Introduction

_Non omne quod fulget est aurum_

This medieval Latin caveat was used by William Shakespeare in 1596 in the Merchant of Venice (Act 2, Scene 7): and by Miguel de Cervantes in 1615 in his Don Quixote (Part 2, Book 3).

All that glisters is not gold

So true. And, in nature, as geoscientists know, a lot of the glittering is done by pyrite "fool's gold." But it is far from being a material worthless to humankind. Indeed, this sulphide itself often contains gold.

Bright, brassy, brittle, ubiquitous pyrite is the most common sulphide. Cryptocrystalline to coarsely crystalline, it crystallises over a wide temperature range and manifests many forms: cubes (with or without striations), prisms, octahedra, pyritohedra (irregular dodecahedra with five sided faces), and granular (no recognisable external isometric features, but the internal structure is cubic). Aggregates of crystals or grains can form nodules, radiating suns, or bars (crystals stacked in one direction). It manifests as disseminations, veins, or massive deposits in igneous, metamorphic and sedimentary settings. Its presence can be boor or bane. Pyrite may be a guide to metallic mineralisation, or, owing to its included gold content, may be economic mineralisation by itself. Pyrite may obscure indications of valuable mineralisation, or pose severe environmental problems in land use. Most geoscientists, in the terrains they investigate, encounter and deal with pyrite sometime, or many times, in their careers.

Pyrite occurs in many modes, from nanocrystalline dust in recent sediments to truly colossal lenses of solid pyrite, associated with quartz porphyries and Palaeozoic slates, in the Rio Tinto deposits of Huelva Province west northwest of Seville, Spain. Here pyrite has been open cut mined for millennia as a source of sulphur (by roasting), and for its included gold. Copper from the chalcopryite also present. In the huge, low grade, auriferous, carbonate hosted Carlin style mineralisation, gold occurs along with mercury, arsenic and antimony as surface coatings on, and fracture fillings in, disseminated pyrite of extremely fine grain size. Australia has many impressive massive pyrite deposits such as those at Mt Lyell, Nairne, Koolyanobbing, and Norseman. Pyrite in less concentrated form pervades the Australian geological scene. It is a persistent mineral below the oxidation zone. Pyrite, its presence, and its physical properties, are very relevant considerations in hard rock, soft rock, engineering, environmental, and hydrology geoscience investigations. It also has a very interesting history.

Rickard (2015), in an outstanding book, comprehensively documents the general science of pyrite, its benefits, and its problems. For the mineralogist or mineral collector, Voynick (2011, 2018a, 2018b) and Jones (2016) provide good guides to pyrite's occurrences and history. Lindgren's (1933) classic text still furnishes useful information on pyrite deposits. Deer, Howie, and Zussman (1992) summarise pyrite's mineralogical features.

This article reviews, quite subjectively, selectively, and discursively, some of pyrite's history, and presents experimental data to shed a little light on a somewhat ambiguous aspect of pyrite's physical properties – its conductivity.

A summary of pyrite's main properties is given in Table 1. Herein, pyrite refers to the cubic sulphide FeS₂; pyrites is used as the umbrella term for a collection of yellowish metallic sulphides, see Table 2. Note that marcasite is pyrite's unstable low temperature dimorph. Marcasite is a pyrites, it is not pyrite.

Three forms of pyrite are shown in Figure 1.

Fire

Humankind's development was facilitated by agriculture, the wheel etc. Predating all this was fire, without which progress would have been impossible. This was appreciated by the rogue Titan demi-god Prometheus (“careful foresight” in ancient Greek) who is said to have fashioned man from clay and to have furnished him with fire (pyr Gk.). The fire was in the form of sparks inside a plant stem stolen from Olympia. This infuriated the boss-god Zeus, who punished Prometheus by chaining him to a rock on Mt Caucasus where an eagle incessantly pecked his innards. So sad, such suffering, but at least, in this mythical version, people had fire. Access to fire for early humans whether by Prometheus’ spark, a forest fire ignited by lightning, or a burning flare of natural gas venting from a fissure, was not much use because such sources were not portable as hunter-gatherers moved around.

Pyrite, which sparks under percussion, provided portability (until the Iron Age). Mastery of fire happened perhaps hundreds of thousands or more years ago (the subject is controversial). It was the great instrument of change. Cooking plants and flesh rendered them safer and easier to digest, so a wider range of foods became available. Smaller digestive systems and larger brains evolved (Wrangham 2009). Fire extended the day. At night, fire kept big bities at bay. Around the hearth, or campsite, brains evolved (Wrangham 2009). Fire extended the day. At night, fire kept big bities at bay. Around the hearth, or campsite, efforts to express opinions and relay information would...
occurs widely in silicates, oxides and sulphides. ∼ of this occurs in iron sulphides, chiefly pyrite. Iron amounts to 5% of the earth's crust and

Note: Sulphur (S, 2.1g/cc) amounts very approximately to 0.1% of the earth's crust; most

Table 1. Pyrite: summary of properties.

| Feature | Value |
|---------|-------|
| Synonyms | Pyrite, iron pyrites, common pyrites, mundic, fool's gold |
| Colour, lustre | Brass yellow, metallic splendid lustre – pyrite has a very high light reflectance |
| Chemical Formula | FeS₂ (46.6% Fe, 53.4% S): Fe²⁺(S²⁻) |
| Molecular Structure | Face centred cubic: Fe atoms occupy the corners and centre faces of cube; S pairs (dumb bells) occupy mid points of cube edges and the cube centre (see Fig.4.7, Rickard (2015)); covalent bonding of Fe and S |
| Stoichiometry | Nonstoichiometric: mineral and trace element inclusions are common, and significant |
| Oxidation | 2FeS₂ + 7O₂ + 2H₂O → 2H₂SO₄ + 2FeSO₄ + 260kJ/mole, in the presence of oxygen and moisture an exothermic reaction occurs — heat + sulphuric acid + ferrous sulphate which when hydrated is the mineral melanterite FeSO₄ · 7H₂O (density — 1.85g/cc) |
| Gottschalk and Buehler (1910) note other possible oxidations of pyrite producing sulphur, sulphur dioxide, and hydrogen sulphide |
| Density | 5.02g/cc, can vary |
| Moh's hardness | 6-6½, very hard but less than flint or quartz, 7 |
| Magnetic volume susceptibility | ≤ 4 x 10⁻⁵SI, a weak paramagnetic |
| Electrical conductivity | Nominally ~1000 S/m but can vary considerably depending on texture and semiconductor type (p, n) |
| P wave velocity | ~8.10 km/s, very high |
| S wave velocity | ~5.18 km/s, very high |
| Poisson's ratio | 0.15, low |
| Young's modulus | 204.8 GPa, very high for a mineral and indicative of stiffness — pyrite is brittle and not ductile |
| Thermal conductivity | ≥20 W/m/K (quite high, compare feldspar, quartz 2, 8 W/m/K respectively) |

Note: Sulphur (S, 2.1g/cc) amounts very approximately to 0.1% of the earth's crust; most of this occurs in iron sulphides, chiefly pyrite. Iron amounts to ~5% of the earth's crust and occurs widely in silicates, oxides and sulphides.

Table 2. Pyrites (collective term for yellowish sulphides): selected pyrite and pyritic samples.

| Name | Colour (shades of yellow) | Formula | Crystallinity | Hardness (Moh scale) | Density (g/cc) | Conductivity |
|------|--------------------------|---------|---------------|---------------------|---------------|--------------|
| Iron pyrites | Bronze yellow to pale brass yellow | FeS₂ | Cubic | ≤6½ | 5.0 | Varies |
| White iron pyrites | Pale bronze yellow | FeS₂ | Orthorhombic | ≤6½ | 4.9 | Low |
| Arsenical pyrites | Silver white – pale copper tarnish | Fe₃As₁ | Pseudo orth. | ≤6 | 6.1 | Low |
| Copper pyrites | Brass yellow | CuFeS₂ | Tetragonal | ≤4 | 4.2 | High |
| Magnetic pyrites | reddish-brown to bronze yellow | Fe₃S₈ (n≤0.2) | Monoclinic (magnetic) & hexagonal varieties | ≤4½ | 4.6 | Very high |
| Capillary pyrites | Pale brass yellow to bronze yellow | Ni₅S₈ | Hexagonal | ≤3½ | 5.5 | Very high |

Notes:
- cited data from various sources, approximate only
- marcasite is a low temperature unstable diomorph of pyrite
- pyrite and arsenopyrite commonly associated with gold deposits and these minerals can host blebs of gold in their own structure
- conductivity qualitative indications: low = 100 S/m or less, high = 1000 S/m, very high = 10,000 S/m or more
- for pyrite’s conductivity ranges see Table 3 (limited data set)
- metallic lustre sulphides only in this Table e.g. orpiment, As₂S₃; a soft lemon yellow mineral is not included
- pyrite is the sulphide with the highest exothermic oxidation and best sparking; marcasite also sparks, as does arsenopyrite (accompanied by a garlic odour)
energy warms the pyrite (the heat mainly dissipates) and dislodges tiny fragments with fresh faces and very reactive sharp edges which are not passivated and react exothermically with oxygen and moisture in the atmosphere (see equation, Table 1). Suitable tinder is ignited by a shower of rapidly oxidising, very hot, clearly visible sparking particles.

The glacier entombed mummy of a man who lived ∼5000 years ago was found in 1991 in the Ötztal Alps of southeast Austria (Figure 4). This late Stone Age/early Copper Age man carried a flint knife, a copper axe, and pieces of flint and pyrite for percussive fire-making.

Pyrite in the ancient and medieval world

Pyrite was recognised as an iron sulphide by German mineralogists in the early 1700s. Before that, it was a collective noun for yellowish metallic sulphides (Table 2). Hoover and Hoover (1950) in their translation of the 1556 edition of the German George Agricola’s monumental De Re Metallica remark in a Book 5 footnote:

The subject of pyrites is a most confused one; the term originates from the Greek word for fire, and referred in Greek and Roman times to almost any stone that would strike sparks. By Agricola it was a generic term in somewhat the same sense that it is still used in mineralogy, as, for instance, iron pyrite, copper pyrite, etc. So much was this the case later on, that Henckel, the leading mineralogist of the 18th Century, entitled his large volume Pyritologia, and in it embraces practically all the sulphide minerals then known.

The cubic mineral pyrite, FeS₂, is so spectacular in its splendid crystalline form that it easily draws the attention of a casual observer. It is not uncommon and it presents quite a contrast to the average drab, dun appearance of most rocks. It is rather odd that pyrite seems never to have been directly and...
Pyritum etiamnum unum genus aliqui faciunt plurimum ignis habentis, quos vivos appellamus, pondersissimi sunt hi exploratoribus castrorum maxime necessarii. qui clavo vel altero lapide percussi scintillam edunt quae excepta sulphure aut fungis aridis vel foliis dicto celerius praebet ignem.

Some regard yet another kind of pyrites as having the most fire (power). Such stones are deemed “live”, they are particularly heavy and are quite indispensable to those scouting campsites. When struck by a nail or, alternatively, by another stone, they emit a spark which, caught by sulphur or dry fungus or leaves, quickly provides fire, to order.

It appears that Pliny has pyrite in mind. The nail would need to be hard (like file steel), and the other stone would be flint, quartz, or quartzite.

Later he refers to a cubic mineral thought by some translators (but not this one) to be pyrite; Pliny NH 37,144:

Androdamas argenti nitorem habet ut adamas quadratis semper tessellis similis magi putant nomen inpositum ab eo quod impetus hominum et iracundias domet.

The man-taming stone “andromas” has the lustre of silver, like hard steel and always resembles squared-off pieces of mosaic stone. Learned Persians reckon that the name was assigned because it subdued the irascibility and passions of men.

Indeed. Surely a handy material for the modern day? What is it? Pyrite crystals can be cubic and they have a splendid metallic lustre. However the obvious adjectives fulvus (yellow) or aureus (golden) are not included in the description, rather silvery and steely are used (note: adamas can also mean diamond). Galena (PbS) is a more likely candidate. It has perfect cubic cleavage (whereas pyrite only has conchoidal fracture), silvery/steely colour, metallic lustre, and galena surfaces can display mosaic texture due to cleavage. Galena crystallises in cubes, cleaves to the faces of the cube, so its cleavage fragments are cubic. Some specimens easily disaggregate into small cubes when hit or even rubbed.

In the early Middle Ages, Marbod (1035-1123) was Bishop of Rennes, ∼300 km WSW of Paris. Between 1061-1081, before the printing press, he compiled the first and most popular of all the medieval lapidaries with sixty minerals, gems, stones and their magical and medicinal properties, in 735 Latin hexameters. Marbod was popular for centuries. Beckmann (1799) gave a listing of the many editions and provided a complete Latin text, and commentary. Marbod’s poem, De Pyrite has only four lines:

Cui fulvus color est, cui nomen ab igne pyrites,
Se vetat astringi, pertractarique recusat.
Tangi vult leviter, povidaque manu retiniri,
Nam pressus nimigit digitos stringentis adurit.

Pyrites derives its name from fire, its colour is yellow, it is not a good idea to grasp it tightly, it does not like to be fondled. Touch it lightly, handle it very carefully, for if you press on it too much it scorches your fingers.

Marbod is not much help either. The colour is right but the rest is adulatory imagination based on scraps of information from others. Marbod, doubtless, was aware of Pliny (NH), 37,189:

pyritus nigra quidem est, sed attritu digitos adurit

certainly pyrites (firestone) is ill-omened and what is more it burns the fingers when rubbed

Pliny’s pyritis has never been identified.

It is clear that, in antiquity and in the Middle Ages, European natural science neither recognised nor understood pyrite as we know it, but it was a basic component of the pyrites group of minerals which were widely used. Societies in Asia and the Middle East also made use of pyrites, and Arab scholars knew pyrites as marcasite, but this will not be pursued here (see: Rickard, 2015).
Pyrite in the pre-modern and modern world

Pyrite continues to occupy a noteworthy place in social, industrial, mining, technical, and environmental matters.

Social pyrite

Pyrite is a cheap, common sulphide, and specimens of superb appearance are available. The variety of attractive forms, the brassy colour and splendid metallic lustre make pyrite an affordable favourite of mineral collectors. They seek individual crystals of striking appearance, and crystal stacks and clusters set in a matrix of other minerals such as quartz thus making attractive composite specimens. Pyrite is also a gemmy ornamental material, but confusingly known as marcasite, an unstable dimorph which is quite unsuitable for this purpose. Pyrite when polished seems whiter than its usual colour. It is widely used in jewellery (Figure 5) owing to its low price (Liddicott, 1909).

Pyrite features in modern day lithotherapy. Pyrite crystals fit readily into the category of attractive diminutive objects not to be regarded merely as ornaments, but rather as sources of positive occult energies when worn as rings, necklaces or amulets or simply carried as pocket stones. If one believes New Age lore, then a hunk of pyrite placed on a conference table invigorates the ambience and optimises decisions – just the thing for a meeting to discuss exploration data? Furthermore, post meeting, the participants can be comforted by their own pet piece of pyrite which, we are assured by crystal therapists, helps breathing, circulation, brainpower, and promotes practicality, harmony, willpower. Perhaps the beneficial effects are due to a massaging of the vascular system by a thermal flux transmitted through the gullibility aether. However, this blood booster hypothesis seems to violate the second law of thermodynamics which does not permit the spontaneous flow of heat from a relatively cool (pyrite) to a warm body (37°C, human). Investigations continue into the fascinating topic of empowerment by pyrite, but the path is daunting, and strewn with credibly hurdles.

Plato (427–347 BC) believed that the world had a soul and that the universe was alive and conscious. A strand of human philosophy, panpsychism, posits that materials can think, more or less, as consciousness is believed to be part of the fundamental nature of all matter. Mind is in all matter; all matter has experience (David 2016; Taylor 2019). Such a philosophical narrative is pregnant with possibilities. In the mineral kingdom consciousness could be the appreciation of the buzz and vibration of existence, if not the complex consciousness of humans. Who knows? One view asks why substances should not be conscious, and asserts that the denigration of panpsychism as loony is simply a manifestation of anthropomorphic bias. Pyrite has impressive physical properties (Table 1) and, being ubiquitous, could be regarded as an elite material, ideal for a consciousness study. What is it like to be pyrite? I glitter, therefore I am (apologies to Descartes). Socially committed geoscientists may find this weirdness a fruitful field of progressive research. It ticks the boxes for: atmospheric hygiene (no nasty carbon in its chemistry), diversity (it is decidedly different), inclusivity (the kinship of consciousness), and sustainability (there is so much of it). An environmental soft-print can be ensured by researchers eschewing vehicular and aeroplane transport for field work and conference attendance; bipedal motion, bicycle, scooter, canoe, ketch, and hot air balloon, are to be used instead. Samples for study would be ethically sourced and respectfully collected. The purity and potential of such a visionary project will attract plaudits, perhaps lavish funding. The result of these endeavours, in the current bracing climate of cultural relativism, would celebrate a non-normative conception of mineralogy. Cutting edge stuff, indeed, and an exhilarating opportunity for virtue signalling.

Pyrite mining

For centuries pyrite was the main source of sulphur until it was displaced by Frasch sulphur from the evaporitic caprocks of saltdomes, and more recently by scrubbed sulphur captured in the smokestacks of low emission coal power plants. However, pyrite is still mined for sulphur to a limited extent in China, Russia and India.

Most pyrite is now mined for its contained gold. These deposits are huge and low grade; the (sub) microscopic gold occurs within the pyrite, e.g. Carlin with 0.37% Au in arsenian pyrite.

Pyrite and alchemy

The dabbings and experiments of alchemy (Figure 6) up to the 18th century led to the development of modern chemistry which analysed and reinterpreted useful empirical data from the often obscurantist writings of early practitioners such as the great Sir Isaac Newton, who wrote over a million words on the subject. The old “chemistry” dealt with primitive pharmacology, chemical reactions and compounding, metallurgy, and the transmutations of base metals into gold. Aristotelian theory reigned: prime matter and forms interacted to produce the four elements fire, air, earth water which in various combinations accounted for all materials. Changing the proportions changed the material; any substance should be changeable into another substance under suitable conditions. Transmutation was the alchemists’ ambition and pyrites encouraged continuing experimentations to achieve it for it was observed that pyrites could be converted into gold, even if the amounts were small. It is now well known that some pyrite deposits contain microscopic and sub-microscopic grains of gold, invisible to

Figure 5. A piece of marcasite jewellery. Marcasite itself is far too unstable for such a purpose. The marcasite is actually polished and faceted pyrite. The pyrite pieces are set in metal for this lizard brooch. https://commons.wikimedia.org/wiki/File:Marcasite_silver_lizard_brooch_2.JPG / Creative Commons Attribution-Share Alike 3.0 Unported
Most sulphide ores require roasting to obtain sulphur dioxide, SO₂, but pyrite has such a high sulphur content (53.4%) that in a most sulphide ores require roasting to obtain sulphur dioxide, SO₂, but pyrite has such a high sulphur content (53.4%) that in a recovery of gold from pyrite. But this was not transmutation, rather the chemical release and concentration of previously invisible gold. Pieter Brueghel the Elder - The Alchemist (1558, Ink on paper) Engraved by Philipp Galle / https://commons.wikimedia.org/wiki/File:Pieter_Bruegel_the_Elder_-_The_Alchemist.JPG / Public Domain

Metamorphosis in the classical sense is the transformation of something into a new form, such as a human being turned into animal, vegetable, or mineral matter. Ancient and medieval cultures were imbued with the idea; it persists to the present day in religion, and fantasy movies. The Roman poet Ovid (43 BC – AD 17) relates some 250 instances of transformations in his Metamorphoses. The possibilities of transformation/transubstantiation/transmutation encouraged metal workers and many others to try to make precious metals from baser materials. They believed metals grew in the earth from an imperfect to a perfect state. Some expended enormous experimental effort to hasten the process by instantaneous transmutation. Others had a more leisurely approach such as the gold-panning Conquistadors in South America who threw lumps of platinum back into rivers to “ripen” into gold.

Pyrite – industrial chemistry

Pyrite provided an essential ingredient, sulphur, for a very dangerous industrial material: gunpowder. In the 13th century the German theologian Albertus Magnus documented gunpowder as a mixture of 2/3 niter (KNO₃ from soils and from pigeon and bat droppings in caves of arid regions) and 1/6 each of sulphur and charcoal. The pyrite-derived sulphur functions as an accelerant giving a bigger bang. The modern mix of 74.6% niter, 13.5% charcoal, and 11.9% sulphur gives an even better bang.

In the 1500s pyrite featured in the improvement of European weaponry, i.e. the facilitation of carnage wreaked on humans and animals. The hand cannon of the 1300s gave way to the slow, clumsy matchlock musket in the 1400s. The matchlock relied on a lighted match of saltpetre soaked hemp to ignite the gunpowder charge through a hole in the top of the musket barrel. It was cheap and, although hazardous, lasted until the 1700s. The projectiles from such weapons were able to penetrate the armour of mobile cavalry who could no longer efficaciously charge the infantry. The wheel lock pistol with a pyrite sparker ignition was developed for use by the aristocrats of the cavalry to fire at a distance on the ranks of the peasant infantry. It was an elite weapon with an ignition mechanism comprising a sprung, hardened steel, serrated wheel revolving rapidly against a piece of pyrite which ejected sparks into the powder pan of the weapon (Figure 7). It was simple, sturdy, reliable, and could be fired in an instant from horseback, but it was expensive so it was mainly used by the cavalry. Pyrite enjoyed a brief moment of military distinction, being a key component of a weapon which radically changed Renaissance battle tactics. It was replaced by the flint lock in the 1600s.

Pyrite – the firestone

Figure 6. Pieter Bruegel the Elders’ 16th century depiction of an alchemist in his laboratory doubtless spurred on in his dead-end endeavours by the recovery of gold from pyrite. But this was not transmutation, rather the chemical release and concentration of previously invisible gold. Pieter Bruegel the Elder - The Alchemist (1558, Ink on paper) Engraved by Philipp Galle / https://commons.wikimedia.org/wiki/File:Pieter_Bruegel_the_Elder_-_The_Alchemist.JPG / Public Domain

the eye. Crushing and powdering this pyrite (known as pyrites to an alchemist) and then adding mercury causes the gold to form an amalgam which when heated vapourises the mercury and leaves visible gold. So pyrites could be changed to gold, seemingly corroborating the theory of transmutation and boosting hopes of converting base metals into gold if only the right conditions could be found. However, they never were. Many lives were spent, and fortunes lost, in these doomed pursuits.

Pyrite – industrial chemistry

Most sulphide ores require roasting to obtain sulphur dioxide, SO₂, but pyrite has such a high sulphur content (53.4%) that in a pure and finely divided form it can maintain its own combustion without an external heat source.

For centuries pyrite was the main source of sulphur and sulphur dioxide used for bleaching, and in the manufacture of sulphuric acid, an important industrial chemical. Sulphuric acid applied to phosphate rock makes superphosphate for agriculture. In the clothing industries, pyrite produced the potassium aluminium sulphate alum indispensable in the chemical fixing of dyes to cloth. One recipe involves pyrite shales where the pyrite reacts with the aluminous clay content of the shales, and added wood potash, to give alum.

Figure 7. A double barrel wheel lock pistol, beautiful but deadly. This type of pistol was fast and reliable, but expensive, and was used mainly by European cavalry in the 1500s https://commons.wikimedia.org/wiki/File:Double_Barrelled_Wheellock_Pistol_MET_2306.jpg / Creative Commons CC0 1.0 Universal Public Domain Dedication. The wheel lock ignition mechanism is shown underneath: when a sprung steel (H ≥ 7) wheel revolved rapidly against a piece of (yellow) pyrite, sparks were generated and detonated a gunpowder charge in the pan of a pistol. Prime position of the pyrite is shown on left; fire position is on the right https://commons.wikimedia.org/wiki/File:Wheellock_mechanism_(animated).gif / Creative Commons Attribution-Share Alike 3.0 Unported
Pyrite and the environment; geohazards

Pyrite often occurs in coal as disseminations, coatings, and lenses. Such pyrite, when exposed, may be inert or reactive. If reactive it can rapidly oxidise in moist mine conditions. Reactivity depends on grain size and shape providing increased surface area of the pyrite and porosity for air to reach reactive sites on the pyrite (Beamish 2017). Under moist mine conditions such pyrite can oxidise rapidly producing iron sulphates such as greenish melaniterite $\text{Fe}_2\text{O}_3\cdot\text{SO}_4\cdot7\text{H}_2\text{O}$ (also known as copperas, green vitriol, iron vitriol). Fine acicular crystals of low density melaniterite (1.9g/cc) readily mix with coal dust and, if inhaled, contribute to coal workers’ lung disease (pneumoconiosis).

Potential acid sulphate soils occur in about 3 000 000 ha of pyritic Australian Holocene coastal floodplains. Pyrite is safely inert in the reducing conditions of its deposition, but oxidises on exposure to oxygen when the soil is disturbed by excavations (e.g. mining) or in engineering infrastructure and agriculture (e.g. drains). The oxidation equations can be complex but are broadly summarised by the entry in Table 1. Oxidation of pyrite generates sulphuric acid; for each mole of pyrite that is oxidised four moles of acid are produced (Indraratna, Blunden, and Nethery 1999). Needless to say, this can have catastrophic environmental effects and requires careful assessment and management in affected areas.

Disseminated pyrite can cause problems in the construction industries using building stone, dimension stone, and rock fill (Ray 1988; McNally 1988; Smith 1999). Small amounts of pyrite can ruin an otherwise attractive stone. In building and dimension stone, such as granites and slates, pyrite oxidation generates rusty blemishes along fissures and on surfaces. In rock fill used for dams and embankments the presence of pyrite leads to pollution from mobile metals and acidic drainage. Alteration can be biochemical (Irdi and Booher 1994). Bacteria do occur in rocks. The bacterium Thiobacillus ferro-oxidans converts pyrite to ferric ions and sulphuric acid. When the ferric ions further react with the pyrite a self-sustaining reaction can ensue. If calcite occurs with the pyrite, as in some roofing slates, gypsum is formed from the sulphuric acid with flaking and spalling.

Pyrite and technology

Pyrite has found applications in modern technology. Rechargeable lithium batteries have aluminium cathodes containing disseminated pyrite grains. Solar energy projects may find a use for semiconducting crystalline pyrite as a cheap photovoltaic absorber of radiant energy when sprayed in thin layers on exposed panels (Voynick 2018b).

Pyrite and early life on Earth

In sediments, a very common type of pyrite occurs as clustered microscopic aggregates. This is known as framboid pyrite. The accumulation of tiny pyrite grains has the appearance of a raspberry, and its formation is thought to be linked to anaerobic bacterial processes, such as the reduction of sulphates to sulphides, which have gone on for billions of years. The “iron-sulphur world” is a supposition of geochemists and biologists and is based on the premise that the origin of life required the active involvement of iron sulphides. These were ubiquitous even before atmospheric oxygen appeared, and acted as catalysts and conductors in biological reactions requiring electron transfer. Where would we be without pyrite? Rickard (2015) provides a full and lucid discussion of this fascinating topic.

Arid zone pyrite

In the field, pyrite in veins or in massive replacement bodies weathers and forms a limonitic capping i.e. a gossan (Blanchard 1968). Limonite is a general field term for a mix of haematite ($\text{Fe}_2\text{O}_3$), goethite $\alpha\text{FeO(OH)}$, and lepidocrocite $\beta\text{FeO(OH)}$. Alteration products of pyrite are frequently seen in arid areas in the oxidation zones of massive sulphides as cellular, spongy, boxwork structures which are developed through limonitic gossans which are ore indicators in economically mineralised pyritic sulphides. Pyrite often forms tough limonite pseudomorphs with the outline of the parent pyrite fully preserved (Figure 8). The replacement may be partial (a coating on the pyrite crystal) or it may be complete.

Pyrite – physical properties

Pyrite, $\text{FeS}_2$, has an intriguing set of physical properties for a ubiquitous mineral (Table 1). Compared to most minerals, it is quite dense, it manifests a very weak para-magnetism (unusual for an Fe compound), it carries a very fast compressional wave, it’s Young’s Modulus (a proxy for low ductility or stiffness) is extremely high, as is its thermal conductivity. All these make for a salient combination of characteristics that are, more or less, consistent for various pyrite occurrences. However another important property, perhaps of most importance to a geophysicist, is resistivity, (or its inverse: conductivity), and this is certainly not consistent. Thousands of resistivity measurements have been made on pyrite, perhaps more than any other sulphide. Most of these measurements have been on single crystals. Pyrite’s resistivity, generally, is low, but it is quite variable and difficult to predict or anticipate in field work even if important factors such as mode of conduction, crystallinity, alteration, and texture are known. Information on pyrite resistivities can be found in Harvey (1928), Telkes (1950), Parasnis (1956), Hill and Green (1962), Parkhomenko (1967), Shuey (1975), and Olhoeft et al. (1981). Pyrite is a semiconductor. Conduction can be n type (electrons) or p type (holes, actually electrons hopping into lattice holes and leaving holes in their wake). Trace or minor

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**Figure 8.** Pseudomorphs of limonite, $\text{FeO(OH)}_n\text{H}_2\text{O}$, after pyrite, result from extreme alterations in arid zones. The external features of the original cube (left) and pyritohedron (right) have been preserved. The cube is from Nilinghou South Australia, the pyritohedron is from Mkushi Zambia. Density for each is 3.7 g/cc, and mag k $110 \times 10^{-10}$ SI. Both samples have very high resistivity, > 100 000 ohms.
amounts of Cu, Co, Ni function as donors of electrons in n type, while As is the acceptor of electrons in p type. Note that arsenic can be quite common in pyrite environments e.g. as paragenetic white iron pyrites Fe As S. Shuey (1975) gives a modal resistivity of $\sim 1 \times 10^{-1}$ ohm m for n type, and $\sim 3 \times 10^{-2}$ ohm m for p type pyrite. The n type tends to be more conductive, but the p type seems to be more common. Despite the many measurements and investigations of Hall effect, Seebeck effect, chemistry, mineralogy, temperature dependence, and concomitant magnetic behaviour, it does seem that more studies are needed to understand better natural pyrite's DC and AC electrical behaviour, especially in aggregate rather than single crystal form.

It is interesting that pyrite has the useful electrical property (as does galena) of both p and n semiconductor types sometimes occurring in the one crystal (Shuey 1975). This resulted in pyrite's use as a detector in early radiowave crystal set reception circuits. A “cat's whisker” wire was used to probe the crystal surface until a suitable zone was encountered to fulfil the function. A p-n junction acted as a rectifier. The p type sulphide has no conduction electrons; the n type has no conduction holes. Holes and electrons cross the boundary making the p type more negative and the n type more positive. The application of a potential difference opposite to this interface polarity, a forward bias, gives a large current, but reverse bias decreases the current by orders of magnitude (this diode property of natural pyrite seems to have been little studied). In the radio circuit, virtually, only the positive part of the received alternating waveform is passed, thus achieving the rectification. The crystal detector circuit extracts an audio frequency (AF) signal impressed on the radio frequency (RF) carrier wave (now amplitude modulated, AM) picked up by the receiving aerial. This is connected to the primary of a transformer whose secondary provides input to the detector circuit (Figure 9). An early 1900s radio receiver was simply an aerial, the transformer, the pyrite detector (galena could also be used), and a pair of headphones in parallel with a couple of capacitors. The pyrite detector’s function was to pass only the positive part of the incoming waveform and to produce a pulsating DC signal with RF and AF components. One of the capacitors was manually variable and was used to tune the incoming signal i.e. select the sender’s frequency, the other capacitor sent the RF component to earth thus bypassing the headphones. The headphones were high impedance to maximise the voltage, and provided the listener with a sound similar to that used to modulate the carrier wave. No battery or other power source was required. Sensitivity was low, but adequate. All very simple and still used by hobbyists to this day. Pyrite was one of the key components in the early days of radio transmission. Many a schoolchild made a “bits and pieces” receiver with the silver foil from a bar of chocolate, a thimble, a cardboard roll, some wire and a crystal costing a few pennies.
In the tapped coil, variable capacitor, primitive radio receiver, the cat's whisker crystal detector could be galena, but pyrite was better with regard to: easy placement of the cat's whisker, withstanding ambient conditions, continuity of sensitivity over long periods, and tonal purity in reception. However, apparently, only certain limited types of pyrite were suitable, so galena was more frequently used. The exploration relevance or significance of asymmetric current conduction, or diode effect, in natural sulphide types, would seem to warrant some study.

Pyrite – conductivity

Samples
There is a considerable spread of conductivity values reported for pyrite, 1 to 100 000 S/m (Shuey 1975). To contribute to understanding better pyrite's electrical characteristics, opportunity was taken to carry out conductivity measurements on the suite of 36 pyritics listed in Table 3 in the following ten categories: large single crystal (#1–4), massive medium to coarse grained low porosity aggregate (#5–10, 36-nodular), high porosity aggregate (#11–15), high alteration (#9), massive very finely crystalline with minor silicates and other sulphides (#16–19), massive with minor pyrrhotite and other sulphides (#20–23), minor pyrite-networked veinlet (#25, 26), fine grained banded (#27–33), fine grained banded with minor chalcopyrite (#24, 34, 35). The pyrite in all the samples is networked i.e. there is electrical continuity through the core or across the core in the case of banded samples drilled normal to foliation to give maximum flux coupling in the EM energisation producing eddy currents around the core. Disseminated pyritics with grains or clusters of grains electrically isolated from one another were not included in the sample suite for reasons given below.

Measurements
Laboratory mesoscale measurements were carried out on cored, or shaped, air-dried samples for electrical conductivity and magnetic susceptibility. Induction coils were used and energised to 1 MHz for induced electromagnetic conductivity and 400 Hz for magnetic susceptibility. Changes in the resistance (R) and inductance (L), when cores were inserted, were measured by an RCL metre. Following Yang and Emerson (1997) conductivity was determined from ΔR, and susceptibility from ΔL. Mass properties were measured, following Emerson (1990), so that the conductivity data could be viewed in the perspective of density. Although the writer has carried out many galvanic measurements on pyritics, EM conductivity was the preferred technique here. The EM measurement (Figure 10) is not responsive to insulating minerals, it just "sees" conductors and induces eddy currents in them; also it is quicker to do. Lab EM favours conductive features normal to the core axis; galvanics, parallel to the core axis. The differences, which do exist for banded pyritics, are related to texture and will not be dealt with here where only maximum conductivities are presented and plotted. Auxiliary four electrode DC galvanic measurements were made to check some of the EM measurements, and two electrode galvanic microprobing was also undertaken in investigating alteration films and pockets.

Disseminated pyrite is not included in the test suite. Such pyrite, dispersed and disconnected in a resistive matrix, is not suitable for measurement by EM induction. The conductivity (σ) of such a mix would be quite low. It is best addressed by galvanic methods and modelled by a mixing law such as a modified Maxwell's equation. For dispersed conductive spheres, one approximate version of this equation is (Shuey 1975):

\[ \sigma_{\text{mix}} = \left[ (1+2p)/(1-p) \right] \sigma_m \]

where \( p \) is the volume percent of porphyritic metallic, \( \sigma_m \) is the conductivity of the continuous, insulating matrix, and \( \sigma_p \) the conductivity of the dispersed metallic is assumed to be many orders of magnitude greater than \( \sigma_m \) (so it does not appear in the equation). For \( \sigma_m = 10^{-2} \text{ S/m,} \ p = 10\% \), the overall conductivity of the mix is 0.0013 S/m (-> 752 ohm m res.) barely above the matrix, as one would expect. But in EM testing of such material, a response is obtained from small eddy current loops confined to individual particles and not from eddy currents circulating around the entire core. This gives a pseudo-conductivity dependent on particle conductivity, concentration, diameter and the core diameter (Yang and Emerson 1997). Here the measured conductivity is:

\[ \sigma_p = p \sigma_m (D/D)^2 \]

Results
The mass property, magnetic susceptibility, and EM conductivity data are given in Table 3. Ward (1966) defines a massive sulphide as being at least 50% by volume sulphides and having a minimum density of 3.8 g/cc. However, for this 36 sample data set it is deemed preferable to classify the 25 samples with air dried bulk densities exceeding 4.2g/cc as massive, the five samples (#28–31, 33) with densities in the 3.7–4.0 g/cc range as semi massive, and the remaining six samples (#25–27, 32–34) in the 2.7–3.3 g/cc range as low density pyrite rock. Half the samples tested have inferred grain densities in excess of 4.6 g/cc attesting to their heavily pyritic nature. The presence of minor amounts of sulphate alteration, silicates, and sulphides such as sphalerite, will result in densities below the nominal 5.0 g/cc.
Table 3. Pyrite conductivity data:

| #   | BD g/cc | mag k SI x 10^-3 | EM cond. S/m | DBD g/cc | WDB g/cc | PA % | GDA g/cc |
|-----|---------|------------------|--------------|----------|----------|------|----------|
| 1   | 4.96    | 2                | 2050         | 4.96     | 4.97     | 1.2  | 5.02     |
| 2   | 4.93    | 2                | 1857         | 4.93     | 4.94     | 1.1  | 4.99     |
| 3   | 4.86    | 2                | 4250         | 4.86     | 4.86     | <0.1 | 4.86     |
| 4   | 4.92    | 2                | 4630         | 4.92     | 4.92     | <0.1 | 4.92     |
| 5   | 4.96    | 3                | 116          | 4.97     | 4.98     | 0.7  | 5.01     |
| 6   | 4.89    | 2                | 35           | 4.88     | 4.90     | 1.8  | 4.97     |
| 7   | 4.90    | 2                | 54           | 4.90     | 4.91     | 1.6  | 4.98     |
| 8   | 5.00    | 2                | 186          | 5.00     | 5.00     | 0.3  | 5.00     |
| 9   | 5.02    | 2                | 88           | 5.02     | 5.02     | 0.2  | 5.02     |
| 10  | 4.82    | 2                | 28           | 4.82     | 4.85     | 2.8  | 4.96     |
| 11  | 4.73    | 2                | 59           | 4.72     | 4.79     | 5.6  | 5.00     |
| 12  | 4.53    | 2                | 34           | 4.52     | 4.58     | 5.8  | 4.81     |
| 13  | 4.31    | 2                | 17           | 4.61     | 4.42     | 12.1 | 4.89     |
| 14  | 4.40    | 2                | 20           | 4.38     | 4.47     | 9.2  | 4.82     |
| 15  | 4.60    | 2                | 45           | 4.57     | 4.65     | 7.7  | 4.95     |
| 16  | 4.82    | 2                | 15           | 4.81     | 4.81     | <0.1 | 4.81     |
| 17  | 4.61    | 50               | 11           | 4.60     | 4.63     | 1.9  | 4.69     |
| 18  | 4.30    | 38               | 6            | 4.30     | 4.33     | 3.0  | 4.43     |
| 19  | 4.60    | 1                | 4.2          | 4.60     | 4.61     | 1.0  | 4.65     |
| 20  | 4.39    | 820              | 80           | 4.39     | 4.46     | 2.9  | 4.52     |
| 21  | 4.27    | 491              | 89           | 4.27     | 4.27     | <0.1 | 4.27     |
| 22  | 4.23    | 416              | 69           | 4.23     | 4.23     | 0.3  | 4.24     |
| 23  | 4.47    | 452              | 108          | 4.47     | 4.47     | <0.1 | 4.47     |
| 24  | 4.50    | 8                | 78           | 4.50     | 4.50     | 0.2  | 4.51     |
| 25  | 2.80    | 12               | 0.7          | 2.80     | 2.80     | 0.5  | 2.81     |
| 26  | 2.75    | 4                | 0.5          | 2.75     | 2.75     | 0.3  | 2.76     |
| 27  | 3.12    | 23               | 1.1          | 3.12     | 3.13     | 0.8  | 3.15     |
| 28  | 3.73    | 4                | 2.5          | 3.73     | 3.73     | 0.2  | 3.74     |
| 29  | 3.81    | 25               | 2.3          | 3.81     | 3.81     | <0.1 | 3.81     |
| 30  | 3.99    | 31               | 2.8          | 3.99     | 3.99     | 0.3  | 4.00     |
| 31  | 3.90    | 27               | 1.5          | 3.90     | 3.91     | 1.0  | 3.94     |
| 32  | 3.29    | 21               | 0.6          | 3.29     | 3.30     | 0.5  | 3.31     |
| 33  | 3.05    | 43               | 0.7          | 3.05     | 3.05     | 0.3  | 3.06     |
| 34  | 3.23    | 44               | 3.5          | 3.23     | 3.23     | <0.1 | 3.23     |
| 35  | 3.83    | 25               | 16           | 3.83     | 3.83     | <0.1 | 3.83     |
| 36  | 4.77    | 4                | 8            | 4.76     | 4.77     | 0.5  | 4.78     |

Notes:
- BD – bulk density air dried, as collected; DBD – dry bulk density, 105° dried; WBD – freshwater saturated density; PA – apparent (water accessible) porosity; GDA – inferred grain density; measurements made @ 22°C temperature.
- Magnetic susceptibility, mag k, measures in an induction coil @ 400 Hz.
- Electromagnetic conductivity, EMσ, measured in an induction coil energised to 1 MHz or below onset of skin effect frequency, EM cond. values ≥10 S/m rounded off. The EM conductivity is deemed to be quasi-DC conductivity. The high frequencies are required for a good signal to noise ratio as, pursuant to Faraday’s Law, the magnitude of the induced electromotive force in a conducting loop of material equals the magnitude of the rate of change of flux through it.
- EM conductivity max. measured value given: for a banded sample this is parallel to bedding where energising flux in ind. coil is normal to bedding; some banded samples have silica or silicates between pyrite layers and conductivity normal to bedding is quite low, in such cases the cited conductivity would be apparent as it is only due to the conductive part of the core.
- Measurement accuracy better than 1%, measurements are mesoscale, air dried state. Coil measurements made with Rhodes & Schwarz HM 8118 bridge and Fluke PM 6306 RCL meter.
- Sample locations: #1, 2 Arusha region Tanzania; #3, 4 Navajún, Spain; #5-9, 11-13, 15 Dos de Mayo province Peru; #10, 14 Gumeracha Sth Australia; #16, 17, 20 Elura NSW Palaeozoic; #18 Mt Lyell, Tasmania; #19, 28, 33 Kalgoorlie region Precambrian greenstones Western Australia; #21, 24, 27, 29, 30, 34, 35, Mt Isa Group, Queensland; #22, 23 Woodlawn NSW Palaeozoic; #31 Porgera, Pacific Islands; #32 McArthur Basin Group, Northern Territory; #36 nodular pyrite, Hunan Province, China; total of 36 locations, all hard rock terrain – soft rock sedimentary pyrite not included in sample suite.
for pure pyrite. The cube specimen #3 has a low grain density for pyrite, 4.86 g/cc, which is assumed to be due to internal occluded voids inaccessible to the vacuum saturant.

Porosities are very low (≤0.1%) for eight samples, low (0.2–0.8%) for twelve samples, moderate (1–2.9%) for ten samples, high (5.6–12.1%) for five Peruvian samples (very voidy, visually), and very high (22.9%) for an extremely weathered massive (now skeletal) sulphide (#19).

Magnetic volume susceptibilities (k) are generally low (≤5 × 10⁻⁵SI) except for four samples (#20–23) containing minor pyrrhotite (416–820 × 10⁻⁵SI). Pyrite’s mag k was thought to be -4 × 10⁻⁵SI, but 16 samples have mag k values below this. Sample mag k's up to 50 × 10⁻⁵SI can be ascribed to the presence of minor amounts of Fe paramagnetic silicates, Fe carbonate etc.

The conductivity data are best viewed in the perspective of a density crossplot which is presented in Figure 11 where the sample conductivities from low (0.5 S/m) to high (4250 S/m) are clearly seen to increase, broadly with density.

**Interpretation**

The data have been grouped and trended as follows:

I. massive single crystal pyrite, #1, 2, 3, 4;
II. massive variably porous pyrite, polycrystalline aggregate, #5–15;
III. massive pyrite + minor silicate and sphalerite in siltstone, #16, 17;
IV. pyrite altered-minor alt. #36, moderate alt. #19;
V. pyritic banded metasediment, moderately pyritic to semi massive, #27–33;
VI. veinlet, blebby pyrite in black shale, #25, and quartz #26;
VII. banded, #34, semi massive, #35, and massive, #24, pyrite all with minor chalcopyrite;
VIII. massive pyrite with minor pyrrhotite, #20–23 (note the elevated mag k values in Table 3).

Also shown are chalcopyrite ore with metasedimentary gangue, C, Cobar NSW; and nickeliferous pyrrhotite, K, from Kambalda WA. These two massive sulphide samples contain minor pyrite and are not in Table 3, they are included for comparison only, to contrast with the lower conductivity of massive polycrystalline pyrite.

The pyrite single crystal conductivities (i) are high by any standard, 1000s S/m. However, pyrite of interest in the field occurs massively aggregated and the conductivities of the samples (ii, iii) in this group are two orders of magnitude below that of the single crystals. Conductivities in the 10s to low 100s S/m increase, more or less, with density and diminishing porosity. Voids, microcracking, intercrystalline alteration products, and grain boundary replacement (surface film) of presumably Fe sulphate and/or marcasite (Deer, Howie, and Zussman 1992) can be seen or presumed in the samples. All serve to reduce conductivity and this tendency is exacerbated by pyrite’s cubic blocky crystallinity. So texture, overall, impedes aggregated pyrite attaining its single crystal conductivity, at least in the samples tested here. Contrast this with the pervasive, threading, connecting, dendritic habit of chalcopyrite and pyrrhotite, much better for electrical continuity than sutured pyrite polyhedra.

Minor amounts of insulating minerals diminish conductivity (iii); alteration of the pyrite lowers conductivity yet further (iv).
powdery melanterite, FeSO₄ ⋅ 7H₂O, on grain boundaries and in cracks, together with an acrid smell will serve to identify it. In limited measurements the writer carried out on clearly altering material, conductivity seems to be of the order of a few S/m, Harvey (1928) measured three samples with conductivities ranging from 10 to 1000 S/m, presumably on fresh polished surfaces. Unfortunately fresh unaltered marcasite could not be located to include in the measurements made for this article.

Concluding remarks

A blend of tough iron and soft sulphur could be expected to yield an interesting substance. The covalent chemical combination, as a disulphide, of these two disparate elements does not disappoint. For humankind pyrite has been, and continues to be, a very significant mineral because of its involvement in, and contributions to, culture, industry, materials science, geoscience, and, indeed, to life itself. It has been an impressive set of physical properties which merit appreciation, and it warrants continuing study, especially as to its electrical properties. Pyrite, the firestone, historically and currently is a very important mineral. Pyrite matters. It is advantageous for geoscientists to know if it is about, for one reason or another, for better or for worse.

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