Preview

ISSN: 1443-2471 (Print) 1836-084X (Online) Journal homepage: https://www.tandfonline.com/loi/texp20

Haematite: the Bloodstone

Don Emerson

To cite this article: Don Emerson (2017) Haematite: the Bloodstone, Preview, 2017:191, 43-53, DOI: 10.1071/PVv2017n191p43

To link to this article: https://doi.org/10.1071/PVv2017n191p43

Published online: 16 Jan 2019.

Submit your article to this journal

Article views: 2359

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=texp20

10.1071/PVv2017n191p43

Haematite: the bloodstone

Don Emerson
systemsnsw@gmail.com

Introduction

Any appreciation of significant members of the mineral kingdom should include the humble and ubiquitous sesquioxide of iron, Fe_2O_3 or haematite, also known as the bloodstone. Humble it may be, but its roles in human culture, science, and commerce compare well with any other mineral.

Polycrystalline dark metallic haematite has a distinctive red streak when scratched; when cut it seems to bleed with the saw coolant turning red. In thin plates it is translucent and red. Amorphous earthy haematite can range in colour, on the Munsel scale, from light to dark red.

The ancient Greek for blood is αἷμα, genitive case αἵματος, and it is from this ("of blood") that the name haematite derives; *haematites* in later Latin. Theophrastus (c370-c287BC), Aristotle's pupil and colleague, noted in an abbreviated treatise on stones: "and the haimatitis is a compact material with a rough appearance; and as its name suggests, seems to be made of dried coagulated blood" (πυκνὴ δὲ καὶ αἱματῖτις· αὕτη δ' αὐχμώδης καὶ κατὰ τοὔνομα ὡς αἵματος ξηροῦ πεπηγότος). Caley & Richards (1956), and others, have proposed that Theophrastus was referring to jasper, which is a red chert associated with sedimentary iron beds and comprising mainly cryptocrystalline quartz coloured by iron oxides. Possibly so, but in jaspilites (or banded iron formations) some jaspers can be highly haematitic, (Joplin, 1968), and quite red in colour. A typical haematitic banded iron formation (BIF) is shown in Figure 1.

Three types of haematite can be distinguished visually by colour. Each also has a lustre, which is a qualitative description of the nature and degree of light reflectance from a material's surface dependent on surface smoothness, refractive index, and absorption coefficient (Bloss, 1971). Earthy red haematite has no lustre and appears dull because its myriad sub-microscopic component particles present an optically rough surface to the viewer. Specular grey-black haematite has a metallic to metallic-splendent lustre (*specularis* is Latin for mirror). Steely black haematite with its polygonal structure has a submetallic to metallic lustre. These three categories, in the writer's experience, also usefully serve as resistivity indicators for solid materials in the dry state.

A succinct summary of haematite as a formal mineral can be found in Deer et al. (1992). Details of Australia's commercial haematites can be found in Harmsworth et al. (1990), Yeates (1990), and in many other publications on iron enrichment in the banded iron formations of Precambrian basins. Selected physical features of haematite are given in Table 1.

This article, following the writer's whim, and making no claims to be comprehensive, cherry-picks its way, with a couple of digressions, through haematite's history, lore, and properties.

Red

In the visible spectrum, humankind could, perhaps, manage without indigo, but not without red. For centuries it has ranked high as a colour, which has many shades; it can be dynamic, evocative, stimulating, and emotive. Around the 8th c. BC, in *The Iliad and the Odyssey*, Homer mentions red ochre (μίλτος) as a distinguished colour painted on ships, but elsewhere in his epics Homer did not much refer to colour. In life we respect the Red Cross and its humanitarian works; we delight in the tinted clouds of a sunrise and a sunset; we never tire of gazing at the rainbow with its outer convexity so diffusely red; we gaze in wonder at Jupiter's huge red spot, origin unknown; a red flag alerts us to danger; and red is a common colour in the sunburnt vastness of the Australian outback where the Sturt's desert pea surprisingly thrives, spectacularly red-petaled, on arid sands; and red cliffs overhang the Kimberley's free running water holes.

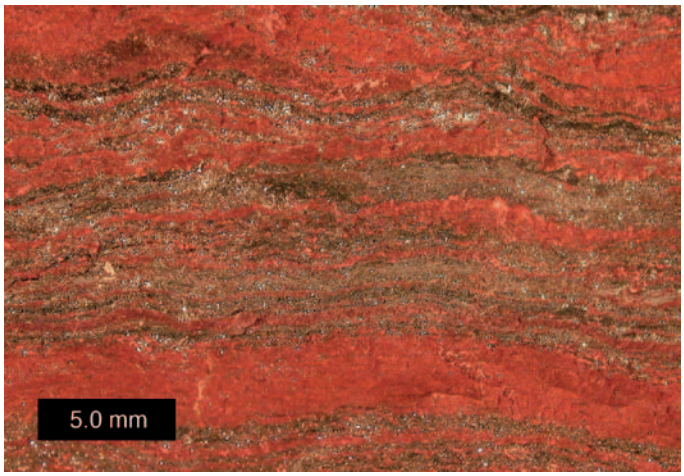

Figure 1. *Haematite in Precambrian iron formation from Upper Michigan, Lake Superior region USA. Photograph taken by Mark A. Wilson, https://commons.wikimedia.org/wiki/File:MichiganBIF.jpg.*

Table 1. Haematite Fe_2O_3

Chemistry	Iron sesquioxide Fe 70%, O 30%	Common iron oxide, which can contain some Ti, an abundant iron ore
Crystallography	Trigonal (hexagonal-scalenohedral)	Crystals thin to thick tabular, but not all that common
Features		
Colour	Red to black	Red ochre (reddle) is an earthy haematite
Hardness (Moh scale)	6 ±	Conchoidal fracture, brittle yet tough
Streak	Distinctive Indian-red	Ti varieties: black streak
Physical forms	Granular Platy Micaceous Reinform/botryoidal Specular Earthy and/or pisolitic	Massive Micro, meso Foliated Fibrous kidney ore Aggregation of thin platy crystals Ochreous
Galvanic elec. Petrophysics categories	Grey-black, specular *Metallic-splendent lustre*	Euhedral, well crystallised, platy aggregates, lustrous shiny, grain sizes fine to coarse
	Steely-black *(Sub) metallic lustre*	Anhedral, to subhedral, fairly well crystallised, interlocking equant grains, polycrystalline mosaic, fine to medium grain size
	Earthy-red *Dull (no lustre)*	Crypto-crystalline to amorphous, extremely fine grain sizes, microporous, diffuse particle boundaries
Density	5.26 g/cc	For crystals, zero porosity solid haematite
Mag. susceptibility, k	$100–1000 \times 10^{-5}$ SI common range, but can be higher, see Hrouda (2002)	Weakly to moderately susceptible, but if Ti present (ilmeno haematite) or trace amounts of magnetite or maghaemite → higher mag k
Remanence, Qn	300 ±	Qn = modulus of J_{NRM}/J_{IND}, J: vector, intensity of mag. J_{NRM}: remanence, can be strong J_{IND}: k F (F, earths field) induced mag.
Conductivity/resistivity	Varies with crystallinity	To be discussed herein

Notes:
• Haematite here is α Fe_2O_3, it is one of the iron oxide "ferromagnetics" (actually canted antiferromagnetic). Maghaemite, γ Fe_2O_3, has haematite's chemistry and magnetite's spinel structure, it is a dense (~4.8 g/cc), red-brown mineral that is very magnetic (not dealt with in this article). See Clark (1997) for a comprehensive discussion of the magnetic properties of iron oxide minerals.
• Goethite, α FeO(OH), a very common mineral, dehydrates to haematite α Fe_2O_3. Lepidicrocite, γ FeO(OH), dehydrates to maghaemite, γ Fe_2O_3. Magnetite, Fe_3O_4, oxidises to haematite (martite) or to kenomagnetite, an intermediate phase between magnetite and maghaemite. Sometimes the low mag k of a haematite host is increased by trace amounts of magnetite and/or maghaemite. See the iron ore literature for details.
• The convenient galvanic petrophysical categories are subjective and based on the writer's experience. Others may prefer a different categorisation.

In matters culinary: raw red steak is the principal meat on any barbeque; red chilli spices our food; at football matches and fairgrounds the hot dog's red frankfurter sustains the enthusiasm of attendees; the glistening dollop of a rich tomato sauce so savours that iconic edible – the Australian meat pie; and the inedible red herring diverts us from our proper purpose. For literature, red is such a handy hue. On the sacred side: the strawberry, red and fragrant, was the symbol of perfect righteousness in medieval art (Post, 1974). Rubrics are the ceremonial directions, written in red, in books of Christian religious rituals, a practice deriving from the ancient Roman lex *rubr(ic)a* – the first words (or more) of a law were written in red, probably with a red ochre paint as *rubricia* is the Latin for red ochre. In medieval manuscripts such as psalters, some of the pigments in illustrations are derived from haematite. The American poet Edwin Markham in 1901 wrote of President Lincoln: "… the colour of the ground was in him, the red earth/ the smack and tang of elemental things …" On the profane side: in Dante's *Inferno*, written around 1314 (see Durling, 1996), the three-throated hell-hound Cerberus has red eyes (canto 6) and one of the three faces on Satan's head is red (representing hatred, canto 24). In *Lolita*, Vladimir Nabokov's 1959 novel, the eponymous, lip-sticked, pink clad nymphet, by playing with an Eden-red apple, induces cardiac quickening in the depraved Humbert Humbert. The vision of the deplorable Roger Micheldene, the lead character in Kingsley Amis' 1963 story, *One Fat Englishman*, is frequently impeded by the red mist of rage rising before his eyes as he waddles, vexatious, from bed to bottle to brawl. Red, as can be seen, is a powerful signifier in human affairs.

In the mineral world, vibrant scarlets are derived from poisonous red lead (Pb_3O_4) and unstable cinnabar (HgS). But for the writer, the rubescence that excels lies in the earthy form of the mineral that sells so well on international markets – robust, brick-red haematite. Published statistics (Resources and Energy Quarterly, March 2017) indicate an Australian production of about 850 000 000 tonnes of iron ore (haematite mainly, and other iron oxides) valued at $72 000 000 000. It is by far our most important individual exported resource, contributing significantly to Australia's prosperity. Haematite has a solid, subdued red, it is not flashy; it is a natural colour of substance. This pleasing and stable shade has been attractive to generations of humankind; it is also a very interesting mineral in other respects.

Red ochre

Ochre is simply a metallic (usually Fe) oxide, in varying amounts, in a base of powdery clay; sometimes the base is chalk. It is an earthy pulverulent, i.e. easily powdered. Haematite (Fe_2O_3) is the oxide in red ochre (reddle, ruddle); goethite FeO(OH) is in yellow/brown ochre. Haematite is the end point of iron oxidation mineralogy in highly weathered environments. Goethite dehydrates to haematite, either naturally in a weathered profile, or by heating in a mill; $2FeO(OH) \rightarrow Fe_2O_3 + H_2O$. The

purest red ochre is mainly just haematite, but this is rare. Red ochre, with up to about 75% haematite, tends to occur in discrete pockets or seams, mined locally, since pre-history, to be used as a pigment, an adornment (of objects or bodies), and in rituals.

Tradition has it that European iron was first discovered in the ashes of a large fire built close to a red ochre deposit: $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$. When the paint-rock and the fire were realised to be the cause, and metal the effect, crude rock furnaces were designed to produce a material whose utility is valued to this day.

The extraordinary cultural role of red ochre in rituals and funerary practices from pre-historic times is documented by Clifford (2012) who argues for its worldwide symbolic use in the Palaeolithic (Old Stone Age), and later. From 100 000 years BP onwards there is evidence of widespread funerary use where red ochre (and, sometimes, pure haematite) was sprinkled on and/or under the deceased. Clifford maintains that the ochre represented the life-giving energy of real blood and so facilitated rebirth in the after-life, a posited belief of early religion (but this is by no means the only interpretation advanced by archaeologists). Apparently, in some regions, the practice continues to the present.

A local example of the red ochre funerary traditions is at Lake Mungo in western NSW. Here the remains of a male who died ~40 000 years BP were found coated with red ochre applied at the time of burial.

In Australia red ochre was and is an important mineral for Aboriginal people. Paterson and Lampert (1985) note its wide use and provide details of a small mine still used by Warlpiri men. The mine is a hillside excavation in the Campbell Ranges, northwest of Alice Springs, NT. The Warlpiri gouge small parcels of the lumpy powdery ore, which is taken outside in buckets and then ground into a fine powder by hammering and abrasion. The seam of ochre contains a soft, mica-speckled haematite and lies at the base of a sequence of quartzite, haematitic sandstone, and pebbly conglomerate. Red ochre has dreaming stories associated with it (Finlay, 2004). Many stories involve the spilling of blood from the slaughter of an animal such an emu or a dog, or from a man. The ochre is the congealed blood.

Pictographs are a type of ancient rock art where pigments have been applied to stone surfaces (Voynick, 2017). Over millennia, different cultures in all the settled continents have left countless sites adorned with symbols and artwork of great interest to archaeologists. To make paint haematite ochre was dispersed as a slurry in a base of water, or suspended in animal fat, or liquid raw material such as seal oil, linseed oil, gum or egg. Variations in local recipes, ochres, and bases gave rise to a range of red colours that survive to this day. Figure 2 shows two haematite pictographs from the Northern Territory in Australia, and one from Spain.

Figure 2. *Pictographs: (a) painting of Dreamtime shapes in rock art at Nurlangie NT, red ochreous haematite pigment (source: Shutterstock.com), (b) red ochre fish. (source: https://commons.wikimedia.org/wiki/File:Red_ochre_fish_-_Google_Art_Project.jpg), (c) painting of a bison in haematite ~16 000 BC, cave of Altamira, Spain, red ochreous haematite pigment (source: https://en.wikipedia.org/wiki/File:Lascaux2.jpg).*

The ancient Mediterranean world

Haematite was a significant mineral in antiquity. Iron ores in ancient Europe seem to have been plentiful in the form of siderite ($FeCO_3$) and limonite/goethite ($FeO(OH)$). Rich deposits of haematite (including the specular variety), mined for centuries, occur on the Isle of Elba just off the west coast of Italy. Secondary haematite would also have been common in the form of cappings, crusts, pockets, and veins formed in the weathering and alteration of iron and other metallic ores (Bateman, 1959).

Celsus (fl AD14–37), in his encyclopaedic compilation on ancient medicine, notes haematite's use as an exedent (to eat

away morbid flesh) and as purgative or cleansing agent (Spencer, 1938).

Pliny the Elder (AD23–79) describes haematite in several passages of Books 33, 36, 37 of his *Natural History*, an extensive compilation of facts and factoids (Rackham, l984; Eicholz, 1971). Pliny's commentary suggests that haematite would have been an ore of iron, and notes its use as a pigment, but it was its application in quite bizarre medications attracted the attention of literary types. Pliny mentions several claims as to haematite's efficacy in treating eye, bladder, blood, and liver problems, burns also; and its use as an ointment beneficial in battle.

The medieval world

The medieval world, like antiquity, was well aware of and interested in mineralogy and stones; much was written about them. Marbod (1035–1123), Bishop of Rennes in Brittany, in his famous book on 62 stones and gems, *Liber Lapidum,* devotes 20 lines of hexameter verse to haematite. Beckmann (1799) compiled and edited Marbod's mineral poems and supplied useful footnotes. The 32nd poem (lines 476–495) is *De haematite*:

Sumsit haematites graecum de sanguine nomen,
Naturae lapis humanae servire creatus,
Styptica cui virtus per multa probatur inesse;
Nam palpebrarum superillitus asperitatem,
Et visus hebetes, pulsa caligine, sanat,
Eius rasurae si glarea mixta sit ovi.
Succo dilutus, quem punica mala remittunt,
In medicinali valet ad collyria cote,
Vel resolutus aqua, iuvat hos, qui sanguinis ore
Spumas emittunt, et quae sunt ulcera curat.
Potatus stringit patitur quem femina fluxum,
Carnes crescentes in vulnere, pulveris huius
Vis premit, et ventrem retinet sine mora fluentem,
Vino dilutus veteri bibitusque frequenter.
Serpentis morsum, vel quod fit ab aspide vulnus,
Egregie curat, resolutus aquis et inunctus.
Mixtus melle potest oculos sanare dolentes.
Vesicae lapidem bibitus dissolvere fertur.
Hic ferrugineo rufove colore notatur.
Africa mittit eum, sed et Aethiopes, Arabesque.

Haematite derived its name from the Greek noun for blood;
a stone created to help humankind;
astringent power is much attested as residing within it,
for if abraded (haematite) is mixed with egg white,
and smeared on swollen eyelids, it heals them,
and dim vision too, by banishing the blurriness;
mixed with pomegranate juice,
it is very effective in ointment preparation on a medical stone,
or dissolved in water it helps those frothing blood in the mouth,
and it cures any ulcers that are there;
drunk by women it tempers excessive menstruation;
powdered, it can suppress swelling in a flesh wound,
and quickly curb diarrhoea,
by frequently drinking it, diluted in old wine;
dissolved in water, it is an outstanding treatment,
rubbed in, for adder and serpent bites;
mixed with honey it can heal sore eyes,
when drunk it is said to dissolve stones in the bladder;
this (stone) is distinguished by a red or rusty colour;
it is supplied from Africa, also from Ethiopia and Arabia

The first encyclopaedia of natural history, *Hortus Sanitatis*, The Garden of Health, of uncertain authorship, was published in the late 15th century and by popular acclaim became a standard reference of the time. Haematite is discussed in the volume devoted to rocks and minerals (Anon., 1491). Much of this is a repeat of Marbod, but, in addition, the compilation states that haematite: mixed with boiling water renders it tepid; scintillates in the sun (true, some haematite is iridescent); and keeps fruit safe from locusts and hailstones. A woodcut (Figure 3) shows haematite being applied to staunch a nosebleed.

A post-medieval compilation of ancient and medieval haematite writings can be found in the comprehensive work of Bauschio (1665) where haematite types, powers, preparations, and substitutes are listed in great detail, far too extensive to summarise here.

Haematite, except as a placebo, achieves none of the effects claimed by authors from antiquity and medieval times. But belief in the bloodstone was widespread. Experiments and observations that refuted the claims could/would have been carried out but, if so, the results were not accepted. The writer can find no direct evidence of such debunking investigations on haematite, but believes there must have been some cynicism. However, it is instructive to consider the published debates on another iron oxide assemblage, the lodestone (Emerson, 2014).

Figure 3. *Medieval medication – an apothecary applying haematite to stop a nose bleed, from Anon. (1491). Modified from University of Cambridge/CC-BY-NC 3.0/, http://cudl.lib.cam.ac.uk/view/PR-INC-00003-A-00001-00008-00037/764/.*

Garlic was believed to disempower the magnet/lodestone. The renowned antiquarian Sir Thomas Browne (Sayle, 1904), following some measurements, dismissed the garlic/magnet antipathy as false in 1646. But the old views persisted into the era of the great Sir Isaac Newton, as evidenced by Ross' (1652) reply to Browne, a model of expediency and casuistry:

> *yet I cannot believe that so many famous Writers who have affirmed this property of the garlick, could be deceived; therefore I think that they had some other kinde of Load-stone, then that which we have now. For Pliny and others make divers sorts of them, the best whereof is the Ethiopian. Though then in some Load-stones the attraction is not hindred by garlick, it follows not that it is hindred in none; and perhaps our garlick is not so vigorous, as that of the Ancients in hotter Countries.*

Wootton (2015) in an insightful and lucid discussion of the controversy comments: "Ross knew perfectly well that he would not be able to confirm the story by testing it, yet he continued to believe it nevertheless". For many centuries reason was no match for the authority of scripture, ancient Greek writings, folklore, traditions, rumour, and the pronouncements of various grandees.

The modern world

Haematite is popular with mineral collectors (Jones, 2015). It has a range of colours (grey, black, red), occasionally it can show iridescence, where surficial mini-platelets diffract incident light. It displays a wide variety of physical forms: crystals, plates, foliae, rosettes, fibres, spheroidal surfaces, columns, grains, oolites. Martite clusters, octahedral after magnetite, make attractive haematite specimens. Haematite is a hard durable mineral that can take a very high polish. The Maya used mosaics of specularite to fashion quite effective mirrors of great spiritual significance to their nation (Voynick, 2016).

Haematite has achieved importance in planetary exploration. It has been discovered in several locations on the red planet, Mars, not in its red form, rather as a grey specularite (Bandfield, 2002). Its occurrence is thought to indicate volcanic activity or the past presence of water as grey haematite is a common precipitate in standing bodies of waters and mineral hot springs.

Currently, haematite is of interest to workers in environmental science, where its mitigating effects on groundwater pollution have been recognised. The haematite mineral surface can act as a platform for contaminant sorption or contaminant transformation. In hydrogen fuel research haematite has been shown to function well as a semiconductor electrode material for solar water splitting. Sulphated haematite has applications in the chemical and petroleum industries where it is catalytically active in a range of organic chemistry reactions (Morel, 2013).

Haemotherapy continues to the present day. In the natural healing literature (leaflets, pamphlets, posts etc.) haematite is believed to assist in promoting blood circulation, energy, and vitality, among other claimed health benefits.

Haematite is also admired as an ornamental, low cost gem. Pretty pieces, polished fondling stones, and rings (Figure 4) are readily available for purchase, as are haematite beads for bangles and necklaces. Beyond adornment any therapeutic effects flowing to the wearer would, naturally, be a welcome bonus. Haematite can contribute to gemminess in other minerals. Sunstone is a reddish plagioclase feldspar displaying adventurescence, i.e. fiery colour flashes from the reflections of incident light by included disseminated haematite flakes.

Haematite in geoscience

Haematite is ubiquitous in the earth's crust. It occurs in: a wide variety of sediments, some igneous rocks, hydrothermal deposits, ore alteration zones, volcanic fumaroles, hot springs, and low, medium and high grade metamorphics (Clark, 1982). Vast amounts are dispersed in soils, red beds, and red earths – the highly leached, clayey, porous, weathered profiles of the humid tropics that are low in silica and high in sesquioxides (Blanchard, 1968; Clark, 1982; Deer et al., 1992; Peters, 1978). In ancient banded iron formations, where enrichment has occurred as a result of alteration and concentration, haematitic iron ores are extracted in huge mines in Australia, North America, and elsewhere (Bateman, 1959). Haematite is the dominant iron oxide in one very important IOCG (iron oxide copper-gold) style of deposit (another style has magnetite). Haematite is the relevant Fe oxide in the major Olympic Dam copper-uranium-gold-silver deposit (Belperio, 2004; Reeve et al., 1990).

Clearly, haematite is one of the very basic minerals in the geosciences, pure and applied. In geophysics, its ability to hold a remanent magnetisation, despite its low magnetic susceptibility, has established it as a key mineral in palaeomagnetic studies, and as a mineral whose effect may need to be considered when interpreting many magnetic anomalies (Clark, 1997). So, haematite, besides being dense, has well documented magnetic properties that are useful in applied geophysics. Multidomain haematite has an unusually high thermoremanent magnetisation because of its weak internal demagnetising field (Özdemir and Dunlop, 2005). This means that in some high metamorphic zones strong magnetic anomalies may arise from remagnetised haematite. Although beyond the scope of this article, haematite

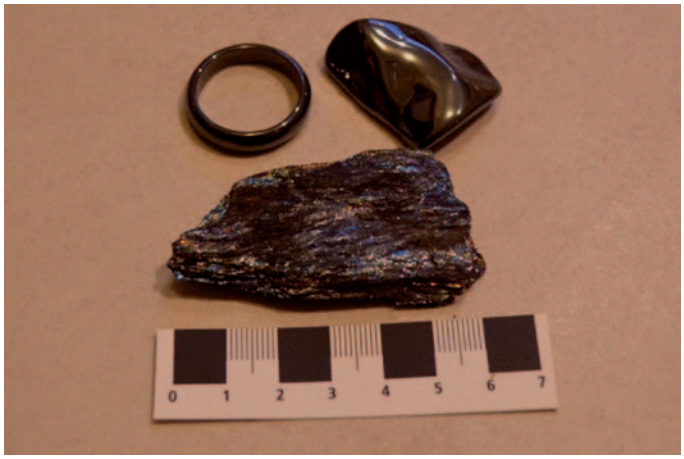

Figure 4. *Haematite in ornaments – a ring, a polished fondling stone, and an iridescent piece of haematite schist on which tiny scaly crystals of haematite have created a thin film causing colour flashes by reflection and diffraction of incident light. These three ornamental haematites are quite resistive; neither polish nor iridescence impart conductivity. The iridescent haematite comes from Nova Lima, Minas Gerais – southeast Brazil (cm/mm scale shown).*

also displays unusual anisotropy of magnetic susceptibility (Guerrero-Suarez and Martın-Hernandez, 2012).

However, the low frequency electrical properties of haematite are another matter. From the physics viewpoint haematite is a narrow band energy gap semiconductor of the *n* or *p* type according to impurity content and oxygen deficiency. Titanium is the most common impurity in natural haematite (Shuey, 1975). The writer first became interested in haematite years ago when frequently encountering puzzling low resistivity and moderate induced polarisation responses in samples from hard rock ore environments. Careful observation (aided by that red streak) and galvanic microprobing demonstrated that haematite was responsible. It is, of course, now well appreciated that haematite has electrical characteristics of interest, but although some information is available (Parasnis, 1956; Vella and Emerson, 2012) there is, in the writer's view, a need for more data especially as it seems that other minerals associated with the haematite may have contributed to, or been responsible for, some previously reported low resistivities, e.g. Zablocki's (1966) work on Lake Superior Fe oxides. Accordingly, out of interest, the writer carried out resistivity / conductivity measurements on some haematites.

Physical properties of some haematites

Twenty two samples of haematite were selected for measurement. The sample suite comprises Australian and overseas materials and includes four red ochres. Some of the samples are shown in Figures 5–8. The writer's main interest lies in the low frequency resistivity / conductivity of the actual haematite material, so in considering, say, a porous haematite, the focus is on the resistivity of the solid matrix and not of the water saturated rock (which, knowing the porosity, can be estimated by the Archie equation or its modifications, e.g. see Parkhomenko, 1967). Accordingly, samples were oven dried to 105°C for two days and 1 kHz galvanic resistivities were measured after cooling to room temperature (20°C) in a desiccator. Four electrode DC resistivities were measured for the more conductive samples ($\sigma > 0.5$ S/m). Densities, porosities, and magnetic susceptibilities were also measured. The data are presented in Table 2 as seven categories of haematite (see the table for details). Pursuant to the leaching mechanisms involved in BIF haematite enrichment (Bateman, 1959), considerable void space is evident in some samples e.g. the top grade iron ore #3H with 19% porosity resulting in a moderate dry bulk density (4.13 g/cc) although the grain density (5.10 g/cc) approaches that of pure haematite (5.26 g/cc). Some of the magnetic susceptibilities are high for haematitics, they could be due to the presence of minor amounts of magnetite and/or maghaemite and/or titanohaematite, but these were not observed under binocular inspection. Anyway, if present, it is considered that they would not contribute significantly to the haematite matrix conductivities especially if disseminated (Emerson and Yang, 1994). All the solid samples manifested a Moh's hardness ~6, and the characteristic red haematite streak. Titanohaematite is the most common impurity in natural haematites (Shuey, 1975), but if considerable titanium had been present in any samples the streaks would have been black, they were not.

The resistivity data in Table 2 are best viewed in the seven group perspective of the density crossplot in Figure 9. The red haematites have the highest resistivities (100 000s ohm m); the black haematite resitivities are lower (1000s ohm m). The red haematites are turning into dielectrics at 1 kHz, i.e. the phase lags, of voltage behind current, are of the order of tens of degrees and displacement currents dominate the ohmic component. The specular haematite in groups 7 and 8 have moderate resistivities (few ohm m) at lower densities (i.e. lower concentrations) and moderate conductivities at higher densities, up to 333 S/m (res 0.003 ohm m) for the coarsely crystalline, grey-black, very lustrous Brazilian sample #16. Specularite occurring as a poorly networked subordinate phase in the group 4 black haematites lowers resistivities somewhat (~1000 ohm m). Networked copper sulphides in the group 6 black haematites lower resistivity significantly (0.1–19 ohm m) and mimic the trend of the group 7 specularites. The sole member of group 5; a coarse grained polycrystalline, metallic lustre haematite, has a resistivity (8 ohm m) intermediate between the duller black haematites and the lustrous specularites. This is thought to reflect its crystallinity and multiple grain boundaries.

These data, though limited, are considered to provide some insight into the lower frequency electrical character of solid haematite minerals. Red haematites are very highly resistive and indeed are virtual dielectrics. Black haematites are quite, but not very, resistive even if they have (sub) metallic lustre; and this type of haematite does manifest minor ohmic conduction. Grey-black, well crystallised, lustrous specular haematites can be moderately conductive. Conductive distributions of specularite will diminish, somewhat, the composite resistivity of black haematite, and in the case of included disseminated/veinlet copper sulphides (cpy, bn, cc) that are networked, the composite resistivity of the black haematite will be similar to some specularites.

Resistivity is plotted against magnetic susceptibility in Figure 10. The sulphidic haematites (# 9, 10, 11) contain relict magnetite. The resistivities of the less resistive coarsely crystalline specularites (#12, 13, 15, 16) are seen to decrease as

Figure 5. *A banded iron formation, or jaspilite, developed from an altered schist in the Krivoy Rog, Donetz Basin, Ukraine. The long dimension is 75 mm. The dark bands are martitic haematite (octahedral after magnetite) and the red bands are jasper (a highly haematitic microcrystalline quartz). There is also vertical texture in the form of micro-fractures and anastomosing veinlets. This sample (3K in Table 2) has a 1 kHz dry state resistivity of 10 800 ohm m along the banding and 14 275 ohm m normal to the banding. The dark haematite virtually carries all the current; the red bands are extremely resistive. The sample represents sub-economic ore.*

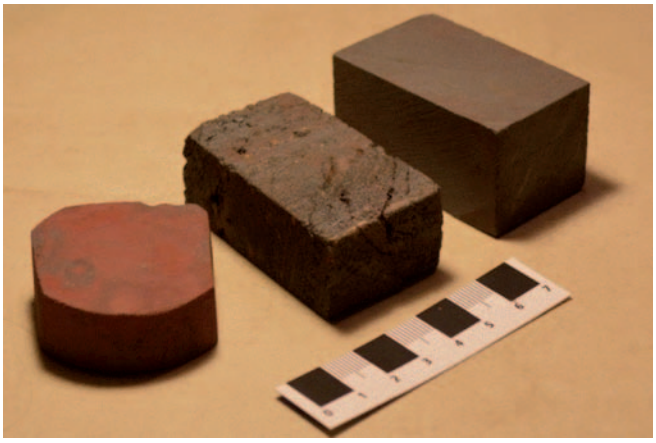

Figure 6. *Finely crystalline Precambrian hard-rock haematites, offcuts from tested samples; left: red and black mixed haematite from Stuart Shelf, South Australia (#1, Table 2); middle: porous martite-microplaty high grade iron from the Hamersley Province, Western Australia (# 3H, Table 2); left: tight, dense martite-microplaty high grade Hamersley iron ore, with reddish undertone. (#2, Table 2) The Hamersley haematites' grain shapes are anhedral to subhedral (cm/mm scale shown).*

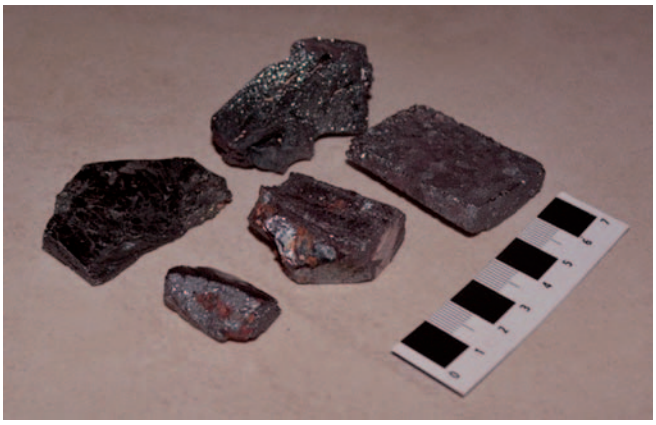

Figure 7. *Relatively conductive specular haematites, tending to euhedral grain shapes, that are offcuts from tested samples: far-left – very coarse grained, very lustrous, platy, crystalline, from Ouro Preto, Minas Garais, Brazil (#16, Table 2); top – coarse grained, martitic (after magnetite), from Payun Volcano, Altiplano de Payun, Mendoza, Argentina (#13); bottom-left coarse grained, platy, from Isle of Elba, Livorno Province, Italy (#15); bottom middle – coarse grained, platy, some felsic material, from Port Sorrell, Tasmania (#12); right – granular, medium grained, from Middlebrack Ranges, South Australia (#8).*

Figure 8. *Ochreous haematites, right – pure haematite powder from commercial source (#5, Table 2); left – South Australian very friable, clayey, ochre from private collection (#E3, Table 2); both samples have extremely fine particle sizes, they are amorphous and non-crystalline. These materials are extremely resistive in the dry state, however, when wet, being very porous, resistivities drop by orders of magnitude (cm/mm scale shown).*

Table 2. Dry state resistivities

Dry state resistivities: haematite (105°C dried – bone dry)

	Group	Code	DBD g/cc	P_A %	GDA g/cc	Bulk mag k SIx10^{-5}	Resistivity ρ_t (ohm m) [oven dried]
Earthy, red haematite (dull, no lustre)	1						
E1			4.54	0.5	4.56	140	72 000
E2			1.74	36.1	2.72	7	341 538
E3		●	1.71	38.4	2.77	17	440 000
E4			1.93	63.4	5.20	42	1 506 818
E5			1.86	65.0	5.26	548	3 530 800
Red and black haematite mix (dull lustre)	2						
1			4.19	3.0	4.32	115	10 309
2		◆	4.92	1.9	5.02	390	5990
3K			3.37	6.2	3.59	168	10 700
Black haematite iron ore (martite/microplaty, dull to submetallic lustre)	3						
3H		◆	4.13	19.0	5.10	444	5736
Black and red haematite + some networked specularite	4						
4			4.12	12.9	4.73	204	1959
5		×	4.21	15.6	4.98	146	1131
6			4.51	12.0	5.12	142	938
7			4.92	5.8	5.22	1192	297
Intermediate haematite (polycrystalline, metallic lustre)	5						
8		■	5.21	0.2	5.22	1517	8
Black and red haematite + networked dissem./veinlet sulphides: cpy, bn, cc	6						
9			4.54	6.9	4.88	1326	19
10		●	4.98	0.6	5.01	8531	0.4
11			5.35	4.0	5.57	266	0.1
Specular haematite (metallic lustre, platy, grey-black, crystalline)	7						
12			4.62	2.0	4.72	998	7
13			4.32	15.7	5.13	2521	0.9
14		◇	4.72	6.2	5.03	639	1.3
15			5.20	1.3	5.27	3938	0.08
16			5.18	1.6	5.24	9339	0.003

Notes:
- DBD – dry bulk density, 105°C dried; P_A – apparent (water accessible) porosity; GDA – inferred grain density.
- Magnetic susceptibility, mag k, induction coil 460 Hz.
- Galvanic resistivity (ρ_t) measured after oven drying 105°C and cooling to room temperature (20°C) in desiccator → ρ_t.
- ρ_t impedance bridge measurement frequency 1kHz, except DC four electrode, used for #10, 11, 13–16; min res. cited generally (sub)parallel to any foliation (some samples anisotropic).
- Australian samples from Precambrian locations: #1, 4, 5, 6, 9, 11, 14 Stuart Shelf SA; #2, 3H, 7 Hamersley Basin WA; #8 Flinders Range SA; #12 Port Sorrell Tasmania (has felsic inclusions).
- Overseas samples: earthy #E1 Taouz Morocco, #3K Krivoy Rog Ukraine; #13 Payun Volcano Argentina, #15 Isle of Elba, Italy, #16 Minas Gerais Brazil.
- Ochres: saprolitic #E2 WA, saprolitic #E3 SA, powder #E4 SA, refined haematite powder #E5 from commercial supplier.
- Grain sizes range from coarse (2 mm+) through fine (0.25–0.125 mm) to cryptocrystalline (<0.004 mm). Platy forms quite common with plate thickness 10s to 100s µ. Grain-shapes generally anhedral to subhedral excepting to specular haematites euhedral i.e. well crystallised. The red and the ochreous haematites comprise myriad randomly sub-microscopic forms that are optically rough and so have an earthy dull appearance i.e. no lustre. The red parts of #1, 2, 4, 6, 11 are cryptocrystalline; #1, 3K, 4, 5, 10 are microcrystalline (0.63–0.004 mm); #9, 14 are very finely crystalline (0.125–0.063 mm); #2, 3H, 7 are finely crystalline; platy specular haematites #12, 13, 15, 16 are coarsely crystalline; #8 is a coarse polycrystalline aggregate.

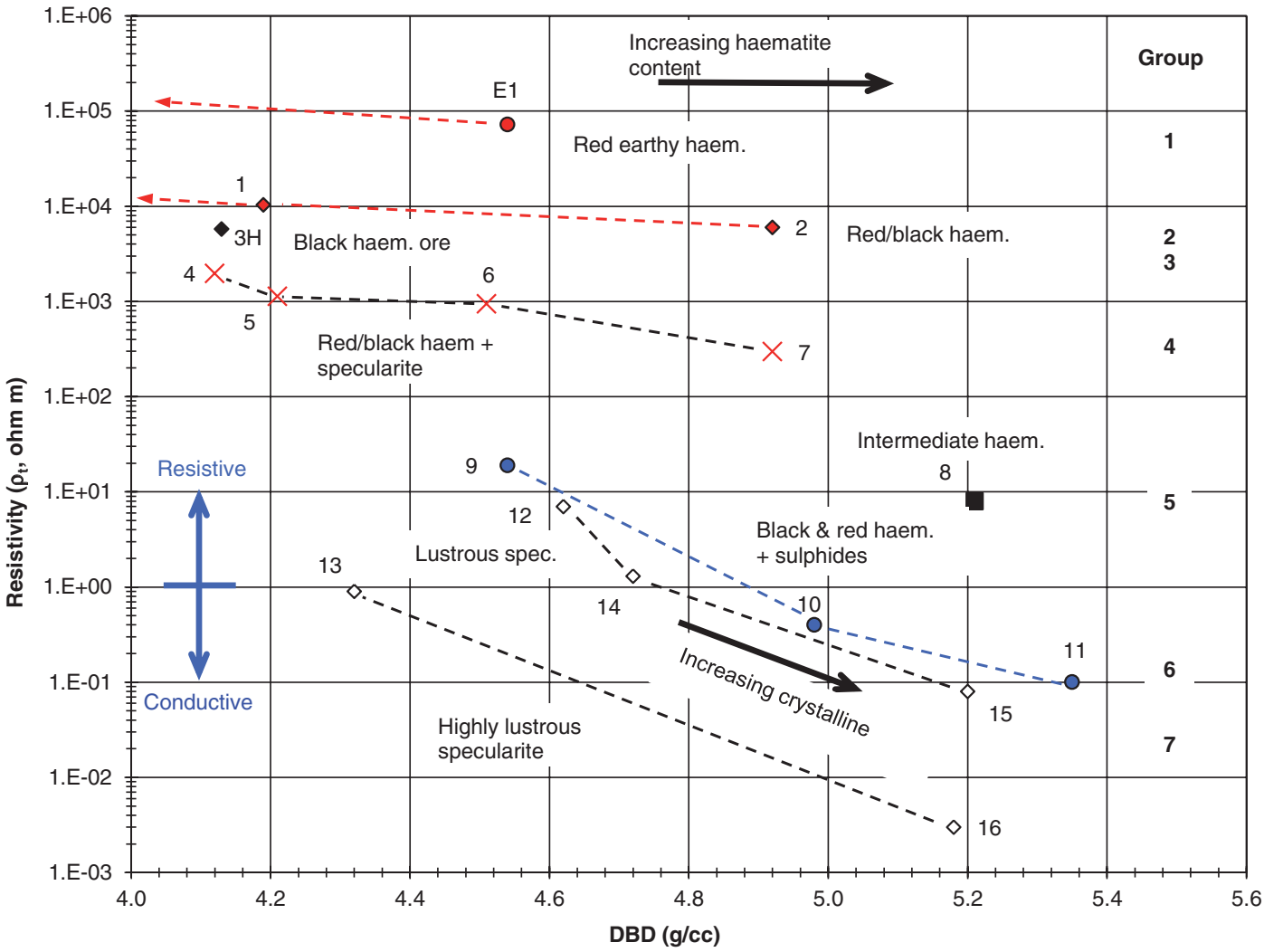

Figure 9. *Crossplot of resistivities 105°C dry against density for haematite samples in Table 2. The "bone dry" resistivities of 17 haematite samples from Table 2 are plotted against dry bulk density (105°C). The very high resistivity, very porous earthy samples E2 to E5 plot a long way off to the upper left and are not represented here, nor is the low density haematitic BIF #3K. Dry resistivities have been used in preference to field or water saturated resistivities as the focus is on the electrical characteristics of the solid haematite rock framework (for samples #1–8, 12–16; E1–E5). Clearly the sulphide-free haematite resistivity depends not only on haematite content (reduced by void space and minor foreign material in many samples) but also on the proportions of highly resistive red earthy haematite, black micromosaic (sub)metallic lustre haematite, and grey-black highly lustrous (even splendent) specular haematite, which is a conductivity booster. It can be seen that minor amounts of networked copper sulphides, in #9–11, substantially lower the resistivity of a black haematite host to give values similar to those of specularite. The specular haematite resistivity seems to diminish most when crystallinity is highest as in # 13, 16. Note that the sample data set is limited, min. res. has been plotted (some samples are anisotropic), and that the trends shown here are speculative.*

magnetic susceptibility increases up to 10 000 × 10^{-5} SI, quite a high value for haematite.

Discussion

In the literature there does not appear to be much information on haematite's resistivity, nor reported detail on the mineralogy/lithology of materials that have been measured. Parkhomenko (1967) cited a value of 2500 ohm m for fine grained haematite from Georgia. In a microelectrode study of Harvard University's collection of mineragraphic polished blocks, Harvey (1928) found only very resistive haematites. Morin (1951) estimated that 1.0 atomic percent Ti, an *n* type impurity, in pure α Fe_2O_3, improved its conductivity by many orders of magnitude (to 20 S/m). Shuey (1975) reported resistivities ~0.5 ohm m, in the basal plane perpendicular to the trigonal axis, for *n* type haematite crystals and resistivities ~0.15 ohm m along the trigonal axis, denoting significant anisotropy. Olhoeft (1981) cited a DC conductivity of 0.01 S/m for haematite. Parasnis (1956) documented a range of haematite resistivities from less than 1 ohm m to over 1000 ohm m; red haematite was very resistive while the black metallic-looking variety was conductive. Fraser et al. (1964) in electrical measurements (0.1–1000 Hz) on samples from the copper-iron mineralisation at Craigmont, British Columbia, found that predominantly specular haematite cores had resistivities of the order of 10 to 100 ohm m, and declared specularite to be a relatively poor conductor, inferring the presence of up to seven percent magnetite in the materials tested. In laboratory measurements, including micro-probing, on banded Ironwood Formation samples from the Gogebric iron range, Wisconsin, Zablocki (1966) noted low resistivities (to <0.1 ohm m) along bands containing networked magnetite and specular haematite, but the conductivity concentration of each was not resolved. All this is useful

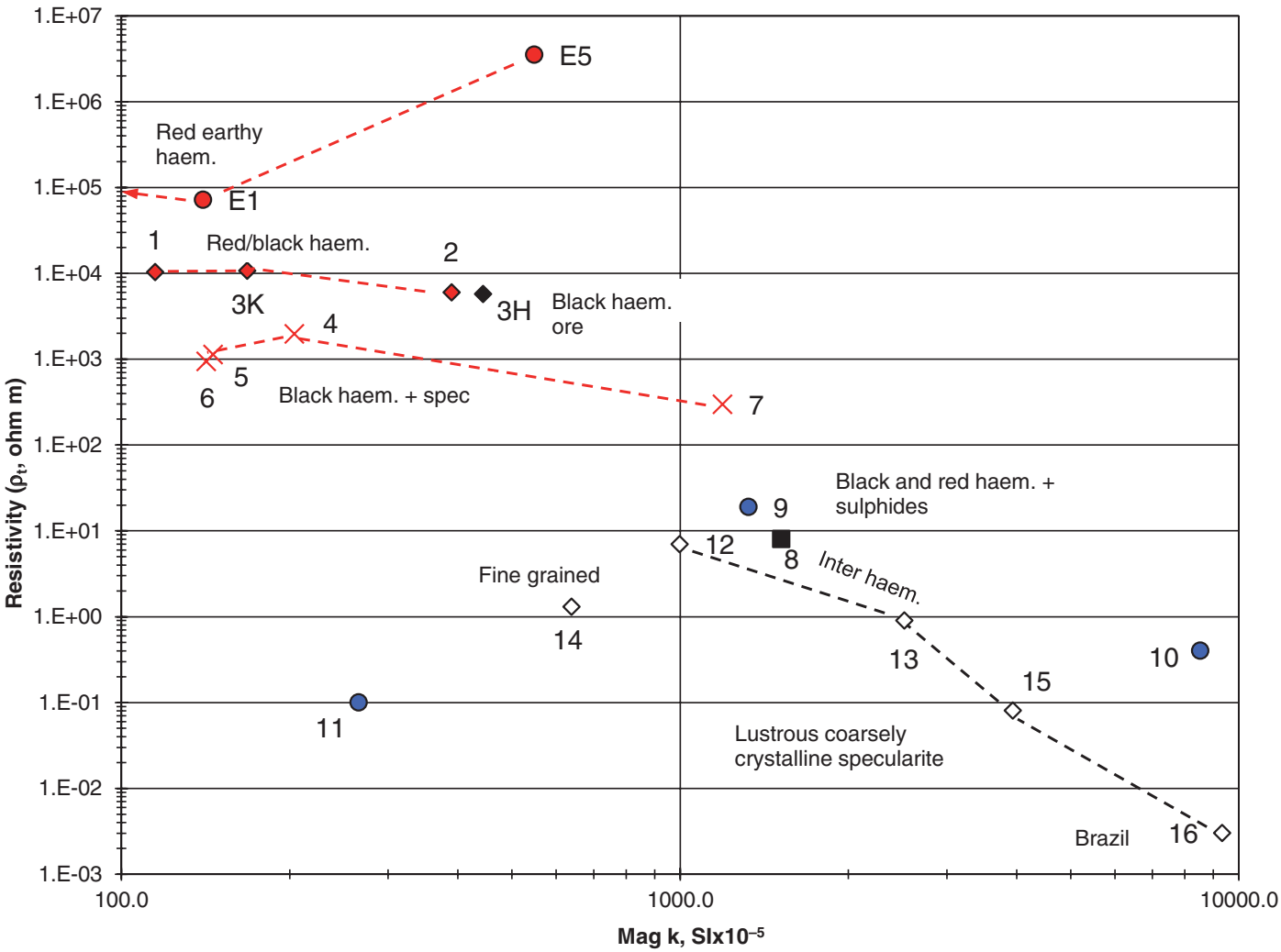

Figure 10. *Crossplot of resistivities 105°C dry against mag k for haematite samples in Table 2. The "bone dry" resistivities of 17 haematite samples from Table 2 are plotted against magnetic susceptibility. Note that specular haematite #14 has a fine grain size and that #8 is polycrystalline; #9, 10, 11 are sulphidic haematites with relict magnetite. There is a considerable spread of magnetic susceptibilities extending from the commonly accepted 100 to 1000 × 10^{-5} SI range up to nearly 10 000 × 10^{-5} SI. There seems to be an inverse relationship between resistivity and mag k for the coarsely crystalline platy lustrous specularites: #12 (with felsic inclusions) Port Sorrell Tasmania, #13 (porous) Payun Volcano Argentina, #15 Isle of Elba Italy, and #16 Minas Gerais Brazil. This correlation may be due to crystallinity. Further study is required.*

information, but it is not possible to link it to definite textural and mineralogical detail.

Apparently the situation is, to some degree, indefinite as regards confidence in predicting reasonable ranges of particular categories of haematite in the absence of actual measurements. Clearly, from Table 2 and the crossplots, haematite does have galvanic electrical character. As a working hypothesis, for the writer's results, three categories are shown in Table 1: red, dull; black, (sub) metallic; grey-black, lustrous. These categories manifest very high, high, and moderate to low resistivities, respectively. A magnetic iron oxide sample that is devoid of silica, silicates, and carbonates, with a colour tending to grey, a very high (almost splendent) lustre, and well-formed platy crystals (the coarser, the better), coupled with a fairly high Moh's hardness (≤6½), and a red streak, is likely to be a moderately conductive specularite, and this is readily checked with an ohmmeter.

It is interesting to compare the resistivities of the two iron oxides most relevant to geophysics. In Table 2 a resistivity of 0.003 ohm m was recorded for the Brazilian specular haematite; #16. In AMIRA Project P416, on magnetite's electrical properties (Emerson and Yang, 1994), the lowest resistivity, 0.002 ohm m, was measured in a coarse grained, well networked, recrystallised magnetite sample from the NW Qld Proterozoic. So, it could be expected that electrical responses in the field would be similar for networked masses of the two iron oxides, and, as these oxides are equally dense, the salient feature presumably would be the magnetisation of the magnetite.

The magnetic volume susceptibility of haematite is a moot point. Generally it is documented as occupying a low range of susceptibility, ~100 to 1000 × 10^{-5} SI, and this seems to cover many haematites. However, Hrouda (2002) measured bulk mag k values of 0.17, 0.29, 0.16 SI for three crystalline haematites from Minas Gerais Brazil, and noted a strong variation of directional k in the basal plane with minimum k parallel to the c axis. These are considerable susceptibilities comparable to those of monoclinic pyrrhotite. Guerrero-Suarez & Martín-Hernández (2012) in investigating fourteen Minas Gerais crystalline haematites for susceptibility anisotropy, measured

bulk mean susceptibilities ranging from 0.01 to 1.8 SI, with an average ~ 0.5 SI. A bulk mag k of 0.02 SI (2000×10^{-5} SI) was measured on a single sample from the Isle of Elba. Accordingly some confidence may be placed in the mag k values, exceeding 1000×10^{-5} SI, for the coarsely crystalline specularites (#12, 13, 15, 16) cited in Table 2 and plotted in Figure 2 herein[1].

In contrast to the extensive and rigorous scientific investigations of the magnetic properties of α Fe_2O_3 haematite, there has been comparatively little work done of the electrical properties, at least in the geosciences. It will require a lot more than the limited preliminary results presented here for the electrical properties to be properly documented and understood. Important factors include the chemistry, for the conductivity of semiconductors is sensitive to even minor content of impurities which serve to act as charge carrier sources, e.g. Ti (Morin, 1951); the crystallinity, for this seems relevant to resistivity and magnetic susceptibility; the fabric, for the juxtaposition of grains controls anisotropy, and the development of high resistivity films between grains is known to be important in synthetic sintered haematites (Shuey, 1975); and, of course, mineragraphy and petrology are essential to the measured data in the real world of field geology and geophysical exploration. High frequency (≥1 MHz) dielectric responses of dry haematites, saturated state resistivities, and induced polarisation effects, are also interesting and fruitful fields of study, but well beyond the scope and intent of this article.

Concluding remarks

For centuries haematite has contributed to human culture and, as an iron ore, to human industry. It is an important economic resource, and also a significant mineral in various geological environments. Its low frequency galvanic electrical properties merit further study to further develop or refine the indications presented in this article: there seem to be three physical phases, i.e. red and amporphous, dark black and (sub)metallic, and grey-black and highly lustrous, having very high, high, and moderate to low resistivities, respectively. Crystallinity (or the lack of it), and, probably, impurity chemistry are likely to be important variables.

Acknowledgements

The writer thanks Susan Franks for compiling the manuscript, Emilija Kalnins for photography, David Kalnins for providing considerable assistance with the manuscript and designing the figures and also suggesting pertinent references in the literature, and Paul Munro for advice on red ochre literature and history. Lisa Worrall and Bob Musgrave provided encouragement for this work. The writer is grateful to Phil Schmidt for advice on the magnetic characteristics of haematite. Tested materials were in the writer's collection or obtained from dealers. References to the measurement techniques applied here to haematite may be found in the *Preview* article on lapis lazuli: *Preview* **179**, December 2015, p. 73. The source of the BIF outcrop image to the left of the title is Alexandr Makarov/Shutterstock.com.

[1]The author is indebted to Phil Schmidt and Dave Clark for pointing out that large crystals of haematite have low coercivities with many mobile domain walls, and these are quite different to single domain haematites, which are very hard magnetically and have much lower susceptibilities. Grainsize, crystallinity, purity, and defects all greatly affect the susceptibility of haematite which mostly – as commonly encountered by geophysicists – is impure and defective, thus wall movements are blocked, coercivity increases, and susceptibility decreases.

Latin

The writer translated the Latin passages herein; the Latin, of course, being an optional extra. In the sixth line of Marbod's poem note that *glarea* (gravel) has been deemed to be equivalent to the French *glaire* (eggwhite) as this is how it appears in a medieval French version of the poem, otherwise a mix of shell grit (*glarea ovi*) and fragmented haematite would have been applied to the eyes – which is highly unlikely. Bauschio (1665) mentions eggwhite being used in this context.

Addendum

An informative outline of colour in haematite was received too late to be considered in this article, see Voynick, S., 2017, *Rock & Gem*, **47**, 11, 34.

References

Anon., 1491, *Hortus Sanitatis, De lapidibus et in terre venis nascentibus*: Jacob Meydenbach Mainz, (haematite is chapter 51, author not known with any certainty).

Bandfield, J. L., 2002, Global mineral distributions on Mars, *Journal of Geophysical Research*, **107**, 2001JE1510.

Bateman, A. M., 1959, *Economic Mineral Deposits*, 2nd edn: John Wiley & Sons Inc.

Bauschio, J. L., 1665, *De lapide haematite et schisto schediasma,* AN Cur, Lipsiae (Leipsig).

Beckmann, J., 1799, *Marbodi liber lapidum seu de gemmis* [Marbod's book of stones and on gems]: J. C. Dieterich, Gottingen.

Belperio, A., 2004, Common geological characteristics of Prominent Hill and Olympic Dam: *AusIMM Bulletin*, **6**, 67–75.

Blanchard, R., 1968, Interpretation of leached outcrops: *Bulletin 66*, University of Nevada.

Bloss, F. D., 1971, *Crystallography and crystal chemistry*: Holt, Rinehart and Windston, Inc.

Caley, E. R., and Richards, J. F. C., 1956, *Theophrastus on stones*: The Ohio State University.

Clark, K. F., 1982, Mineral composition of rocks, *CRC handbook of physical properties of rocks*, **1**, 1, 65–66: CRC Press, Florida

Clark, D. A., 1997, Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys: *AGSO Journal of Australian Geology & Geophysics*, **17**, 83–103.

Clifford, A., 2012, *The geological model of religion*: GMReligion.com.

Deer, W. A., Howie, R. A., and Zussman, J., 1992, *An introduction to rock forming minerals*: Longman Scientific & Technical.

Durling, R. M., 1996, *The divine comedy of Dante Alighieri,* Vol. 1 Inferno: Oxford University Press.

Eicholz, D. E., 1971, *Pliny natural history*, books 36 and 37: Harvard University Press. [Loeb Classical Library #419].

Emerson, D. W., 2014, The lodestone, from Plato to Kircher: *Preview*, **173**, 52–62.
Emerson, D. W., and Yang, Y. P., 1994, Electrical properties of magnetite rich rocks and ores: *AMIRA Project P416 Report (unpubl.),* Australian Mineral Industries Research Association, Melbourne.
Finlay, V., 2004, *Color – a natural history of the palette*: Random House.
Fraser, D. C., Keevil, N. B., Jr, and Ward, S. H., 1964, *Conductivity spectra of rocks from the Craigmont ore environment*: Society Exploration Geophysicists, Tulsa.
Guerrero-Suarez, S., and Martın-Hernandez, F., 2012, Magnetic anisotropy of hematite natural crystals: increasing low-field strength experiments. *International Journal of Earth Sciences: Geologische Rundschau*, **101**, 625–636. doi:10.1007/s00531-011-0666-y
Harmsworth, R. A., Kneeshaw, M., Morris, R. C., Robinson, C. J., and Shrivastava, P. K., 1990, BIF-derived iron ores of the Hamersley Province, in: *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. F. E. Hughes), pp. 617–642. (The Australasian Institute of Mining and Metallurgy: Melbourne).
Harvey, R. D., 1928, Electrical conductivity and polished mineral surfaces: *Economic Geology and the Bulletin of the Society of Economic Geologists*, **23**, 778–803. doi:10.2113/gsecongeo.23.7.778
Hrouda, F., 2002, Low-field variation of magnetic susceptibility and its effect on the anisotropy of magnetic susceptibility of rocks: *Geophysics Journal International*, **150**, 715–723.
Jones, B., 2015, Hematite – a black mineral with a red streak: *Rock & Gem*, **45**, 28–33.
Joplin, G. A., 1968, *A petrography of Australian metamorphic rocks*: Angus and Robertson.
Morel, D., 2013, *Hematite – sources, properties and applications*, Nivinka, New York.
Morin, F. J., 1951, Electrical properties of α Fe_2O_3 and α Fe_2O_3 with added titanium: *Physical Review*, **83**, 1005–1010. doi:10.1103/PhysRev.83.1005
Olhoeft, G. R., 1981, Electrical properties of rocks, in: *Physical properties of rocks and minerals*, Vol. 11–12, (Eds Y. S. Touloukian, et al.), **9**, 259–320, McGraw Hill.
Özdemir, Ö., and Dunlop, D. J., 2005, Thermoremanent magnetization of multidomain hematite: *Journal of Geophysical Research*, **110**, B09104. doi:10.1029/2005JB003820
Parasnis, D. S., 1956, The electrical resistivity of some sulfide and oxide minerals and their ores: *Geophysical Prospecting,* **4**, 249–278.
Parkhomenko, E. l., 1967, *Electrical properties of rocks*: Plenum Press.
Peters, W. C., 1978, *Exploration and mining geology*: John Wiley & Sons.
Paterson, N., and Lampert, R., 1985, A Central Australian ochre mine: *Records of the Australian Museum*, **37**, 1–9. doi:10.3853/j.0067-1975.37.1985.333
Post, W. E., 1974, *Saints, signs and symbols*: SPCK London.
Rackham, H., 1984, *Pliny natural history,* books 33–35: Harvard Uni. Press [LCL #394].
Reeve, J. S., Cross, K. C., Smith, R. N., and Oreskes, N., 1990. Olympic Dam Copper Uranium-Gold-Silver Deposit: *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. F. E. Hughes). pp. 1009–1035 (The Australian Institute of Mining and Metallurgy Melbourne).
Ross, A., 1652, *Arcana microcosmi:* T. Newcomb, London.
Sayle, C., 1904, *The works of Sir Thomas Browne, Pseudodoxia epidemica,* **1** (book 2, ch. 3): Grant Richards, London.
Shuey, R. T., 1975, *Semiconducting ore minerals*: Elsevier.
Spencer, W. G., 1938, *Celsus de medicina,* book 5: Harvard University Press [LCL #304].
Vella, L., and Emerson, D., 2012, Electrical properties of magnetite- and hematite-rich rocks and ores. http://www.publish.csiro.au/ex/pdf/ASEG2012ab232
Voynick, S., 2016, Mirror: *Rock & Gem*, **46**, 36.
Voynick, S., 2017, Pictographs and petroglyphs: *Rock & Gem*, **47**, 48–53.
Wootton, D., 2015, *The invention of science*: Allen Lane.
Yeates, G., 1990, Middleback Range iron ore deposits, in: *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. F. E. Hughes) pp. 1045–1048. (The Australasian Institute of Mining and Metallurgy: Melbourne)
Zablocki, C. J., 1966, Electrical properties of some iron formations and adjacent rocks in the Lake Superior region: *Mining Geophysics* **1**, 465–492.

Don Emerson is a geophysical consultant specialising in hard rock petrophysics. For a long time he has been interested in the mineralogical and geological information contained in ancient and Medieval Latin and Greek texts.