determined from rocks and archeological materials, has been used to provide an understanding of the history and behavior of the geodynamo and to constrain models of fluid motion in the Earth's core (Tarduno 2009 this issue). The magnetic signals recorded by meteorites allow us to study the processes that occurred during the very earliest history of the solar system, as well as the metamorphic processes and shock events that led to the ejection of meteorites from their parent body (Rochette et al. 2009 this issue). The mineralogy and grain size of magnetic minerals can be used to trace changes in paleoclimate, as magnetic properties are highly sensitive to climatic variables such as rainfall, temperature, wind speed, and biological productivity. For example, magnetic susceptibility measurements of sediments from the Chinese Loess Plateau reveal one of the longest-duration and highest-resolution records of continental climate change available, providing a detailed picture of glacial and interglacial cycles and variations in the Asian monsoon stretching back 2 million years. More recently, magnetic measurements of marine sediments have been used to determine paleooceanographic circulation patterns by constraining the geographical extent of ice-rafted detritus during the last glacial maximum. Even the spread of anthropogenic pollutants can be traced throughout a city environment by measuring the magnetic properties of leaves, which trap magnetic particles from passing vehicles (Maher 2009 this issue).

In addition to the many geoscience applications, the discovery of magnetotactic bacteria containing submicron-size magnetic particles—used by the bacteria to align themselves with the geomagnetic field, thus providing an efficient method of swimming up and down the water column—has opened up a new area of research into the role of magnetic minerals in biological systems (Pósfai and Dunin-Borkowski 2009 this issue), and has even led to speculation that the famous meteorite ALH84001 contains the fossilized remains of magnetotactic bacteria from Mars (McKay et al. 1996). Biomagnetism has been applied in studies of how animals such as fish, sea turtles, and birds make use of magnetic minerals to navigate over hundreds of kilometers using maps of geomagnetic field anomalies and in investigations of the possible links between magnetic minerals in brain tissue and the occurrence of neurodegenerative diseases such as Huntington's, Alzheimer's, and Parkinson's. Magnetic minerals are also increasingly being used in medical applications such as targeted gene therapy, whereby therapeutic genes are attached to magnetic nanoparticles and then focused on the target cells via high-field/high-gradient magnets (Dobson 2008).

WHAT IS MINERAL MAGNETISM?

All these applications require a thorough understanding of the fundamental magnetic properties and behavior of magnetic minerals. This is the realm of rock and mineral magnetism. Rock magnetism is primarily concerned with understanding the processes by which rocks become magnetized in nature and the factors influencing their ability to maintain a faithful record of the Earth's magnetic field over geological time (the reader is referred to Dunlop and Özdemir 1997 for the definitive guide to this subject). Mineral magnetism, on the other hand, deals mainly with the physical, chemical, and thermodynamic properties of the magnetic minerals themselves and, in particular, how their magnetic properties are influenced by their structural and microstructural characteristics.

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WHAT MAKES A MINERAL MAGNETIC?

Iron makes up around 5 wt% of the Earth's crust and is second in abundance after Al among the metals and fourth in abundance behind O, Si, and Al among all elements. Metallic Fe is the dominant magnetic phase in meteorites and lunar rocks, whereas on Earth the dominant magnetic minerals are Fe oxides or Fe–Ti oxides containing Fe^{2+} (ferrous) and Fe^{3+} (ferric) ions (Fig. 1; Table 1). Iron has a partially filled 3*d* electron shell containing several unpaired electrons, giving it a permanent magnetic moment (Fig. 2).

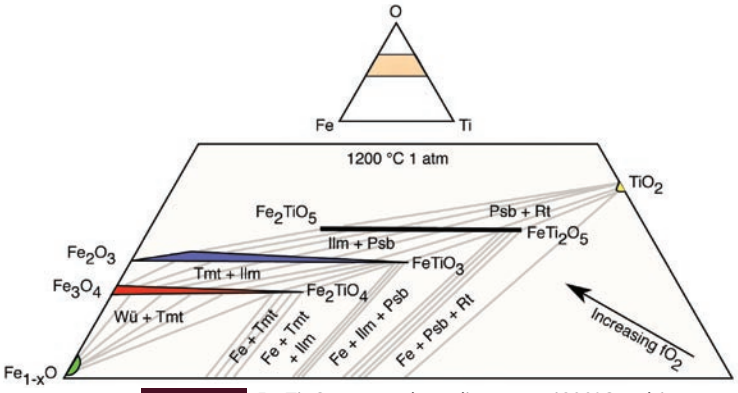


Figure 1 Fe–Ti–O ternary phase diagram at 1200°C and 1 atm, illustrating the compositional ranges of the dominant magnetic minerals in terrestrial rocks. The two magnetic solid solution series are the magnetite–ulvöspinel ("titanomagnetite") and the hematite–ilmenite ("titanohematite") series. The pseudobrookite solid solution (black) is paramagnetic at room temperature. Magnetic end members are magnetite (Fe_3O_4) and hematite (Fe_2O_3). Grey lines indicate tie lines for coexisting compositions in two-phase regions. Tmt = titanomagnetite; Fe_2TiO_4 = ulvöspinel, Wü = wüstite ($Fe_{1-x}O$); Ilm = ilmenite ($FeTiO_3$); Psb = pseudobrookite (Fe_2TiO_5–$FeTi_2O_5$); Ru = rutile (TiO_2); Fe = metallic iron. Based on Lattard et al. (2005), redrawn after Grey et al. (1974) and Grey and Merritt (1981)

Table 1 MAGNETIC PROPERTIES OF SELECTED MINERALS*

Mineral	Formula	Magnetic structure	Curie/Néel temperature (°C)	Saturation magnetization ($A \cdot m^2/kg$)
OXIDES				
hematite	α-Fe_2O_3	canted antiferromagnetic	675	0.4
maghemite	γ-Fe_2O_3	ferrimagnetic	~600	70–80
ilmenite	$FeTiO_3$	antiferromagnetic	-233	0
magnetite	Fe_3O_4	ferrimagnetic	575–585	90–92
ulvöspinel	Fe_2TiO_4	antiferromagnetic	-153	0
magnesioferrite	$MgFe_2O_4$	ferrimagnetic	440	21
jacobsite	$MnFe_2O_4$	ferrimagnetic	~300	77
trevorite	$NiFe_2O_4$	ferrimagnetic	585	51
SULFIDES				
troilite	FeS	antiferromagnetic	305	0?
pyrrhotite	Fe_7S_8	ferrimagnetic	320	20
greigite	Fe_3S_4	ferrimagnetic	~333	~25
OXYHYDROXIDES				
goethite	α-FeOOH	antiferromagnetic/ weak ferromagnetic	~120	<1
feroxyhyte	δ-FeOOH	ferrimagnetic	~180	<10
lepidocrocite	γ-FeOOH	antiferromagnetic?	-196	?
METALS AND ALLOYS				
cobalt	Co	ferromagnetic	1131	161
wairauite	CoFe	ferromagnetic	986	235
iron	Fe	ferromagnetic	770	218
nickel	Ni	ferromagnetic	358	55
awaruite	Ni_3Fe	ferromagnetic	620	120
tetrataenite	FeNi	ferromagnetic	550	?

*Data compiled from Hunt et al. (1995)

The magnetic moment is generated via a quantum effect associated with electron spin (*S*). Each electron has a spin of 1/2 and generates a magnetic moment of one Bohr magneton ($1\ \mu_B = 9.274 \times 10^{-24}\ A \cdot m^2$). Fe^{3+} contains 5 unpaired electrons ($S = 5/2$) in the 3*d* shell, giving it a moment of 5 μ_B. Fe^{2+} contains 4 unpaired electrons, giving it a moment of 4 μ_B. In many elements there is an additional contribution to the magnetic moment from the orbital angular momentum of the electrons (*L*). In Fe^{3+}, the orbital contribution is absent because the 3*d* shell is exactly half filled and $L = 0$ (Fig. 2). In Fe^{2+} ($L = 2$), nearly all the orbital contribution is eliminated by electrostatic interaction with the surrounding oxygen ligands (a phenomenon known as "quenching"), leaving the spin contribution as the dominant source (95%) of magnetic moment.

In most Fe-bearing minerals, the magnetic moments on neighboring ions do not interact strongly with each other. In this case, thermal energy causes the moments to continuously change their orientation, leading to a dynamically disordered paramagnetic state with no spontaneous magnetization (Fig. 3). In magnetic minerals, however, the magnetic moments on neighboring atoms interact strongly, causing them to align either parallel or antiparallel to each other (see Box 1). This tendency to line up is overcome by thermal energy at high temperatures, leading once more to a disordered paramagnetic state. As the temperature decreases below a critical "Curie" or "Néel" temperature, however, the interactions dominate and the moments become spontaneously aligned. Depending on the nature of the interactions, a rich variety of ordered magnetic struc-

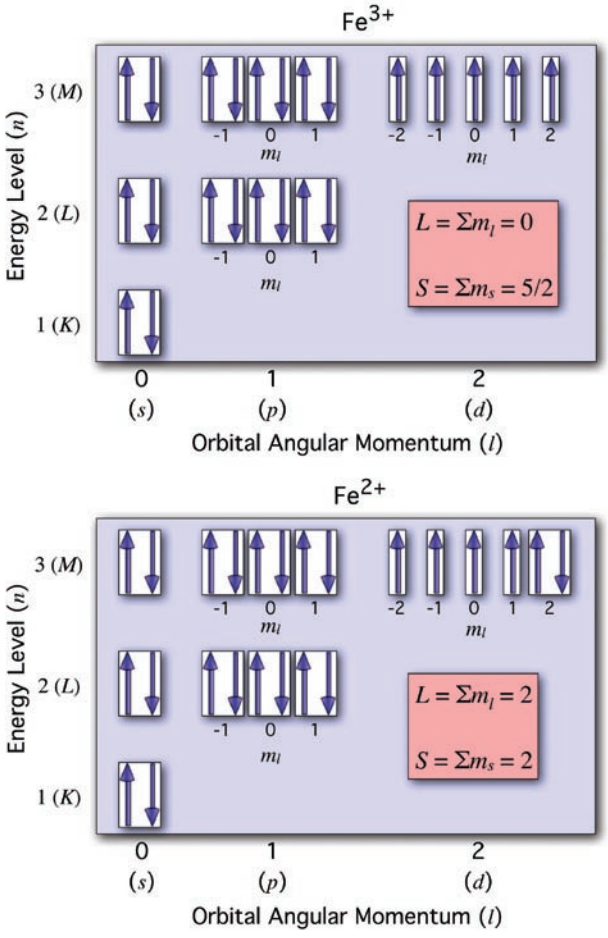


Figure 2 Electronic configuration of Fe^{3+} and Fe^{2+} cations. Arrows represent electrons with either an "up" or "down" spin of 1/2. The presence of unpaired spins in the 3*d* shell generates a magnetic moment of 5 μ_B and 4 μ_B in Fe^{3+} and Fe^{2+}, respectively.

tures may be obtained (Fig. 3), some of which generate a net spontaneous magnetization. In ferromagnets, all moments are aligned parallel to each other. Antiferromagnets consist of two equal and opposite magnetic sublattices, yielding zero net spontaneous magnetization. In ferrimagnets, as exemplified by magnetite, there is antiferromagnetic alignment between two sublattices of unequal magnitude, yielding a large net spontaneous magnetization. In the canted antiferromagnetic structure, as exemplified by hematite, spins are tilted by a fraction of a degree out of perfect antiparallelism, yielding a small net spontaneous magnetization (directed into the page in Fig. 3).

In the absence of an applied magnetic field, the magnetic moments in an ordered structure will lie along certain crystallographically defined "easy axes." This phenomenon, referred to as "magnetocrystalline anisotropy," is caused by coupling between the spin and orbital contributions to the magnetic moment. Each structure has two or more energetically favorable easy directions for magnetization, separated by energetically unfavorable "hard axes." The variation in energy as a function of magnetization direction can be illustrated as a surface consisting of energy minima (the easy axes) separated by energy barriers (the hard axes) (Fig. 4). Anisotropy is one of the most important concepts in mineral magnetism. Once a grain has been magnetized along a particular easy axis (e.g. by the application of an external magnetic field), the magnetization direction will remain fixed so long as the energy barriers are higher than the available thermal energy. In this state the grain is said to be "blocked," and the remanent magnetization it carries will remain stable over millions, potentially even billions, of years. If the temperature is raised above the grain's "blocking temperature," thermal energy will cause the magnetization direction to "unblock" and flip between alternate easy axes, and the remanence will be lost. This state is known as "superparamagnetic." Hence, anisotropy is crucial to the process of acquiring a remanent magnetization: without it, the field of paleomagnetism would simply not exist.

For many minerals, such as magnetite, the magnetocrystalline anisotropy alone is not sufficient to create an efficient paleomagnetic recorder. In this case, an extrinsic source of anisotropy comes to the rescue, provided by the elongated shape of individual grains. Anyone who has tried to magnetize a steel needle by stroking it with a bar magnet will be familiar with the fact that an elongated body has a natural tendency to become magnetized along its length rather than perpendicular to it. The origin of this "shape anisotropy" can be visualized in terms of the magnetic poles that are generated at the surface of a uniformly magnetized grain (see Box 2). For an infinitely long needle, the energy required to magnetize it parallel to its length is a factor of 2 smaller than that required to magnetize it perpendicular to its length. To put this into context, the corresponding magnetic field needed to reverse the magnetization direction of an infinitely long needle of magnetite would be 300 millitesla (mT), i.e. around 4 orders of magnitude larger than the Earth's magnetic field.

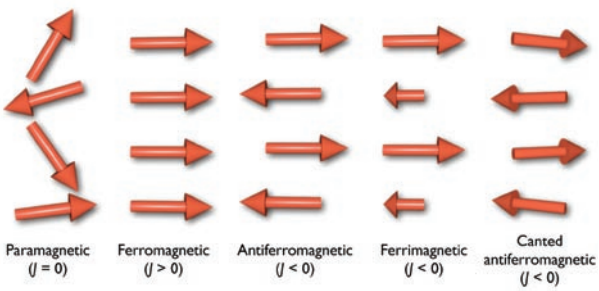


Figure 3 Examples of disordered and ordered magnetic structures. Arrows represent the directions of atomic magnetic moments. J = exchange integral

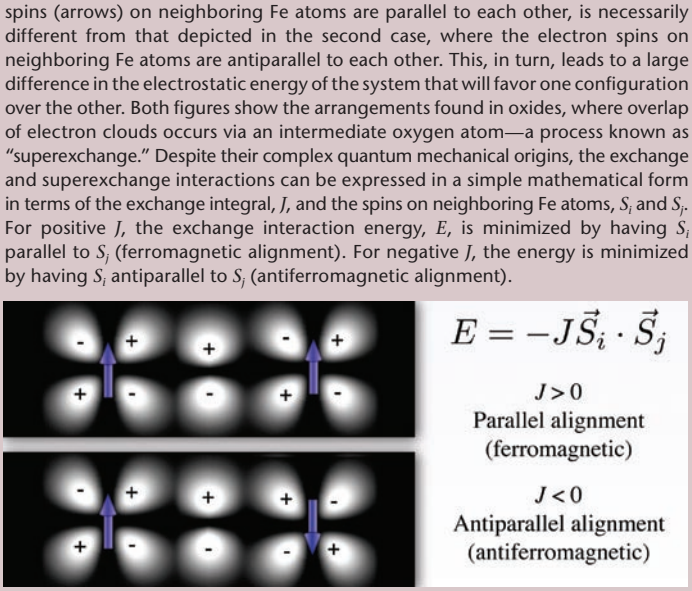
The equilibrium magnetic state of a grain is obtained by minimizing the sum of four main energies:

- The **exchange energy** (Box 1) drives magnetic ordering and can be minimized by keeping neighboring magnetic moments either parallel or antiparallel to each other depending on the type of magnetic order.
- The **anisotropy energy** (Fig. 4) is minimized by keeping the magnetization oriented along an easy axis.
- The **demagnetizing energy** (Box 2) is minimized by keeping surface poles of opposite charges as far apart as possible or by eliminating them altogether by the formation of magnetic domains.
- The **magnetostatic energy** (Box 3) represents the effect of an external field and is minimized by aligning the magnetization of the grain parallel to the applied field (just as a compass needle rotates to point along the magnetic field of the Earth). The field experienced by a given grain includes both the external field (e.g. the geomagnetic field) plus any interaction fields generated by other magnetic grains in the rock.

These energies can be calculated effectively using computers (Fig. 5). The results of such calculations depend greatly on the size and the shape of the grain. For grains smaller than a critical size (around 65 nm for an equidimensional grain of magnetite), the exchange energy dominates the demagnetizing energy, and the grain is uniformly magnetized along an easy axis. Such grains are referred to as single-domain (SD) grains. For particles approaching the critical size, the demagnetizing energy starts to dominate. The magnetization becomes non-uniform as the grain attempts to eliminate surface poles. This process begins as a slight "flowering" or deflection of the magnetization towards the magnetized surfaces (Fig. 5a). Above the critical size, the flower state becomes unstable with respect to the highly non-

Box 1 THE EXCHANGE INTERACTION

The ordering of magnetic moments is driven by a quantum effect known as "exchange." When the electron clouds of atoms overlap, the distribution of electrons across the system as a whole must obey the Pauli exclusion principle (no two electrons may occupy the same quantum state). This means that the distribution of electron density for the first case depicted below, where the electron spins (arrows) on neighboring Fe atoms are parallel to each other, is necessarily different from that depicted in the second case, where the electron spins on neighboring Fe atoms are antiparallel to each other. This, in turn, leads to a large difference in the electrostatic energy of the system that will favor one configuration over the other. Both figures show the arrangements found in oxides, where overlap of electron clouds occurs via an intermediate oxygen atom—a process known as "superexchange." Despite their complex quantum mechanical origins, the exchange and superexchange interactions can be expressed in a simple mathematical form in terms of the exchange integral, J, and the spins on neighboring Fe atoms, S_i and S_j. For positive J, the exchange interaction energy, E, is minimized by having S_i parallel to S_j (ferromagnetic alignment). For negative J, the energy is minimized by having S_i antiparallel to S_j (antiferromagnetic alignment).



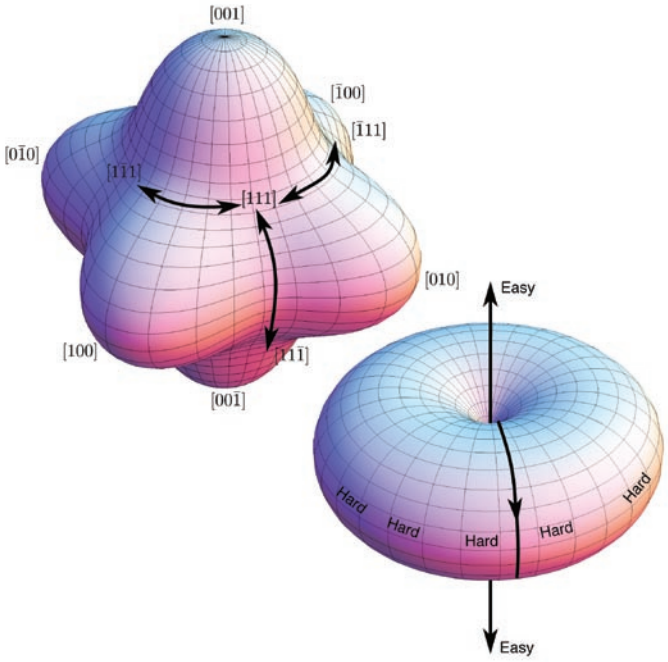
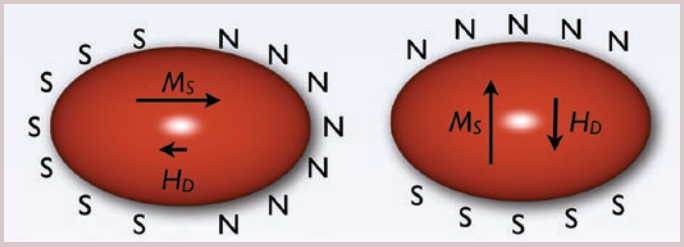
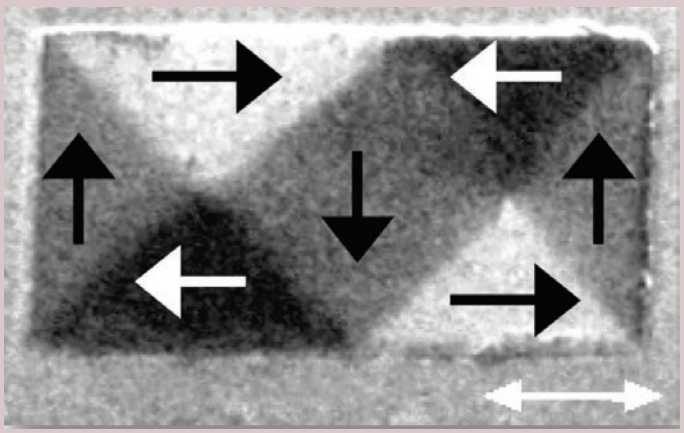


Figure 4 Energy surfaces illustrating the concept of magnetic anisotropy. The energy is highest when the system is magnetized along a "hard" direction and lowest when magnetized along an "easy" direction. The upper figure illustrates the magnetocrystalline anisotropy of magnetite at room temperature (easy axes are <111>, hard axes are <100>). The lower figure illustrates the uniaxial shape anisotropy associated with an elongated needle of magnetite. The easy axis is parallel to the elongation direction.

Box 2 THE DEMAGNETIZING FIELD

When the magnetization of a grain (M_S) intersects a surface, the normal component of magnetization creates a surface density of N or S magnetic "charges" or "poles." When the grain is magnetized along its length, N and S surface poles are separated by a greater distance than when the body is magnetized perpendicular to its length. The surface poles generate an internal magnetic field (pointing from N to S) that opposes the direction of magnetization of the grain. This demagnetizing field (H_D) is smaller when the surface poles are further apart, so the demagnetizing energy of the grain is low when it is magnetized along its length and high when magnetized perpendicular to it. The demagnetizing energy can be completely eliminated by subdividing the grain into a number of uniformly magnetized domains separated by domain walls, such that the magnetization remains parallel to the surface at all points.





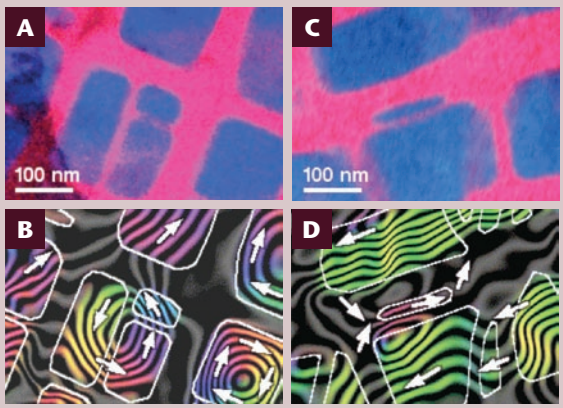
uniform vortex state (Fig. 5b), whereby the magnetization curls round a central magnetic core, eliminating the majority of surface poles and minimizing the demagnetizing energy at the expense of the exchange and anisotropy energies. Such grains are referred to as pseudo-single-domain (PSD) grains. It is possible, however, for the SD state to remain metastable up to an upper critical size, especially if the grain interacts strongly with the magnetic fields generated by neighboring grains (Box 3). For very large grains, the energy is efficiently minimized by subdividing the grain into a number of uniformly magnetized domains separated by domain walls (see Box 2). These are referred to as multidomain (MD) grains.

SD grains are the holy grail of rock magnetism. They give rise to highly stable remanent magnetizations, and their behavior as a function of temperature, time, and applied field can be predicted exactly using well-established theories (based on the pioneering work of Louis Néel). In fact, many established paleomagnetic techniques, such as those used to determine the paleointensity of the geomagnetic field, only work if the rock contains predominantly SD grains. Unfortunately, the vast majority of natural samples contain a wide distribution of grain sizes, which are often predominantly in the PSD-MD state. Accounting for the presence of such grains and selectively demagnetizing their contributions is one of the main challenges in rock and mineral magnetism.

Box 3 MAGNETIC INTERACTIONS AND MAGNETIC SUPERSTATES

A magnetic grain acts as a mini bar magnet, generating an external magnetic field around it that may attract or repel neighboring magnetic grains. The image below shows the magnetic flux in and around a 50 nm diameter grain of magnetite extracted from a magnetotactic bacterial cell. The grain is below the threshold size of single-domain behavior and is therefore uniformly magnetized internally. The dipole-like external magnetic field generated by the grain is clearly resolved using electron holography.

Magnetic interactions between grains become very important when the separation between grains is less than their size. The four images below show the distribution of magnetic flux in a natural exsolution intergrowth of magnetite (blue regions in **A** and **C**) within a matrix of paramagnetic ulvöspinel (Harrison et al. 2002). In **B**, we see two 100 nm blocks of magnetite at the right edge of the image that are above the critical size for single-domain behavior and that contain conventional vortex states. The magnetite block at the top is in a metastable single-domain state. In the center, a group of three magnetite blocks that individually would be below the single-domain threshold collectively form a vortex "superstate" due to the strong magnetostatic interactions between them. In **D,** we see a small elongated particle forced to become magnetized antiparallel to the larger adjacent blocks by their dipole interaction fields.



NEW DEVELOPMENTS

As we continue to push the boundaries of what can be achieved using rock and paleomagnetic techniques, mineral magnetism becomes increasingly important. Recent attention has been focused on processes occurring at the nanometer scale. Nanoscale microstructures are common in magnetic minerals and have a profound impact on their macroscopic magnetic properties. Arguably the most significant recent advance in mineral magnetism is the application of off-axis electron holography, a transmission electron microscopy (TEM) technique that yields a two-dimensional map of magnetization vectors with nanometer spatial resolution. Electron holography is capable of imaging the magnetization states of individual magnetic particles and the magnetostatic interaction fields between neighboring particles—two factors that play a central role in the interplay between magnetism and microstructure.

Imaging Magnetic Flux at the Nanometer Scale

The grain sizes of primary magnetic minerals in most igneous and metamorphic rocks exceed the MD threshold. Such rocks are less likely to maintain strong and stable natural remanent magnetization (NRM) over geological times than those containing SD grains. It has long been proposed, however, that solid-state processes such as subsolvus exsolution can transform an MD grain into a collection of SD grains, thus increasing the stability of the NRM (Davis and Evans 1976). This transformation is brought about by the formation of intersecting paramagnetic exsolution lamellae, which divide the host grain into a three-dimensional array of isolated magnetic regions that have SD-PSD sizes. An excellent example of this phenomenon occurs in the magnetite–ulvöspinel (Fe_3O_4–Fe_2TiO_4) solid solution (Davis and Evans 1976; Price 1980). This system forms a complete solid solution at temperatures above ~550 °C but unmixes at lower temperatures (Ghiorso 1997). Intermediate bulk compositions exsolve during slow cooling to yield an intergrowth of SD- or PSD-sized magnetite-rich blocks that are separated by non-magnetic ulvöspinel-rich lamellae. FIGURE 6 illustrates the typical microstructure observed in a natural sample of exsolved titanomagnetite (Harrison et al. 2002). This image is a composite chemical map, obtained using energy-filtered TEM imaging, showing the distribution of Fe in blue (magnetite) and Ti in red (ulvöspinel). Ulvöspinel lamellae form preferentially parallel to {100} planes of the cubic magnetite host lattice. In TEM sections that are oriented parallel to {100}, this symmetry generates a rectangular array of cuboidal magnetite blocks.

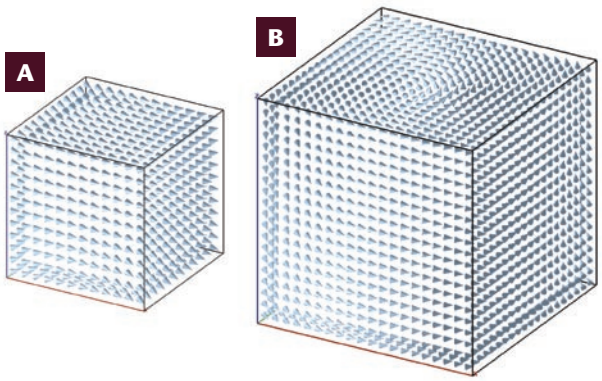


FIGURE 5 Micromagnetic simulations showing (**A**) a flowered SD state in a 60 nm magnetite cube and (**B**) a vortex state in a 100 nm magnetite cube

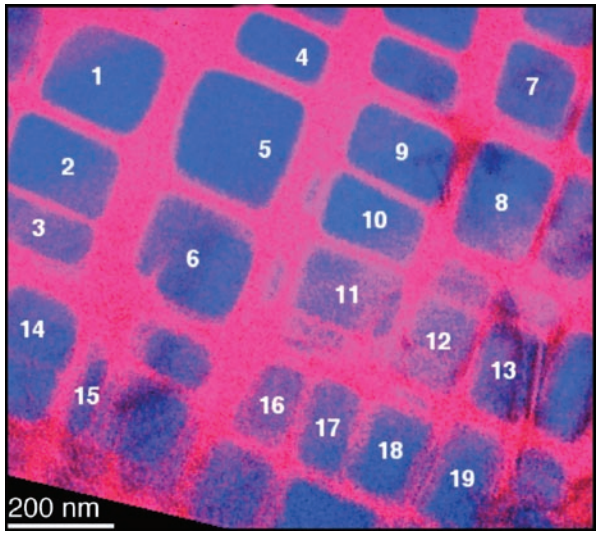


FIGURE 6 Composite chemical map (Fe = blue, Ti = red) of an exsolved titanomagnetite crystal, showing magnetite blocks within a paramagnetic ulvöspinel matrix

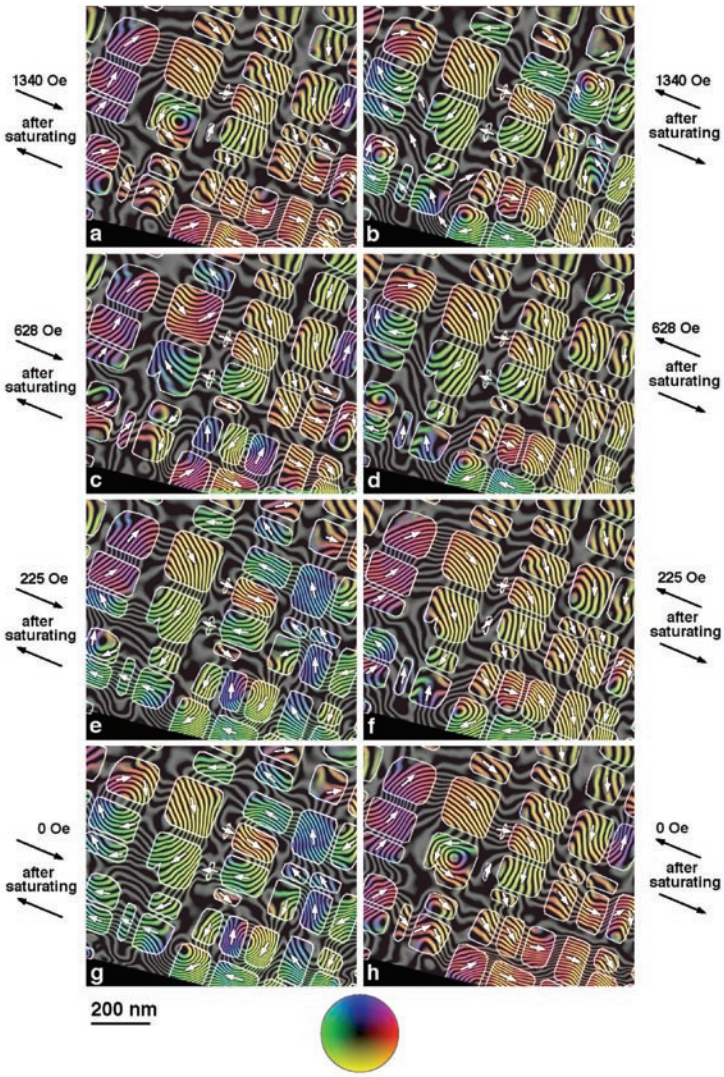


FIGURE 7 Magnetic phase contours from the region shown in Figure 6, measured using electron holography. The outlines of the magnetite-rich regions are marked in white, while the direction of the measured magnetic induction is indicated both using arrows and according to the color wheel shown at the bottom of the figure (red = right, yellow = down, green = left, blue = up). A, C, E, G: obtained after applying a large (1 T) magnetic field towards the top left, then the indicated field towards the bottom right (Oe = oersted). B, D, F, H: obtained after applying identical fields in the opposite directions.

Harrison et al. (2002) used electron holography to determine the magnetic remanence states of this intergrowth (Fig. 7). The magnetite blocks were found to be primarily in SD states. The dimensions of the blocks indicate that the vast majority would display vortex states at remanence if they were isolated and at equilibrium. Strong interactions between the blocks helps to stabilize the SD state, as illustrated in Figure 8. Several blocks act collectively to form magnetic "superstates" that would normally be observed in a single, larger magnetized region. One example is where two or more blocks interact to form a single vortex superstate (see Box 3). Two-, three-, and five-block vortex superstates are visible in Figure 7 (e.g. blocks 1 and 2 in G and blocks 1, 2, 3, 5, and 6 in E; refer to Fig. 6 for block numbering). At first glance it appears that the resulting remanences of interacting magnetic grains would be zero, but it is important to emphasize that certain superstates do produce useful, finite remanences.

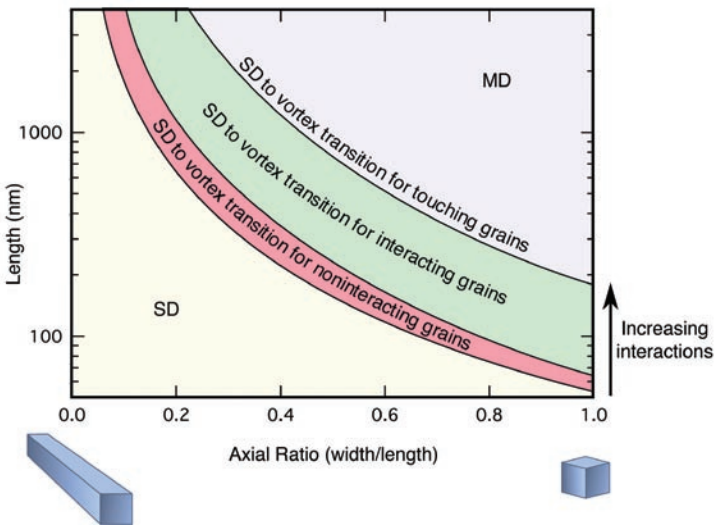


Figure 8 Calculated magnetic domain state as a function of particle size, shape, and interparticle spacing. Modified from Muxworthy and Williams (2006)

FUTURE DIRECTIONS

Research in mineral magnetism is expanding at an astonishing pace on a variety of fronts, only some of which are described in this issue. Workers are adopting tools from complementary disciplines as they try to explore the effects of nanometer-scale mineral structures on magnetic behavior. One promising technique from the materials science community is focused ion beam (FIB) thinning, whereby a beam of ionized gallium atoms is targeted at a region of interest and is used to carefully carve electron-transparent wafers suitable for TEM analyses. This allows researchers to study only those areas that are pertinent to their research and is an improvement over traditional argon ion milling.

Another exciting development is quantitative scanning SQUID microscopy (Rochette et al. 2009 this issue), which has the potential to enable paleomagnetic studies at the 100-micron length scale. Such scanning techniques open the door to mapping remanent magnetism over the area of a standard thin section.

The field of environmental magnetism continues to mature as researchers aspire to link changes in the magnetic properties of soils and sediments more directly (and quantitatively) to chemical and granulometric alteration caused by climate change and anthropogenic pollution (see Maher 2009 this issue).

We hope that this issue of *Elements* conveys some of the excitement in the field of mineral magnetism and that it demonstrates how the properties of magnetic minerals can be used to learn about an incredibly broad range of geologic processes, ranging from biomineralization to climate change to planetary geology.

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GLOSSARY

Anhysteretic remanence (ARM) – An artificial remanence produced by exposing a sample to an alternating magnetic field of steadily decreasing amplitude in the presence of a small DC bias field. ARM is carried most efficiently by SD grains.

Anisotropy – Refers to the fact that the energy of a magnetic particle varies according to the orientation of its magnetic moment

Antiferromagnetic – A state of magnetic order in which two ferromagnetic sublattices of equal magnitude are aligned antiparallel to each other

Blocking temperature – The temperature below which a particle's magnetic moment becomes permanently oriented along an easy direction. Above the blocking temperature, thermal activation causes the moment to continuously switch between alternative easy directions.

Bohr magneton – The magnetic moment associated with a single unpaired electron ($1\ \mu_B = 9.274 \times 10^{-24}$ A·m^2)

Canted antiferromagnetic – A derivative of the antiferromagnetic state, whereby the two ferromagnetic sublattices deviate from perfect antiparallelism, leading to the generation of a small net magnetic moment

Chemical remanent magnetization (CRM) – A remanent magnetization acquired as magnetic minerals undergo some chemical change (e.g. oxidation) in the presence of a magnetic field

Coercivity – The magnetic field required to reduce the magnetization of a material to zero (after it has been exposed to a saturating field)

Curie temperature – The temperature above which the spontaneous alignment of magnetic moments in a ferromagnetic or ferrimagnetic material is lost

Demagnetizing field – The magnetic field that is generated inside a magnetized body by the presence of uncompensated magnetic poles on its surfaces. The demagnetizing field varies according to the geometry of the particle and the direction of magnetization, leading to shape anisotropy.

Detrital remanent magnetization (DRM) – The acquisition of remanence caused by physical rotation and alignment of magnetic particles in the presence of a magnetic field as they are deposited to form a sediment

Easy axis/axes – The most energetically favorable direction(s) for the magnetic moment of a particle

Ferrimagnetic – A state of magnetic order in which two ferromagnetic sublattices of unequal magnitude are aligned antiparallel to each other

Ferromagnetic – A state of magnetic order in which the magnetic moments are aligned parallel to each other. This leads to a large spontaneous magnetization.

Frequency-dependent susceptibility – Describes the difference in magnetic susceptibility of a material measured using alternating magnetic fields with different frequencies. Often used to identify the presence of SP grains close to their blocking temperature.

Hard axis/axes – The most energetically unfavorable direction(s) for the magnetic moment of a particle

Low-temperature susceptibility – Measurement of magnetic susceptibility below room temperature. Often used to detect the presence of minerals, such as magnetite and hematite, that display characteristic behavior at low temperatures.

Magnetic field – A vector field that surrounds magnets and electric currents. When placed in a magnetic field, magnetic dipoles tend to align their axes parallel to the field. Magnetic fields can be defined either in terms of the "H" field, measured in A/m, or in terms of the "B" field, measured in teslas (T) (note $B = \mu_0 H$, where μ_0 is the permeability of free space).

Magnetic moment/dipole moment – Quantifies the magnitude and direction of a body's magnetism and hence the strength and orientation of the dipolar magnetic field generated around it. Magnetic moments are measured in A·m^2.

Magnetic susceptibility – Measures the increase in magnetization of a material per unit applied magnetic field. For volume-normalized magnetization, susceptibility is a dimensionless quantity. For mass-normalized magnetization, susceptibility is expressed as m^3/kg.

Magnetization – Expressed as the magnetic moment per unit volume (A/m). Sometimes measurements of magnetic moment are normalized by the mass of the sample rather than by its volume, yielding units of A·m^2/kg.

Magnetocrystalline anisotropy – Anisotropy caused by the coupling between the spin and orbital contributions to the magnetic moment of an atom

Natural remanent magnetization (NRM) – A generic term referring to the remanent magnetization acquired by a rock through natural processes (as apposed to artificial remanence imposed by a laboratory field)

Néel temperature – The temperature above which the spontaneous alignment of magnetic moments in an antiferromagnetic material is lost

Orbital momentum – The angular momentum associated with electrons orbiting a nucleus, leading to the generation of an orbital magnetic moment

Paramagnetic – A state of magnetic disorder in which the magnetic moments are randomly oriented due to thermal agitation

Quenching – The reduction of the orbital contribution to the magnetic moment of an atom caused by interaction of its outer unpaired electrons with the electron clouds of surrounding ligands

Remanent magnetization/remanence – The magnetization of a particle that remains after a magnetizing field has been switched off

Shape anisotropy – Anisotropy related to the shape of a magnetic particle. Its origin is the shape dependence of the demagnetizing field.

Shock remanent magnetization (SRM) – Remanence acquired by a material as it is exposed to a physical shock; especially important in meteorites

Spin – The quantum property of particles such as electrons and neutrons that causes them to possess an intrinsic magnetic moment

Thermoremanent magnetization (TRM) – A remanent magnetization acquired as magnetic minerals are cooled through their blocking temperature in the presence of a magnetic field

Viscous remanent magnetization (VRM) – A gradual buildup of remanence over time at a given temperature as magnetic minerals are exposed to a constant magnetic field

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