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Lapis lazuli – the most beautiful rock in the world

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Introduction

Lapis lazuli is a striking rock: intense, vivid, shimmering, deep blue (Figure 1). It is rare, semi-precious and non-metallic and has been found, so far, in only a few places. The main source of best material is Afghanistan where, at the 4000 m level, it has been mined for millennia and was traded along the Silk Road from Central Asia to the Mediterranean. It is valued to this day as a middle-ranking gem.

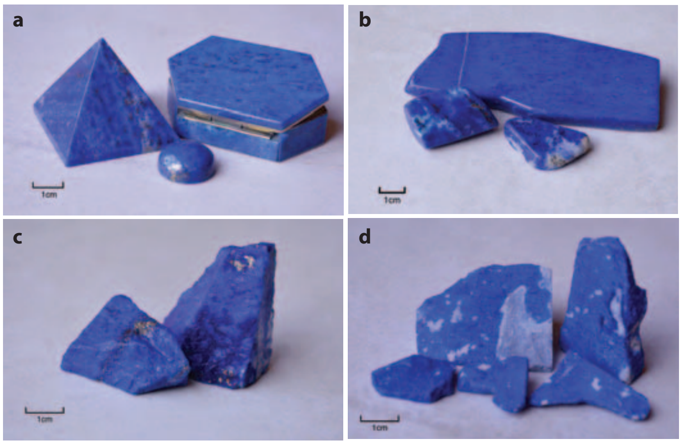

Figure 1. *(a–c) Average (medium) grade Afghan lapis; (d) Chilean lapis. (a) Crafted lapis lazuli. The pyramid's density is 3.01 g/cc. Pyrite occurs irregularly in disaggregated layers with grainsize 0.01-0.1 mm. The small hemisphere has less pyrite, the disseminated pyrite grains are ~0.2 mm diameter. In this, and in a jewellery box, inter-pyrite electrical continuity is absent. (b) Polished lapis lazuli. The large plate's density is 3.01 g/cc, and the disseminated pyrite has ~0.15 mm grainsize. The cylinder's density is 2.97 g/cc and its pyrite occurs in bands with pyrite grainsize ~0.3 mm, and in disseminations ~0.1 mm grainsize. The triangular plate, density 2.85 g/cc, has considerable carbonate (white), and sparse disseminations of pyrite ~0.2 mm grainsize. Inter-pyrite electrical continuity is absent. (c) Lapis from a block of somewhat better grade. The density of the right hand side piece is 2.84 g/cc. The left hand side piece (from the same block) is more pyritic, its density is 2.94 g/cc. In both, the pyrite occurs as grains (~0.1 mm diameter) and small grain clusters. There is electrical continuity intra-cluster but none between grains or between clusters. (d) Chilean lapis. The density of the larger right hand side sample is 2.71 g/cc. The larger left hand side sample's density is 2.76 g/cc. The three smaller sample densities are 2.76 g/cc. Note the white carbonate spotting and zoning. Sparsely disseminated pyrite occurs in all, with grainsizes varying from 0.01 mm to 0.1 mm approx.*

Lapis and its derivatives have been intrinsic to exquisite works of art and construction across cultures. Overlaying many of these and other mundane applications of lapis is a mystique of metaphysical attributes.

Many types of rocks can be dressed, shaped, and polished to an appealing sheen. They have been used to great decorative effect, on a large scale, in buildings, monuments, and tombs. Red imperial porphyry, for example, with red feldspar and manganiferous epidote imparting a sombre, rosy lustre, was much admired by the ancients. Magnificent marbles continue to grace many constructions, large and small. But only one rock, lapis lazuli, has exhibited a beauty so superlative that, in addition to building adornment, it has long been used in panels, inlays, necklaces, ring stones, and sculptured ornaments such as vases (Figure 2). When powdered it was the pigment for the stunning blue ultramarine[1] paint used in many a medieval painting (Figure 3). It is still employed by specialist artisans.

Through the ages lapis lazuli has indeed had an interesting history, and this is touched upon in this paper, briefly and selectively. The physical properties of this attractive material are sparsely documented so the results of some tests on Afghan and Andean Chilean lapis are also presented.

Figure 2. *Illustrations of carved artwork in lapis lazuli. (a) The Mughal elephant is 8 cm long. Photo by Adrian Pingstone (February 2003) and released to the public domain https://commons.wikimedia.org/wiki/File:Lapis.elephant.800pix.060203.jpg. (b) The urn in the State Hermitage Museum in Saint Petersburg is two meters high. Photo by Dezidor / CC BY 3.0 https://commons.wikimedia.org/wiki/File:Ermitáž_(28).jpg. (c) The bowl is from Iran and is dated to around the third millennium BC. Photo by SiefkinDR / CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:Lapis_bowl_Iran.JPG.*

[1] Ultramarine: of foreign origin, beyond the sea, as the raw material had to be imported into Europe.

Lapis mineralogy

The essential components of lapis lazuli are the azure-blue felspathoid lazurite, usually finely granular, and small amounts of fine grained pyrite which impart a sparkle (stars in the deep blue of the heavens). Calcite / dolomite is often present; the less the better. Gangue mineralogy can include amphibole, pyroxene, mica, and others. Some would regard pyrite as gangue. Excessive pyrite and calcite are certainly deleterious to the quality of lapis. Table 1 lists the mineral components. For a gemmy material lapis lazuli's hardness is not high, being ≤6 (impurity dependent) on the Moh scale, but it is durable enough and can be quite resistant to crushing.

Lazurite is a member of the sodalite-haüynite group of cubic felspathoid minerals. Minor amounts of other felspathoids often occur in lapis lazuli. These are gemmy minerals of relatively low density. Na, Ca and Mg are important elements in the mineral chemistry of lapis deposits. Sulphur, picked up from "impure" limestone (Ca) or dolomite (Ca, Mg), is essential for colour (Jones 2015). Gradations in chemical composition result in variations in colour (blue to green) and intensity of colouring. Impurities are quite common in the original sedimented carbonate, and, when metasomatised, can form suites of calcium and magnesium silicates including relatively dense amphibole, pyroxene, and Mg olivine. The fine detail of gem felspathoid genesis has yet to be formulated, so the origin of lapis is unclear.

Lapis geology

Finlay (2004) investigated lapis lazuli's history as the basic ingredient of medieval ultramarine paint and gives an absorbing account, with a good sketch map, of her travels to the historic mines at remote Sar-e-sang, south of Faisabad, in the Kokcha River valley, Badakshan Province, northeast Afghanistan, in the rugged Hindu Kush massif. There, in a valley lateral to the Kokcha, she saw the splendid sight of white country rock, speckled with blue, gleaming in the morning sun. Later she inspected hillside adits where lapis lenses were being mined. Voynick (2011), in a brief account of the mining history at Badakshan, mentioned that variable grade lapis occurs in lensoid bodies "several hundred feet long". Jones (2015) noted that the grey-white marble host is up to 400 m thick.

Kostov (2004) summarised the Badakshan geology as involving metasomatic processes associated with pegmatitic and aplitic granitoids intruding dolomitic marbles. Variably coloured lazurite mineralisation lenses can occur in Ca Mg alteration zones that contain a variety of silicates, or also in interbedded calcified formations with gneiss and amphibolite. So, the ore mineralogy and the host geology are both complex. Such deposits could perhaps be regarded as low Fe skarns. Pure lazurite, either massive or crystallised in rhombic dodecahedral form, is very rare. More commonly lazurite is the chief component of the rock lapis lazuli, and it is this rock that is herein discussed.

Lapis seems to be confined mainly to limestones and dolomites contact metamorphosed by igneous intrusions, according to Zöldföldi & Kasztovsky (2009) who provide a map indicating 13 occurrences of lapis worldwide. Deposits near Lake Baikal in Russia are thought by some to have been another important lapis source in ancient times. Chilean lapis, currently extracted from north of Santiago, is of paler hue. Other lapis sources have been reported in Central Asia, Canada, USA, Algeria, Angola, and Burma. The writer is not aware of any Australian contact metamorphosed carbonate localities that contain lapis.

Commercial lapis

Afghan best quality lapis, rich in lazurite, has three grades: indigo blue, sky blue, and greenish blue; all quite expensive. High quality lapis can sell for $5 or more per gm; medium grade fetches around a tenth of this price. Top grade blue pigment, milled and washed, is worth about $10 per gm. Lapis is a valuable material; it's value is directly related to the volume and blue colour intensity of the silicate lazurite. The best lapis is rich in lazurite with a homogeneous appearance and a minimum of accessory minerals, some of which have a relatively high density. Lower grades of lapis are textured, often banded, with significant and obvious amounts of carbonate and silicates. Pyrite is common to all grades, but can vary from sparse disseminations to heavier concentrations of clots, shards, grains, and veinlets. The mineralogy, and thus the value, of lapis lazuli rock can vary considerably.

Poor grade lapis lazuli can be enhanced (often unbeknown to the buyer) by dyeing, especially on the whitish carbonate spots, and then by paraffin impregnation to seal the dye and improve the polish. Such treatments are detectable by acetone or dilute HCl which often will wash off the dye. The use of a hot needle should detect any paraffin.

The application of HCl to lazurite should release H_2S leaving gelatinous silica; this is one of the tests for lapis. If HCl is put on sodalite, another somewhat similar bluish felspathoid, only gelatinous silica is formed. The presence of pyrite, even in small amounts, in a blue mineral matrix helps identify a sample as lapis.

Many synthetic versions of lapis have been made, e.g. dyed jasper. Most of them are pretty obvious as imitations on careful inspection. Synthetics are discussed by Anderson & Jobbins (1990), GIA (1995), and Schumann (2006).

Persian blue was used in glazes on mosque and palace tiles in the Middle East e.g. the vast Shah Mosque in Isfahan, Iran. This colour, derived from cobalt minerals plentiful in the region, represented or emulated the lapis colour and effect, but it is not lapis (Mishmastnehi & Holakooei, 2015).

Lithotherapy

Worries and troubles have ever distressed humankind. The Bible gloomily declares that man, born of a woman, lived briefly and miserably (Job, xiv, 1). Hesiod (~700 BC), the Greek epic poet, related in his *Works and Days* (100-1) the myth of Pandora's jar, a wedding present from Zeus, to explain the origin of toil and suffering. Pandora, the first woman, opened the jar and let slip a multitude of evils:

> *full the earth, and full the sea, of evils*
> *unbidden miseries, now by day, now by night,*
> *beset us of their own accord*

Minerals, for many, were the prophylactics to employ against these blights. Materials from the mineral kingdom, seemingly so inert, were seen to be wondrously dynamic: nondescript lodestone, powerfully magnetic; cool quartz, thermally quite conductive; resinous sphalerite, triboluminescent when scratched;

golden pyrite, sparking when struck; and lapis, viewed as the purest blue.

The veneration of minerals has a long history in myth, magic, and medicine. A beautiful gem, such as lapis, seemed to offer relief from life's woes to many. Gems still do – visit any crystal shop for an abundance of pocket fondling stones. Modern beliefs reflect those held in the Middle Ages and earlier. Marvellous powers, particular properties, and mystic virtues were believed to be divinely implanted in gems. Consequently gems provided a medium by which the divinity may be approached and ameliorating favours obtained.

Schumann (2006), in a concise account of the alleged curative powers of gems, notes that lapis is currently prescribed for headache, sore throat, and sciatica. George (2004) mentions several attributes reputed to be associated with lapis. These include: benefits in creative expression, vitality, virility and strength; alleviation of problems with the thyroid and throat; and the enhancement of psychic abilities. It will be shown that medieval writers believed in kindred qualities too.

Placebo comfort has always been, and still is, part of the human experience. Or is there more to all this?

The ancient world

Theophrastus (c.370-c.287 BC), Aristotle's pupil, in his treatise *On Stones* included lapis lazuli in the category of valuable stones. Lapis was known as *σάπφειρος* or *sapphirus,* in the ancient world and in medieval times too. A purer deep blue variety, low in pyrite, was known as *κύανος* or *cyanus*, a term which was also applied to other blue minerals, such as azurite (Caley & Richards, 1956). Transparent corundum in its blue gem form is now known as sapphire.

Lapis features in the Christian Bible as a precious item prominent in priestly and divine functions. Aaron's holy garments were fashioned for glory and beauty with lapis set in a second row of decorative stones (Exodus xxviii, 2, 18). In his vision of God, Ezekiel (i, 26) noted the likeness of a lapis throne in the firmament overhead. In St John's Apocalypse the foundations of the new Jerusalem's jasper walls were described as adorned with precious stones; the second foundation was of lapis lazuli (Revelation xxi, 18, 19).

Deep blue lapis was the premier blue pigment in Roman times. Azurite was popular too, but in time converted (or degraded) to green malachite (Voynick, 2015). Lapis lazuli, along with red garnet and amethyst, was also very popular in Roman jewellery (Hornblower & Spawforth, 2012).

The natural historian Pliny the Elder (AD 23–79), comparing azurite and lapis lazuli, commented, *Naturalis Historia* 37.119–120:

> *dividitur autem et haec [cyanus] in mares feminasque. inest ei aliquando et aureus pulvis non qualis sappiris, in his enim aurum punctis conclucet. Caeruleae et sappiri rarumque ut cum purpura. optimae apud Medos, nusquam tamen perlucidae. praeterea inutiles scalpturis intervenientibus crystallinis centris. quae sunt ex iis cyanei coloris mares existimantur.*

> *Azurite [blue copper carbonate] too is separated into male and female types. Sometimes a golden powder [cuprite?] occurs in azurite differing from that found in lapis lazuli where the gold glistens as spots [pyrite grains]. Lapis lazuli is also blue, and, rarely, purplish. The best comes from Persia [i.e. central Asia], but translucent lapis occurs nowhere. Furthermore lapis stones are impractical for engraving when knots of rock crystal get in the way. Lapis lazuli coloured like azurite is considered to be male.*

In antiquity stones had gender. Those with relatively more marked characteristics were male (darker, more brilliant), those with less (paler, duller) were female. In discussing sard, a dark red-brown chalcedony, Pliny, *Naturalis Historia* noted, 37.106:

> *et in his autem mares excitatius fulgent feminae pigriores et crassius nitent.*
> *among these stones too the males glow more intensely, but the females with a duller sheen are less lively.*

Medieval beliefs

Marbod (1035-1123), Bishop of Rennes in Brittany, in his famous book on gems, *Liber Lapidum,* devoted 26 lines of hexameter verse to lapis lazuli. Beckmann (1799) compiled and edited Marbod's mineral poems and supplied useful footnotes. The fifth poem (lines 103–128) is *De sapphiro*:

Sapphyri species digitis aptissima regum,
Egregium fulgens, puroque simillima coelo,
Vilior est nullo virtutibus atque decore.
Hic et Syrtites lapis a plerisque vocatur,
Quod circa Syrtes Lybicis permixtus arenis,
Fluctibus expulsus, fervente freto reperitur.
Ille sed optimus est, quem tellus Medica gignit.
Qui tamen afferitur nunquam transmittere visum,
Quem natura potens tanto ditavit honore,
Ut sacer et merito gemmarum gemma vocetur;
Nam corpus vegetum conservat et integra membra.
Et qui portat eum, nequit ulla fraude noceri.
Invidiam superat, nullo terrore movetur,
Hic lapis, ut perhibent, educit carcere vinctos,
Obstructasque fores, et vincula tacta resolvit,
Placatumque deum reddit, precibusque faventem.
Fertur et ad pacem bonus esse reconciliandam;
Et plusquam reliquas amat hanc necromantia gemmam,
Ut divina queat per eam responsa mereri.
Corporeis etiam morbis lapis iste medetur.
Scilicet ardorem refrigerat interiorem,
Sudorem stringit nimio torrente fluentem.
Contritus lacti superillitus ulcera sanat,
Tollit et ex oculis sordes, ex fronte dolorem;
Et vitiis linguae simili ratione medetur.
Sed qui gestat eum, castissimus esse iubetur,

Fine is the appearance of lapis lazuli – so very suitable for kings' fingers,
Splendid its glitter, so much like the unsullied heavens,
Inferior to none in miraculous powers and charm.
It is commonly called the stone of Syrtis
For around the Gulf of Sirta, mixed with Libyan sands,
Driven about by waves, in seething waters, it is found.
But the best stone is the one that central Asia produces.
Despite its documented opacity,
Powerful nature has enriched it with so much beauty,

That it is rightly regarded as the sublime gem of all gems;
For it keeps the body vigorous and the limbs healthy.
He who carries it cannot be injured by any crime.
He survives hatred, dread troubles him not.
This stone, so they say, releases the shackled from prison,
Unfastens closed doors and loosens applied bonds,
And appeases god who becomes well disposed to one's prayers.
It is said to be good for restoring harmony.
The art of divination esteems this gem more than mortal remains,
As, through it, the divine answers can be obtained.
This stone heals diseases of the body.
One can rely on it to relieve internal inflammation,
It limits sweating in excessive heat.
Ground up with milk, applied as ointment, it heals sores,
It recovers dirt from the eyes and banishes headaches;
Likewise it cures speech disorders.
But he who carries it about is bidden to be a most upright person.

So, in Marbod's view, the power and character of lapis offer impressive lithotherapeutic benefits: miracles, access to the divinity, energetic soundness of body, security in the face of malefactors and the envious, passage through barriers, promotion of serenity, and medication. Clearly, lapis must be the talisman of choice for the anxious, and even for the able.

Beckmann (1799) in his scholarly footnotes pointed out that: (1) in the first line of the poem Marbod's *sapphirus* was not a hard, dense, adamantine gem, rather it was lapis lazuli, whose location could not really be referenced to Libya where, it seems, Pliny had noted the occurrence of another mineral. (2) In the eighteenth line it is assumed that divination or necromancy is prophetic communication with the remains of the dead, especially those of saints, whereby the future, and the locations of hidden objects could be revealed, or enigmatic data interpreted, through trances or exalted states. This was real magic, although with unreal expectations. The cultish invocation of the dead was big business in Marbod's time. It is quite astonishing to see that talismanic lapis lazuli was put on par with a venerated body, or relic of a body, as an efficacious prophetic or propitiatory tool. In a footnote Beckmann cited an opinion that *necromantia* is the calling up of the ghosts of the dead. (3) Regarding the last line of Marbod's poem: Beckmann shrewdly noted that this was a canny proviso used by lithotherapists in the case of clients who failed to elicit the stone's powers, and then proceeded to deny those powers existed; obviously the clients were not holy enough. Presumably few would want to advertise the lax state of their souls, so the stone's reputation survived. Very clever.

Marbod's claims for the lapis lazuli were quite extraordinary, and surely must have raised the eyebrows, if not the ire, of the church hierarchy. To say that its agency mollifies god and results in prayers being answered favourably is extreme theology to say the least, even allowing for gems to be divinely impregnated material.

The double whammy of birth and death bracketed many a mentally bleak medieval life. At birth, it was defiled by original sin, according to St Augustine, ever admonitory; in death, it awaited punishment, according to the Apocalyptic visionaries. The ultimate forensic event, the Day of Judgement, as gruesomely depicted by Hieronymus Bosch, was a lifetime worry, if not dread. All were aware of the unending torment of the damned as portrayed by preachers and publications. So, although devotion to a stone may seem strange now, it helped then. Prominent among the available aids against damnation was lapis, along with icons, images, and the Rosary – the closed string of five decades of beads for counting repeated prayers. Lapis beads on a Rosary would have been quite desirable for aesthetic and eschatological reasons. Dire prognostications were believed and feared by medieval people. Their attitudes are utterly unlike the attitudes of most people today. Now scripted Armageddons regularly entertain blithe multitudes in movie theatres, and video games, around the world.

Later writings

Agricola (1546, *De Natura Fossilium VI*) in his early pre-modern mineralogy discussed lapis, but really only repeated Pliny. In evaluating the worth of sixteen leading gems he ranked the best quality lapis lazuli in seventh place, ahead of blue sapphire, and after diamond, pearl, emerald, opal, carbunculus (literally a small glowing coal, but possibly a red spinel or a ruby), and plasma (a bright green translucent chalcedony). The middle ranking of lapis lazuli more or less mirrors current valuations of gemmy materials, except that now good sapphire and aquamarine (gem beryl) would outrank lapis lazuli.

Lapis (after washing 50 times) was mentioned by Burton (1628) as a purging remedy for melancholy, but whether it should have been used as pill, powder, or potion was not stated. Kircher (1678), the Jesuit polymath, in a comprehensive book of pre-modern gemmology, described lapis as opaque blue, speckled with golden spots, and a rival in colour to sapphire. He listed powers peculiar to lapis such as curing fever, invigorating vision, inducing sleep, and relieving arthritis.

More precious than gold

Ultramarine owes its colour to the sulphur ion in the lazurite cubic lattice. As the charge on the ion varies, so does the lazurite tint. Pure lazurite being very rare, the colour was extracted from lapis lazuli. Thus lapis had a firm place in the visual arts culture of the Renaissance and the Middle Ages where it contributed to paintings, psalters, illuminated manuscripts, and frescoes (on plaster). It is still used in its natural form.

This medieval paint pigment was so scarce that it was more valued than gold. The deep blue of ultramarine was, and still is, fairly cheaply synthesised or imitated by various techniques. However, none can match the subtly impressive character of natural ultramarine with its virtually ineradicable content of associated minerals (see Table 1) interacting in nuanced plays of light that delight the viewer. Some connoisseurs consider its effects to be perfect, unsurpassed by any other colour or hue. This priceless pigment was often rationed to parts of a painting, such as the robes of the Virgin Mary, or as an overcoat to a base of cheap blue azurite. Diluted it served as an optical filter in a final varnish on a whole picture.

Kircher (1678) outlined the use of colour in the paintings of his time, and the special use of ultramarine ash (lower grade pigment) in a neutral transparent glaze, thinly applied, for optical enhancement of the subject and preservation of the work. *Mundus Subterraneus* 10, 13:

Table 1. Mineralogy of lapis lazuli

Mineral	Hardness (Moh scale)	Density (g/cc) (approx.)	Comments
Lazurite $(Na,Ca)_8(AlSi0_4)_6(SO_4,S,Cl)_2$ [the amounts of SO_4, S, Cl can vary considerably] *a rare and valuable mineral*	≤5½	2.45	Sulphur-related colour centres, deep azure-blue, waxy/vitreous lustre when polished, commonly granular massive, semi-translucent
Calcite $CaCO_3$	3	2.72	Inclusions and bands; transparent to opaque white-grey carbonate
dolomite $(Ca,Mg)CO_3$	≤4	2.85	
Pyrite FeS_2	≤6½	5.02	Disseminations – grains, shards; opaque sulphide, splendent yellow
Some other constituents (not all listed) may be present with varying degrees of translucency			
Afghanite	≤6	2.60	Na, Ca, K felspathoid, bluish, rare
Haüynite	≤6	2.50	Na, Ca felspathoid, blue-green, rare
Nepheline	≤6	2.60	Na, K felspathoid, greyish
Nosean	≤6	2.35	Na felspathoid, blue-green, rare
Sodalite	≤6	2.20	Na felspathoid, lavender blue
Albite	≤6½	2.62	Na plag. felspar, whitish
Marialite	≤6	2.55	Na scapolite (alt fels.), blue-grey
Mica	≤7	2.86	Phlogopite, K Mg silicate brown-green
Pyroxene	≤6	3.25	Diopside, Ca, Mg, silicate, white/green
Forsterite	ϖ6	3.20	Mg olivine, silicate, greenish
Lazurite can be regarded as a mixed crystal of the sodalite-hauynite felspathoid group			
Lapis lazuli's colour depends on its chemical composition: it is basically blue but can vary from marine blue to violet blue, sometimes greenish tinges are present; commonly it is opaque			
Lapis lazuli's density is ~2.75± g/cc depending on mineral components; note that lazurite itself is a relatively low density mineral			
Lazurite can exhibit short wave ultraviolet yellowish fluorescence – may vary; contained calcite may respond to long wave UV with pinkish fluorescence			
Lazulite or blue spar is a dense (3.06 g/cc) dark blue-green hydrous Mg phosphate that, despite the name, is not a component of lapis lazuli, nor is turquoise a blue Ca, Al, phosphate (2.70 g/cc)			

Propter immensum coloris ultramarini pretium non solent eo uti pictores, ut aliis coloribus, sed pingunt imagines, quas caeruleas volunt, communi caeruleo ex Armenio praeparato, aut ex vitro illius coloris, quod Smaltum vocant; deinde partes eas, in quibus lux haeret, cerussa, postmodum coloribus istis, ut res postulat, rite adhibitis iisque optime exsiccatis, ultramarino colore humectato oleo nucum, & spiritu terebinthinae totam illam picturam caeruleam tanquam vernice, ….. Hoc modo per obductum colorem tanquam per glaciem aut vitrum subjecti resplendent, pulchritudinem non solum excellentiorem a velamine nacti, sed & perpetuitatem, ut ne ducentis quidem annis, vel minima lucis, vel pulchritudinis portio decedat.

Owing to the enormous cost of ultramarine, painters do not usually use it as they do other colours, but they paint semblances with a common blue derived from prepared Armenium [azurite, copper carbonate], or from glass of that colour [derived from cobalt compounds] which is called Smalt. Next they paint those parts wherein brightness abides with white lead, and after that with those particular colours as the layout of the painting requires. When all these are properly applied and thoroughly dried, they smear a blue all over that picture using ultramarine colour moistened with nut oil and spirit of turpentine, like a varnish ….. In this way the subject matter of the picture glitters through the applied surficial colour as if through ice or glass, with not only outstanding beauty but also temporal durability. As a result not even in two hundred years does the least part of its brightness or beauty degrade

Kircher (1678) also provided a recipe for making ultramarine pigment extracted in solution from lapis lazuli. The procedure involving powdering, dissolving, leaching and filtering, must surely rate as a unique alchemical ritual for leaching a rock. *Mundus Subterraneus, Color ultramarinus Lazuli,* 10, 14:

Recipe lib.1.lapidis in tenuissimum pulverem redacti, ac cum aqua clara ad porphyrium triti, & impone scutellae vitriatae, donec pulvis in umbra exsiccetur, quem iterum, si in massam coierit, in pulverem redige; deinde habeas in promptu Resinae pini uniiii. Picis graecae, Mastiches, Thuris, ana uniii. Olivarum unii. Patellam vitream supra lentum ignem pone, ac primo imponas oleum, & cum bene calidum erit, adde resinam, postea picem, deinde thus, ac postremò mastichen, ac move optime: postea alteri *scutellae infunde, ut ebulliat parum. His peractis habeas ad manum aliud vasculum, in quod pones siccum lapidis pulverem, cui affundes unguentum dictum, paulatim movendo spatula, ut bona fiat mixtio. Tum relinque per diem mixturam, & cum auferre vis colorem, funde pastam supra aquam bullientem, ac move & agita optime materiam, & cum aqua incipit refrigerari, ejice, ac aliam calidam affunde; idque fac, donec aqua colorem trahat, atque repete toties, donec omnem colorem extraxeris. Singulas extractiones separare potes, ut distinctos colores habeas.*

Take one pound [327.45 gms = 12 unciae/ounces] of lapis stone reduced to the finest powder and ground with clear water until purple. Put this into a glazed dish away from sunlight until the powder has dried out. Reduce to powder a second time if the material coagulates. Then have ready four ounces of pine resin; three ounces (each) of turpentine resin [colophony/Greek pitch], mastic [pistacia lentiscus gum], and frankincense [boswellia gum resin]; and two ounces of olives [presumably oil]. Place the dish above a slow fire, put in the oil and when it is very hot firstly add the resin, then pitch, then frankincense, and lastly the mastic. Agitate thoroughly then pour into a second dish to bubble a little. On the completion of these procedures have ready another small vessel and place the dry lapis powder in it. To this add the specified aromatic grease gradually, stirring with a spatula, so that all is well mixed. Then leave for a day. When you wish to extract the colour pour out the doughy material on top of boiling water and stir and shake thoroughly. When the water begins to cool take it out [this contains suspended ultramarine pigment] and pour in another lot of hot water and continue to do this as long as the water keeps drawing out the colour. Repeat the process until you have extracted all the colour. You can separate the extractions, one by one, so that you have different shades of colour.

The writer is not too sure about the chemistry and physics of this involved mineral processing operation. Used in Kircher's time, among other similar techniques, it is no wonder that the pigment cost a fortune given the ritual of its preparation and the very high cost of the lapis lazuli. The manufacture of natural ultramarine requires high quality lapis, then, and now, not always available. It also requires skill, patience, and thoroughness to produce the compelling tone and brilliance of a colour with the character that is so attractive in artwork.

Gazo (2015) extracts pigment powders from Afghan lapis in four grades using, after much research, a modified version of another recipe found in Cennino Cennini's treatise on painting, written in Italian ~1390. Gazo kneads milled and washed lapis with beeswax, mastic, and pine resin and then extracts the ultramarine colour in solution in a painstaking, lengthy, manual operation. Gazo's top grade Fra Angelico pigment and his minimally treated plain lapis lazuli powder are shown in Figure 3. Some tests were carried out on these materials.

The beautiful ultramarine effect can be seen in Figure 3 in two famous works of art: Girl with a Pearl Earring by Vermeer (~1665), and the Virgin in Prayer by Sassoferrato (~1645). The eye immediately focuses on the blue. Evidently, the ultramarine preparation techniques of earlier times resulted in a quite satisfactory product.

Figure 3. *Illustrations of ultramarine pigment and it's use in two famous paintings. (a) The dish on the left contains the highest grade "Fra Angelico" ultramarine produced by Master Pigments of California and the dish on the right contains the basic material – Afghan lapis lazuli ground to powder. Reproduced with permission, Gazo, A/Copyright 2015 MasterPigments. http://www.masterpigments.com/categories/pigments/lapis-lazuli-pigments.html. (b) The Girl with the Pearl Earring was painted by Johannes van der Meer (Jan Vermeer, 1632–1675). Photographer unknown/Public Domain https://commons.wikimedia.org/wiki/File:Johannes_Vermeer_(1632-1675)_-_The_Girl_With_The_Pearl_Earring_(1665).jpg. (c) The Virgin in Prayer was painted by Giovanni da Sassoferrato (1609–1685). Photograph Web Gallery of Art/Public Domain https://commons.wikimedia.org/wiki/File:Sassoferrato_-_Jungfrun_i_bön.jpg.*

The Renaissance bishop

Robert Browning was a Victorian man of letters, and one of the great English poets. Lapis lazuli has a key role in his masterly *The Bishop orders his tomb at Saint Praxed's church* (Kenyon, 1912). The poem is a withering commentary on the vanity, hypocrisy, materialism, and immorality of a Renaissance bishop deemed to be typical of a corrupt time. Saint Praxedes was reputed to be a Roman virgin, of exemplary compassion and charity, who sheltered Christians during the 2nd century persecutions of Marcus Aurelius. She has a church in Rome, but the bishop of the poem is not buried there; he is fictional.

Browning's unrhymed iambic pentameters are the perfect medium to convey the rambling monologue of the dying bishop. He exhorts his sons to do him proud in ensuring that he has an ornate burial vault befitting his exalted status. This must be more elaborate than that of his predecessor Gandolf, a rival, who much to the bishop's vexation died first and secured the best niche in the church. However, Gandolf's tomb is only of a modest stone and this is a consolation. Fading from life he thinks not of repentance, but of revenge on Gandolf who will have to look at his splendid tomb for all eternity. The bishop also takes satisfaction that Gandolf envied him for the woman he had as his lover, and will now envy him in his tomb. The lapis verses, in part of the poem, follow:

Draw close: that conflagration of my church
-What then? So much was saved if aught were missed!
My sons, ye would not be my death? Go dig
The white-grape vineyard where the oil-press stood,
Drop water gently till the surface sink,
And if ye find…ah God, I know not, I!...
Bedded in store of rotten fig-leaves soft,
And corded up in a tight olive-frail,
Some lump, ah God, of lapis lazuli,
Big as a Jew's head cut off at the nape,
Blue as a vein o'er the Madonna's breast…
Sons, all have I bequeathed you, villas, all,
That brave Frascati villa with its bath,
So, let the blue lump poise between my knees,
Like God the Father's globe on both his hands
Ye worship in the Jesu Church so gay,
For Gandolf shall not choose but see and burst!
Swift as a weaver's shuttle fleet our years:
Man goeth to the grave, and where is he?
Did I say basalt for my slab, sons? Black –
'Twas ever antique-black I meant! How else
Shall ye contrast my frieze to come beneath?

Previously the bishop had stolen a large piece of lapis from a church destroyed by fire. Now he wants it retrieved as the piece de résistance for his tomb. The hallowed Christian figures of John the Baptist (Jew's head) and the Virgin Mary (Madonna) are mentioned not for their goodness, but as violent and prurient yardsticks for the size and quality of his lapis. The wish for the lapis to be placed between his knees (under his loins) seems to have been inspired by God the Father holding a large globe of lapis in an adornment on the altar of the Jesuit Church of St Ignatius in Rome.

In death the bishop is the centre of attention, and the focus is the lapis stone. The tomb is an emblematic extension of his vain life and intended to be venerated. The lapis is the chief drawcard.

In his damning depiction of a repellent prelate, Browning did not choose gold, or silver, or diamonds, or pearls, but the rock lapis, as a suitably powerful symbol of human vanity. This compelling poem has become a much discussed classic since it was published in 1845.

Perhaps enough has been said of the reputation of lapis, now for some facts.

Some physical properties of lapis lazuli

As little seems to be known about the physical properties of lapis lazuli rock, the author investigated some samples. The test techniques are referenced in the bibliography. Average grade Afghan and Chilean lapis rock chip samples were cut and shaped into discs and prisms. The various tests used different subsamples i.e. an individual subsample did not necessarily undergo each test. The lazurite in each subsample was checked by HCl (releasing H_2S, a standard identification test) and applied to a streak plate (to show a blue streak). All the Afghan samples were textured i.e. they showed either coarse or fine banding. Most were cut in a direction oblique to any such foliation.

The Afghan lapis produced a yellowish fluorescence (to short wave ultraviolet) which had an irregular appearance owing to the presence of non-fluorescing gangue minerals. However, the Chilean lapis did not respond at all, except for some of its carbonate that fluoresced pink (long wave ultraviolet).

In non-destructive testing by prompt gamma activation analysis, to obtain chemical elements profiles of S and Cl, Zöldföldi & Kasztovsky (2009) showed that Afghan and Chilean lapis were different, with the Chilean variety having higher S/Si and Cl/Si ratios. Principal component analysis showed the Chilean lapis to be quite different, chemically, from Afghan lapis.

Mass properties

Following vacuum saturation with fresh water, and oven drying, water-accessible porosities of 0.9% and 1.5% were determined as averages for the Afghan and Chilean subsamples respectively. These porosities are low, so air dry and oven dry and saturated densities are similar. However, although the porosities are not high, they are finite, and typical for skarn material (Emerson, 1986). The porosity may be associated with alteration, microcracking, and, perhaps, incipient weathering, as the samples came from high altitude. Some of the porosity could be "blind" or dead end. It is thought that the porosity may be mainly associated with the carbonate in the lapis, especially the Chilean lapis. The residual water saturation in the porosity was estimated to be around 50% i.e. the porosity had air and water in comparable amounts.

Given the altitude of the deposits, it seems best to quote air dry bulk densities (BD), which include minor residual pore moisture, assumed to be fresh water. The Chilean BD's averaged 2.77 g/cc from 8 subsamples. For a carbonate gangue subsample, with minor sulphide content, BD was 2.93 g/cc; this sample appeared to be at least partly dolomitic. For 27 subsamples of Afghan material the BD average was 3.00 g/cc, which is on the high side of the usual lapis lazuli density range. The total density range for all samples was 2.70 to 3.08 g/cc. For the materials tested, Chilean lapis appears to have a lower density than Afghan lapis, which has a variety of silicates and is generally more pyritic.

Zöldföldi (2011) investigated the densities of 38 lapis beads from the Qaṭna royal tomb. For 23 of these the densities ranged from 2.4 to 3.0 g/cc and were deemed to be true lapis. Those with densities under 2.4 g/cc were thought to be imitation lapis. Attempts to manufacture artificial lapis have been known from the second millennium BC, such was its value.

Anderson & Jobbins (1990) state that 2.7 to 2.9 g/cc is the normal range for lapis and that fine pieces average about 2.8 g/cc. GIA (1995) specifies 2.75 ± 0.25 g/cc as the normal range for lapis. An appreciation of the straightforward, non-destructive property of density is useful in assessing this valuable and widely used material. Consider, by way of example, a notional lapis lazuli comprising 50% by volume lazurite, 15% other blue felspathoids, 10% pyroxene/mica, 10% pyrite, and 15% carbonate. Using the densities in Table 1, and ignoring porosity, the resultant composite density is 2.8 g/cc which would be typical of a good grade of pyritic lapis having plenty of blue minerals. If the proportion of blue mineral is diminished with corresponding increase in other minerals then densities exceed 3.0 g/cc. If the proportion of blue mineral is very high, as in a top grade lapis, then densities can be of the order of 2.5 g/cc. For a hard rock, as compared to, say, a granite, lapis lazuli is

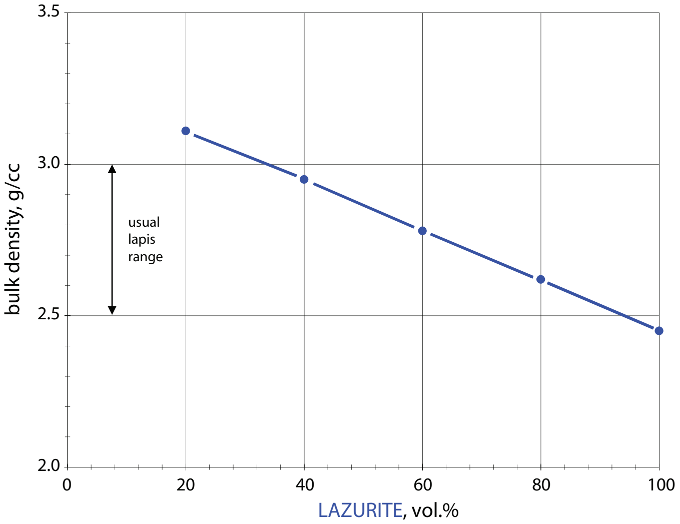

Figure 4. *Density variation in notional lapis lazuli. Increasing the amount of low density lazurite (and any other felspathoids) decreases bulk density and the quality of material would improve, provided that the overall blue colorations and textures are satisfactory. In the mineral mix presented here porosity is regarded as negligible; for 80% lazurite the amount of other felspathoids, carbonate, pyroxene et al, and pyrite were each assumed to be 5%; for 20% lazurite the amounts were each assumed to be 20%. See Table 1 for densities of components. This figure is simply illustrative of one range of mixes, it is not definitive for lapis assessment. The density range measured for the 35 subsamples reported in the text was 2.70 to 3.08 g/cc.*

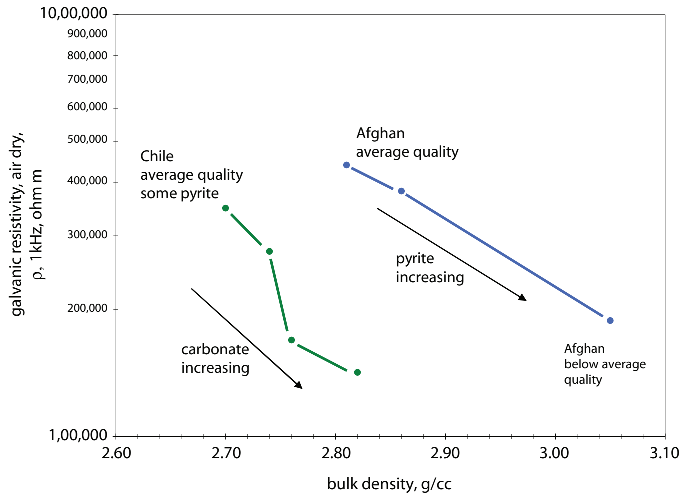

Figure 5. *Galvanic electrical resistivities measured air dry at 1 kHz. The materials are quite resistive and are changing into dielectrics, with high phase lags between voltage and current, at 1 kHz. Resistivities decrease as carbonate increases in the Chile samples and as pyrite increases in the Afghan samples.*

seen to have a wide density range; a sample's position in this range is an indication, but not a definition, of lapis lazuli grade. Figure 4 attempts to illustrate this with a synthetic mineral-mix. Many mineral mixes could be assumed and each would give a different plot. However, a common feature would be that as felspathoid content increases, and pyrite and pyroxene decrease, the density would decrease.

Inductive properties

Induction coil measurements at 400 Hz showed that the magnetic susceptibility of subsamples was near zero (actually some were diamagnetic, i.e. slightly negative). Some Fe infused skarn deposits can be quite magnetic (Emerson, 1986). However, it seems that Fe is not a feature of most lapis deposits, except in pyrite which itself has a very low magnetic susceptibility. Energisation at 2.5 MHz failed to produce electromagnetic conductivity responses from pyrite grains. It is possible that higher frequency energisation could have excited a response from the disseminated pyrite, but this was not pursued.

Galvanic properties

The air dry materials could be considered dielectrics loaded with semiconducting pyrite grains (sparsely for Afghan, and very sparsely for Chilean subsamples). Their measured DC conductivities were of the order of nanosiemens/m to microsiemens/m. Galvanic resistivity measurements, carried out at 1 kHz, with impressed current generally oblique to any bedding, showed ohmic current was subordinate to displacement current i.e. large phase lags of voltage with respect to current were observed. The very high resistivities, as shown in Figure 5, seem to depend inversely on density. Resistivity decreases with an increase in pyrite content in the Afghan lapis. An increase in carbonate has a similar effect in the Chilean lapis; the carbonate is impure and contains minor amounts of sulphides and clays.

Galvanic micro probing showed intra-semiconductor particle electrical continuity at microscale in pyrite grains, shards, clusters but no inter-particle continuity at mesoscale as the semiconducting pyrites are isolated electrically. The pyrite grain etc. conductivities were estimated to be in the order of ~ 1000 S/m. So the galvanic electrical properties are dominated by the insulating silicates in the matrix. However, in the field, such high resistivities may not be observed or resolvable if host and country rocks (e.g. marbles) have similar features. Also, if moist or wet macrofractures or fault damage zones are present, and shunt current through or away from such highly resistive lithologies, then field electrode arrays, in such environments, may map structure, rather than lithology.

The effect of pyrite on the resistivity on a lapis block at mesoscale may be estimated roughly from Maxwell's Equations (Shuey, 1975) which, for heterogeneous media, give an approximation of a mixture's conductivity up to about 10% volume fraction of dispersed spheres in a continuous matrix. If pyrite is represented by conductive spheres and the silicates are the resistive matrix then the formula, $\sigma_c/\sigma_m \approx (1 + 2f)/(1 - f)$ suggests that, for 10% pyrite ($f = 0.1$), the mixture (σ_c) to matrix (σ_m) conductivity ratio would be of the order of 1.3 i.e. about a 23% drop in resistivity. However, other factors need to be considered such as actual grain shape. This subject will not be pursued further here.

Dielectric properties

The 1 MHz real permittivities were determined and are shown in Figure 6, where K' is seen to increase with density. K', the permittivity, is the relative dielectric constant, a measure of charge polarisabilities. The reference minerals are from Olhoeft (1981) – regard as approximate. Again pyrite content is inferred to have a significant effect, boosting polarisabilities beyond that expected of silicates and carbonates. Note that the concept of K for a conductor, such as pyrite, is meaningless but in the application of mixing laws, by convention, a high value (quasi K) can be ascribed to conductive particles to give the resultant composite effect

In the samples measured (Fig. 6) the average tan δ (K''/K') values for three groups were 0.07 (Chile), 0.03 (low pyrite

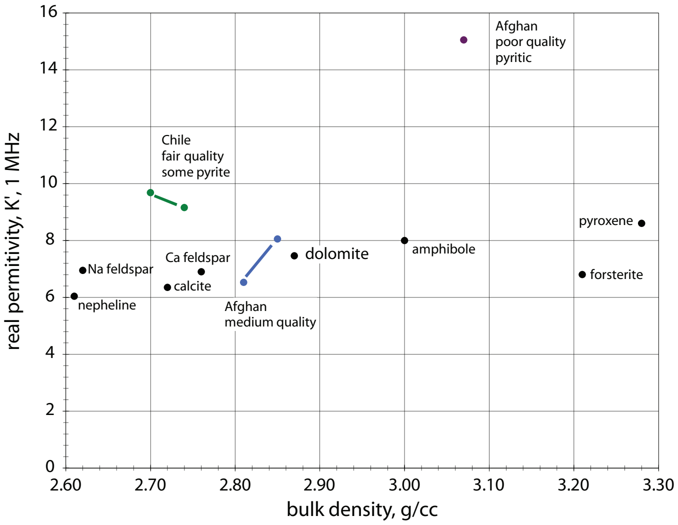

Figure 6. *Plot of real permittivity (relative dielectric constant) measured at 1 MHz on Chile and Afghan lapis samples in the air dry state. It is inferred that lapis of reasonable grade would have a permittivity similar to that of feldspar. The reference minerals are from Olhoeft (1981).*

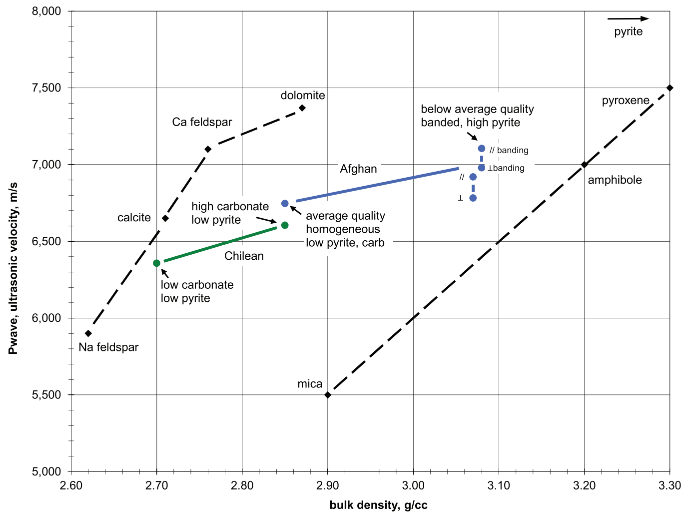

Figure 7. *Ultrasonic (200 kHz) compressional (P) wave velocities measured, under 10 kN uniaxial load, on five lapis samples. The results suggest a Pwave velocity of around 6700 m/s for an average quality lapis with minor amounts of pyrite and carbonate. The poorer quality Afghan material showed velocity anisotropy, (// = parallel to banding, ⊥ = normal to banding) and higher velocities. The reference minerals are approximate only.*

Afghan), 0.14 (relatively pyritic Afghan). K'' is the out of phase or imaginary permittivity which represents energy loss mechanisms associated with polarizations in the dielectrics. These loss mechanisms would be in phase with any galvanic (ohmic) loss. [Complex $K^* = K' - jK''$, $K = \varepsilon/\varepsilon_o$; ε is dielectric constant; free space dielectric constant $\varepsilon_o = 8.85 \times 10^{-12}$ F/m]

The dielectric effects observed were for frequencies below that usually employed in ground probing radar. At higher frequencies, in the field, the real and imaginary permittivities control EM propagation i.e. reflection and attenuation. The results given here are still instructive. The polarisabilities are thought to be associated with limitations imposed on charge movement by inhomogeneities (interfacial i.e. Maxwell-Wagner effects), and by charge carriers bound to attracting centres and capable of only very limited movement to a choice of immediately adjacent locations (dipole effects). The dielectric loss is the special type of friction associated with these limited movements of charge. Interfacial effects would include those associated with pyrite set in silicate; dipole effects would include those related to the molecular structure of silicates and carbonates, and to residual moisture bound to pore or crack walls or to hydrated alteration products such as clays (thought to be present in the Chilean lapis carbonate phase).

For the limited tests on the lapis, pyrite is seen to boost permittivities above those of the silicate / carbonate background. Lazurite and any associated felspathoids could be inferred to have a permittivity similar to albite (Na feldspar). The results here seem akin to work on epoxies (dielectric) loaded with aluminium (conductor) powder reported by Paipetis et al. (1983) who modelled their data with various mixing laws. Polarisation and loss increased with the volume of aluminium.

The pyrite content of the samples tested was within the range regarded as reasonable (i.e. not too much) for inferior to medium quality lapis. The pyrite, being effectively isolated, formed no semiconducting loops or threads to respond readily, in the form of conductivity responses, to induced (pyrite loops) or galvanic (pyrite threads) energisations. Electrically lapis could be viewed basically as an insulator with a low, but variable, semiconductor content. At meso-scale its best regarded as a leaky dielectric when the effects of the pyrite and any moist porosity are considered. At macroscale it would be resistive, but the rock mass resistivity, as seen by field arrays, could diminish if wetted macrofractures transect the rock mass.

Acoustic properties

Ultrasonic (200 kHz) compressional (P) wave velocities were measured under 10 kN uniaxial loading. The very limited test results shown in Figure 7 seem explicable in terms of silicate and carbonate mineralogy, and the pyrite content. Velocity increases with density for two types of lapis. Again it is inferred that lazurite and related feldspathoids may have a velocity similar to feldspar. It is possible that useful velocity or acoustic impedance (VxBD) contrasts could exist between lapis and any carbonate host if the lapis has a lot of pyrite and amphibole / pyroxene.

Pigment powders

Three grades of ultramarine pigment powders ground to ~25 μ (+/-) were obtained from Master Pigments: top grade Fra Angelico (Figure 3), ultramarine ash which is a low grade used in the surface glazing of a painting, and raw lapis lazuli (Figure 3). XRay Diffraction scans were run on these materials and the results are presented in Table 2. The solid material composite grain densities were obtained by pycnometry.

A feature of the results is the spread of eight mineral phases in the ash, and nine in the Fra Angelico and lapis; the dominance of dense diopside in the ash and lapis and its large presence in the final pigment; the significant amounts of blue or bluish feldspathoids (mainly lazurite) and the small amounts of pyrite for this particular type of Afghan lapis. This is a rich mineral mix producing blue pigment of quality.

Density, especially in the ash and lapis, is increased not by pyrite but by phlogopite and diopside. Pyrite is less than 2% by volume in this lapis. The volume percentages of mainly blue feldspathoids are 58%, 20%, and 26% approximately for the Fra Angelico, ash, and lapis, respectively. In the lapis trace amounts

Table 2. Lapis pigment powders; XRD results

Mineral	Fra Angelico weight %	Ultramarine ash weight %	Lapis lazuli weight %
Felspathoids			
Lazurite	32.4	12.4	14.1
Nepheline	10.4	2.8	4
Sodalite	2.7	0.9	1.4
Nosean	1.9	–	–
Afghanite	3.5	–	0.9
Feldspar			
Albite	3.6	1.8	2.3
Altered feldspar			
Marialite	4.2	1.2	2.6
Other Silicates			
Diopside	37.3	67	62.7
Phlogopite	4	13.2	9
Sulphide			
Pyrite	–	0.5	3
Pycnometry			
Grain density solid phase	2.74 g/cc	3.03 g/cc	3.01 g/cc

of carbonate were detected by HCl, but the carbonate content was below the XRD detection limit.

Summary

Lapis lazuli, being a mix of physically ordinary silicates with subordinate pyrite and carbonate, does not have any salient physical properties (except for colour in outcrop) to contrast with likely host and country rocks, especially in complex skarn settings.

Density, carefully interpreted, is a convenient, simple, and non-destructive indicator of lapis quality, especially if the mineralogy can be ascertained.

The inference that gemmy felspathoids are probably similar in some physical properties to feldspars is not surprising, given that felspathoids, chemically, can be regarded as silica deficient-feldspars.

Concluding remarks

Lapis lazuli is an intriguing material valued by many over the ages. It has been used, ornamentally, religiously, and medicinally, from the earliest times. Accordingly, it has been a well-represented species in the history of gemmology. Afghanistan still supplies markets with diverse materials some of which, of average quality, have been investigated. Lapis is the only gemmy material that is a rock, and the very limited results presented here suggest that, except for colour and optical character, it is a silicate-carbonate-pyrite rock of an unexceptional physical nature. Basically, when pyrite is low, as in the better grades of lapis, it has silicate / carbonate features. Chilean lapis lazuli seems to be a different variety. The non-destructive density test is useful and serves as an indicator of quality, in a supplementary role to visual and other techniques. In exploration, the application of geophysics would seem to be better devoted to locating possible favourable geological environments, regionally and locally, rather than attempts at direct detection of lensoid bodies of the peculiar blend of silicates that constitute grade lapis lazuli.

Perhaps geophysicists inspired by the third line of Marbod's poem could carry a nice piece of lapis around in their pockets and be blessed in their exploration endeavours. It may be worth a try, in the solidly empirical spirit of scientific testing, of course. However, the questing he, or the searching she, should bear in mind the last line of the poem.

Acknowledgements

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Lapis with pyrite & calcite. Lazurite polie (first page) photo by Parent Géry / CC BY-SA 3.0. https://commons.wikimedia.org/wiki/File:Lazurite_polie_-_53_mm_-_(Afghanistan).JPG.

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