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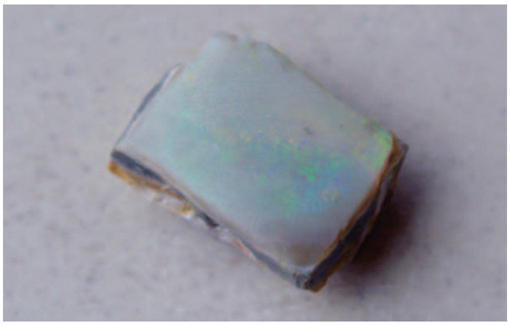

Andamooka S.A. common opal.

Opal: the queen of gems

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Introduction

In this article the writer continues a quite subjective and idiosyncratic ramble through the mineral kingdom's garden of gem showpieces (Editor's note: See *Preview* 173 and 179 for other articles by Don Emerson in this vein).

For the novelist and psychopharmacological guru Aldous Huxley (1956), gemstones were the manifestation of a heightened mystical experience promising an environment:

> *of curved reflections, of softly lustrous glazes, of sleek and smooth surfaces. In a word, the beauty transports the beholder, because it reminds him, obscurely or explicitly, of the preternatural lights and colour of the Other World.*

And none more so than the opal, the subject of this article. Over the ages gem opal has always been desired for jewellery and, as the queen of gems, regarded as an eminently collectible stone.

Silica, $Si0_2$, is the second most common material in the earth's crust, after the feldspars. There are several varieties in the silica group. The six types of interest to earth scientists and collectors are quartz, chalcedony, cristobalite, tridymite, lechatelierite, and opal (Table 1). Natural hydrous silica, loosely known as opaline

Table 1. Six silicas

	Quartz SiO_2	Chalcedony	Cristobalite	Tridymite	Lechatelierite	Opal $SiO_2.nH_2O$
Crystal system	Trigonal		Tetragonal	Orthorhombic	Amorphous glass	Amorphous mineraloid,
Type	Crystal quartz, accessory mineral, ubiquitous occurrence	Cryptocrystalline quartz, fibrous or granular, widespread occurrence	Precipitated from hot fluids in cavities in volcanics, widespread occurrence in minor amounts		Fulgurite, lightning strikes on silica sand, rare	Weathered zones, volcanics, sediments, in cracks, cavities, nodules; and in marine seds., widespread occurrence
Density (g/cc)	2.65	2.60±	2.33	2.26	2.20	2.10±
RI	~1.55	~1.53	~1.48	~1.47	~1.46	~1.45
Hardness on Moh's scale	7	<7	<7	7	6±	6±
Void space	No water accessible porosity but can contain occluded fluid filled micro pores	Minor, microscopic	Minor, when in disordered form		Nil	Significant, interstitial to silica spheroid packs, but infilled and not accessible by external water

- The key optical property RI, the refractive index, is the ratio between velocities of light in air and in the mineral
- Note the decrease in density, RI, and hardness left to right in this table
- Chalcedony includes the microfibrous silicas: agate, chrysoprase, sard; the microgranular silicas (flint, chert, jasper) are more compact and tougher
- Opaline silica is a general term used when there is insufficient X-ray et al information to categorise material as opal-CT (disordered cristobalite and tridymite) in volcanic opal or opal-A (highly disordered virtually amorphous) in sedimentary opal
- In diatomaceous and radiolarian marine muds the biogenic silica in the organism alters diagenetically: siliceous ooze/opal-A-> porcellanite/opal-CT-> chalcedony/chert.
- Precious opal has a play of colours from close packed arrays of translucent silica spheres (~0.25 μ), the play of colours depends on the silica sphere size and uniformity and on random discontinuities
- Precious opal is a fragile, brittle material; the gem form of quartz, rock crystal, is tougher and more stable, and less valuable.
- Hydrothermal volcanic opal usually is more transparent than sedimentary basin opal which tends to be opaque or translucent
- In the writer's view and experience, low density opaline silica occurs frequently in several geological environments, certainly more so than is usually recognised.

Sources: Anderson and Jobbins, 1990; Deer et al., 1992; GIA, 1995; Gübelin and Koivula, 2004; Kerr, 1977; Schumann, 2006.

silica, $SiO_2.nH_2O$, occurs widely. It is a recognised regolith category in the highly weathered regions of Australia (Eggleton, 2001), and elsewhere. Opal is hydrous and not as hard and dense as other silicas. Under special conditions it can acquire unrivalled brilliance with vibrant colour flashes manifesting a splendid play of colour (POC) that changes with aspect. The colour structure, though variable, is distinguished from all imitations by iridescence from 'flat planes with striated satiny finish that are the glory of true precious opals' (Anderson and Jobbins, 1990).

The famous opal deposits at Lightning Ridge and White Cliffs in New South Wales, Andamooka and Coober Pedy in South Australia, and the spread of occurrences in Queensland, contain considerable resources of gemmy opal. The host rocks are of sedimentary origin. The small mine and individual miners of the Australian opal industry produce material valued, in the rough state, at about $70 000 000, annually.

The opal occupies an important place in the Aboriginal legends of central Queensland. In the young world of the Dreamtime a giant celestial opal dictated tribal laws and punishments. The details of this elaborate myth have been explained by Melva Roberts (Roberts, 1975). The birth of the Australian opal has been depicted in a painting by Ainslie Roberts (Figure 1).

The writer will not attempt to summarise the considerable information in numerous books and papers devoted to Australian opal and the fields in which they occur. Smallwood (2014) provides an excellent scientific discussion. For a good overview of commercial opal types and value factors see the Opal Down Under website. The aim of this article is to present some historical and background information on a beautiful, desirable and fascinating gem material, and to investigate, in a limited way, some of its lesser known physical properties and their relevance, if any, to exploration geophysics.

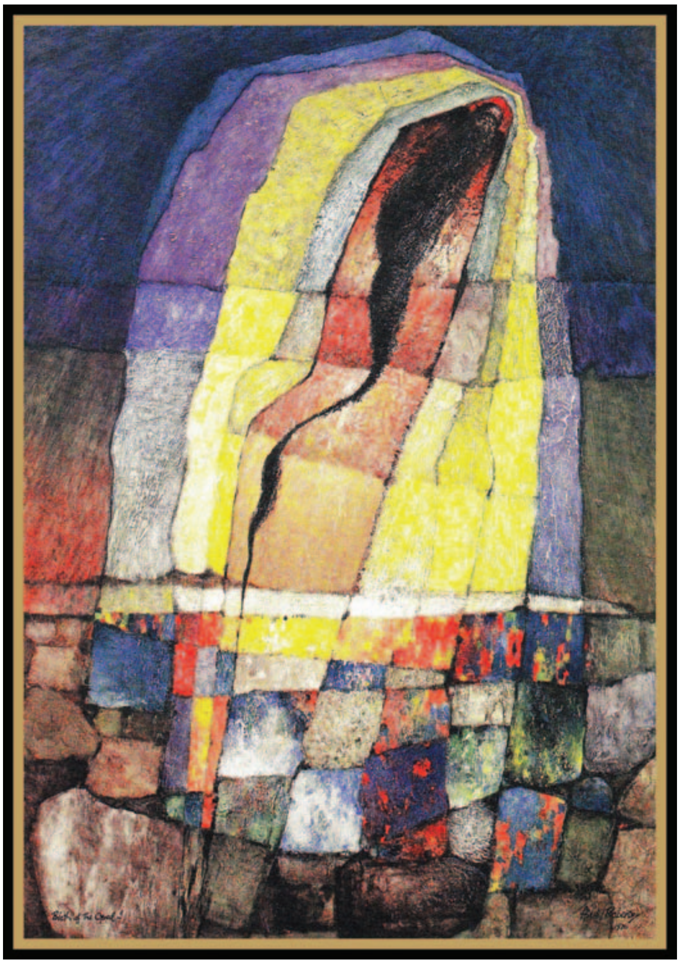

Figure 1. *Ainslie Roberts' painting of the Birth of the Opal. This acclaimed artwork evokes the formation of a marvellous material in the fractured beauty and the harshness of central Queensland. Source: Ainslie Roberts, Birth of the Opal (1975), acrylic on board © Ainslie Roberts/Licensed by Viscopy, 2016.*

Opal's occurrence

Opal is deposited at low temperatures from silica-bearing groundwater. It breaks white light into its spectral colours owing to its unusual porous mineral gel structure, comprising amorphous silica, voids, and water. In its precious form, regularly stacked, submicroscopic (.14–.30 μ diam) silica spheres of uniform size form a 3D diffraction grating with the adjacent voids which contain silica jelly cement and water. It is this arrangement of spheres and voids and the changes in refractive index at their interfaces that give the interference and dispersion, of incident white light, so pleasing to the eye (Sanders, 1964, 1968). Smaller spheres diffract the blue end of the spectrum; larger spheres, the red. In precious opal the spheres are stacked in the stable face centred cubic array. The porosity of the interstitial space, for equal diameter spheres, is 25.95%. Common opal (potch, opalite) is material consisting of irregularly sized and spaced spheres and voids that do scatter light, but only give a milky, opaque effect (Perry, 1984), but sometimes with an attractive impurity generated colouration. Distinctive or unique character is imparted to an opal by random internal discontinuities, such as sphere stacking defects and micro faults, and inclusions or patches of materials such as potch or sand. These features modify the colour generation. A flat opal surface limits the POC owing to total internal reflection of some wavelengths. Hence the use of convex surfaces or the covering of opal with a dome of material of similar refractive index.

A characteristic of opal is its water content. Opal contains 10% +/- H_2O (by weight, more by volume). This water could be in the form of both bound and molecular water. Pore wall silica has sufficient negative charge to ionise water in contact with it to form bound surface hydroxyls. Molecular water includes water in silica cages, in occluded voids between the spheres, in capillaries, and as inclusions in opal itself. It is *not* free draining water such as may occur in a porous, permeable sandstone. Opals are virtually impermeable in the absence of fractures (which would flaw the material anyway).

Precious iridescent opal includes: white opal, which has a light basic colour, black opal with a dark basic colour, boulder opal, which is precious opal on, or as seams in, a host rock (e.g. ironstone), and matrix ('pinfire') opal with precious opal disseminated in a host rock. The beauty of boulder and matrix opal is enhanced by the drabness of the host. Common opal, which lacks POC, includes agate opal with light and dark opal layers, porcelain opal with an opaque white milkiness, fire opal with a milky orange colour, and several other varieties (Sutherland & Webb, 2000; Schumann, 2006). Opals with a dark underlying colour are more valuable than those with a light background as the darker stones tend to a more vibrant colour display. Australian black opal is highly prized; a quality stone may fetch $15 000 per carat ($75 000 per gram) – serious money.

Figure 2 illustrates black opal, white opal, boulder opal, and common opal. Figure 3 shows two Australian opals set in gold rings.

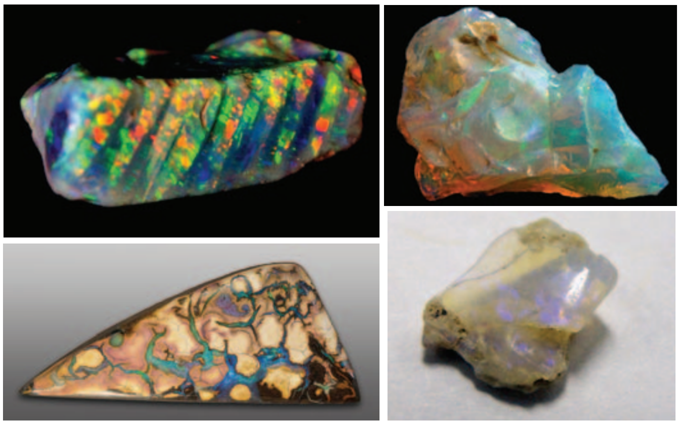

Figure 2. *Four of the main types of opals: top left – black, top right – white (light precious), bottom left – boulder (opal in ironstone), bottom right – opalite (common opal). The depicted opals each weigh ~60 carats i.e. ~12 grams; their volumes are small (~6cc). In opalised sedimentary strata, or in volcanics, opalisation may be widespread, but the opal material occurs in concentrations as small pockets or nodules, or as thin erratic seams; the opal is a minor constituent of the host lithology. Sources: top left – 'The Dream' kingstone of black opal rough parcel (cropped) by Danmekis/CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:58.05ct_Lambina_Black_Opal_Rough.JPG, top right – photo by Lech Darski/CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:Opal_Welo_-Welo,_Afar_Province,_Etiopia,_Afryka.jpg, bottom left – photo by Hannes Grobe/CC BY-SA-2.5 https://commons.wikimedia.org/wiki/File:Opal-f_hg.jpg, bottom right – photo by CRPeters/CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:Potch.jpg.*

Figure 3. *Opals for adornment. These fine Australian opals, photographed on ferruginous sandstone, have been set in gold rings crafted in Australia; they belonged to Annette Emerson. Left – Queensland boulder opal, long dimension 18 mm; right – South Australian white opal, long dimension 14 mm. Photo by Lainie A Kalnins/CC BY-SA 3.0.*

Opals occur as nodules, veinlets, cavity fillings, layers, seams and encrustations. Many kinds of rocks host opal. They are found in volcanics in Australia (e.g. Tintenbar, NSW), the Americas, Africa and Europe. It is believed that deposits in Czechoslovakia-Hungary supplied the ancient world. The famous and extensive Australian deposits, discovered in the late 1800's, are different, being mainly hosted by weathered Cretaceous sediments. These are in the Surat Basin's Finch Claystone (Lightning Ridge, NSW) and in the Eromanga Basin's Bulldog Shale (Coober Pedy, SA) and Winton Formation (Winton, Qld). Opal is often hosted by or associated with 'ironstone'. Pseudomorphs of opal after fossil animal remains are found in these sedimentary deposits. Precious opal specimens are small. Usually, if three dimensional, they are in the mm-cm range; two dimensional materials, such as seams or layers, commonly are quite thin, of the order of mm.

An expanding industry has developed from the 2008 discovery of 'Welo' opal to the north of Addis Ababa, Ethiopia. Colourful opals are found in nodules formed in volcanic ash layers (Downing, 2011). These opals now compete with Australian materials in the cheaper light opal category in markets worldwide. An example is shown in Figure 2 (top right).

Table 2 indicates some differences between sedimentary and volcanic opal. Australian opals generally are denser and more responsive to long wave ultraviolet than overseas volcanic types, which also tend to have lower refractive indices.

Opal in ancient times

The Latin for opal is *opalus*, apparently derived from the Sanskrit *upala* for 'precious stone' thought to have come from India. This source was pure conjecture and seems unlikely. India probably was a code word for remote locations known only to traders. Cavity-fill opal is known to occur at several locations in eastern European volcanic regions. The Slansky Highlands' andesites, trachytes, and tuffs, in the east of present day Slovakia (formerly Hungary) supplied white opal during the 17th to 20th century period and probably much earlier. The opals came mainly from the area around the old mining town of Dubnik. So ancient opal in the Mediterranean world could have been sourced from such settings.

The author of *Naturalis Historia (NH)* Gaius Plinius Secundus (AD 23–79) was, and is still, rightly renowned for his encyclopaedic work of 37 books containing a vast number of facts, and factoids, on numerous topics, including gemstones presented in Book 37 (Bostock and Riley, 1857; Mayhoff, 1897; Eicholz, 1971). Indefatigable as ever, he died investigating the catastrophic eruption of Vesuvius. The opal of his day is described *NH* 37.80,81:

> *…. opali, smaragdis tantum cedentes … atque ut pretiosissimarum gloria compositi gemmarum maxime inenarrabilem difficultatem adferunt. est in his carbunculi tenuior ignis, est amethysti fulgens purpura, est smaragdi virens mare, cuncta pariter incredibili mixtura lucentia. alii summam fulgoris Armenio colori pigmentorum aequari credunt, alii sulpuris ardentis flammae aut ignis oleo accensi. magnitudo abellanam nucem aequat.*

> …. in value opals yield only to emeralds …. as they embody the splendour of the costliest gems they present the

Table 2. Some physical features of precious opal (after Smallwood, 2014)

Precious opal type	Density (g/cc)	Refractive index	Ultraviolet light response (LWUV, long wave UV)
Australian white, sedimentary Opal-A	≤2.15	≤1.45	Bluish white fluorescence then yellow-green phosphorescence
Overseas; white, volcanic Opal-CT	2.05±	<1.45	Usually none
Australian black, sedimentary Opal-A	≤2.15	≤1.45	Similar to Australian white opal but less intense

greatest difficulty of description. They display the delicate fire of ruby, the purple brilliance of amethyst, and the sea-green of emerald, all combined in concert with incredible brilliance. Some regard the effect of the vivid colouring as resembling azurite pigment; others the flames of burning sulphur or of a fire lit with olive oil. The size of an opal is that of a hazel nut' [the ovoid hazelnut is ~15 × 10 mm].

Pliny's extensive compilation of materials and things occasionally includes interesting anecdotes, and the opal has one of them. It concerns the turbulent times of proscription in Rome in 43–42BC when hundreds were outlawed and their goods confiscated by the triumvirs Mark Antony, Octavian (later Caesar Augustus), and Lepidus. It seems that Mark Antony liked opals *NH* 37.81,82:

> *insignit etiam apud nos historia, siquidem exstat hodieque huius generis gemma, propter quam ab Antonio proscriptus est Nonius senator …. ille proscriptus fugiens hunc e fortunis omnibus anulum abstulit secum. certum est sestertio vicies tum aestimatum, sed mira Antoni feritas atque luxuria propter gemmam proscribentis, nec minus Noni contumacia proscriptionem suam amantis, cum etiam ferae abrosa parte corporis, propter quam periclitari se sciant, et relicta redimere se credantur.*

> also there is for us a noteworthy story in that there is in existence a precious opal (ring) for which the senator Nonius was outlawed … This Nonius, proscribed and fleeing, took away with him, out of all his wealth, this ring alone. There is no doubt that the ring was then valued at 2 000 000 sesterces. What is more remarkable is the brutality and immorality of Antony invoking proscription because of a gemstone, and the obstinacy of Nonius in refusing to part with the reason for his outlawry. For even wild creatures are believed to save themselves by gnawing off the body part, which they would know imperils them, leaving it behind (for the hunter).

An explanation of the allusion can be found in the Aesopian fable, The Beaver, *Fiber*, a frequently hunted wild creature. Phaedrus (*c.*15BC–*c.*AD50) is believed to have written this (Perry, 1965):

> *Canes effugere cum iam non possit fiber*
> …
> *abripere morsu fertur testiculos sibi,*
> *quia propter illos sentiat sese peti.*
> *divina quod ratione fieri non negem;*
> *venator namque simul invenit remedium,*
> *omittit ipsum persequi et revocat canes.*
> *Hoc si praestare possent homines, ut suo*
> *vellent carere, tuti posthac viverent.*

> When the beaver cannot escape the dogs … they say he gnaws off his gonads because he knows that it is for them he is pursued. I cannot deny that this happens by sacrificial foresight, for the hunter, as soon as he has found the raw material for his potions, disregards the beaver and calls back his dogs. If men could take it on themselves to forfeit their property they would live safe into the future.

Actually the beaver was hunted for the pungent liquid (*castoreum*) in two sacs in his nether regions; this was used in perfumes and medicines. However, the moral of the tale is that it is better for one to lose the family jewels than one's life. Nonius really must have loved that opal. A *sestertius* then had several times the purchasing power of today's dollar. Some stone indeed.

Medieval and pre-modern opal

Marbod (1035-1123), Bishop of Rennes in Brittany, was an eminent literary figure in his day. He was devoted both to the Christian and classical worlds. He wrote attractive hymns, but he and the finest minds of his contemporaries were especially enchanted by the emblematic signs regarded then as hidden in nature, and especially by the mystical and inexplicable powers deemed to reside in precious stones. His *Liber Lapidum* (Book of Stones) was immensely popular for centuries. Lines 633–637 *(De opthalmio;* Beckmann, 1799; *opthalmius* is a medieval corruption of *opalus*) account for opal:

> *Avertens oculis morbos ophthalmius omnes,*
> *Asseritur furum tutissimus esse patronus;*
> *Nam se gestanti visus conservat acutos,*
> *At circumstantes obducta nube retundit,*
> *Ut spoliare domos possint impune latrones.*

> Opal diverts all evils from the eyes
> It is claimed to be a very reliable protector of thieves
> For it maintains the keen vision of the opal carrier
> But clouds the sight of bystanders
> So that robbers can plunder residences with impunity

Marbod's devoting only five lines to prey-dazzling by the prettiest of gems seems curious given his effusions on others, e.g. 26 lines on lapis lazuli, 21 on pearls, 20 on lodestone, and 18 on the *alectorius* – a castrated cock's gizzard stone valued for its medical and mystical properties. Marbod, indubitably, did not want to highlight an instrument for the facilitation of sin to his eager and pious readers. Perhaps the negative aspects of opal's reputation commenced around this time.

The belief in the relationship between opal and sight continued on to the 17th century. In 1630 the English dramatist Ben Jonson (New Inn 1, 6) wrote: 'I had no medicine, sir, to go invisible; nor opal wrapped in bay leaf in my left fist, to charm their eyes with.'

In 1601 Shakespeare (Twelfth Night, 2, 4, 77) referred to opal's mutable colours in a clever metaphor delivered by the clown to Duke Orsino: 'Now, the melancholy god protect thee, and the tailor make thy doublet of changeable taffeta, for thy mind is a very opal.' Taffeta is an expensive, shimmering silk with a reflectivity that varies depending on the light and angle of view. Here, the opal indicates an excitable, changeable personality.

One of the most passionate and evocative descriptions of any gemstone was written by Petrus Arlensis (1610). He waxed eloquently on the opal, presumably a milky white precious opal from the volcanic occurrences in Hungary-Slovakia. One wonders what he would have said about high quality Australian black opal.

> *Colores varii in Opolo ad visionis oblectamentum conferre multum valent, imo ad corda & interiora alteranda efficaciam maximam praestant, & mirantium oculos summopere oblectant. Unus prae aliis ad meas pervenit*

manus, in quo tanta pulcritudo, decor, & venustas elucebat, ut vere lapides omnes ad se vi trahere gloriari posset, cum aspicientium corda indeflexe, & indefinenter everteret, deverteret, ac alligaret: Grossitie unius avellanae ab Aquilae aurea miro elaboratae artificio unguib(us) strictus erat, coloresque tam vividos & varios habebat, ut tota caeli pulcritudo in illo conspiceretur: Decor ex illo exibat, Majestas ex fulgore prope divino erumpebat. Radios tam claros & graves emittebat, ut aspicientibus terrorem incuterent. Quid plura? virtutes & proprietates a natura sibi insitas deferenti concedebat: nam corda aspicientium invisibili jaculo jaculabatur, oculos caecutiebat: pectora licet animosissima fortissimaque concutiebat, totum denique astantis corpus terrore replebat: ad amandum, honorandum & colendum fatali quadam coactione impellebat. Vidi, expertus, & coram Deo testificor, vere talis lapis summo & inaestimabili pretio adstimandus erat.

The kaleidoscope of colours in an opal conveys an abundance of delight to the eyes. I should say, more correctly, they offer a very effective means of changing one's soul and character, and also ravish the sight of astonished viewers. An exceptional specimen came into my hands. In it there was manifest a graceful comeliness and a charming quality of such intensity that it could truly take pride in all other stones trailing in its wake; it completely reorients and firmly grips the viewers' emotions inflexibly and without limit. Thick as a hazel nut, it was clasped in the claws of a golden eagle fashioned with wonderful skill, and had such lively and varied hues that the beauty of the heavens, in its entirety, was discerned. An attractiveness and a grandeur akin to celestial lightning all but issued forth from it. The flashes it released were so bright and overpowering that they instilled great fear in those beholding it. What more to say? It transferred the special properties and qualities, implanted in itself by nature, to the person carrying it around. Moreover it struck the minds of onlookers with an invisible arrow; it blurred vision; it upset even the bravest and strongest hearts; in short, it filled the whole body of the bystander with terror. It set in motion, by some kind of fatal compulsion, feelings of love, respect, and religious awe. Out of the basis of what I saw and experienced, I testify in the presence of God, truly such a stone had to be considered worth an incalculably great amount.

What more to say, indeed?

Unlucky opal

In myth and anecdote opal has been reviled as the evil eye, the stone of disaster. This does not bear examination. For example, Evans (1970) reports that Alphonso XII of Spain (1857-1885) gave an opal to his wife on his wedding-day, and her death occurred soon afterwards. Before the funeral he gave the ring to his sister, and she died a few days later. The king then presented it to his sister-in-law, who died within three months. Alphonso, astounded by these fatalities, decided to wear the ring himself, and within a very short time he, too, was dead. The Queen Regent then suspended it from the neck of the Almudena Virgin in Madrid. This act of piety halted the deadly chain of events. However, the carved Virgin was doubtless immune to the 1885 cholera epidemic that raged through Spain then, killing over 100,000 people from every level of society, and so, it seems, the four unfortunates in the royal family. All these Spaniards were unlikely to have owned a piece of opal.

In the last of his novels, Anne of Geierstein, Sir Walter Scott gratuitously and probably unintentionally damaged opal's reputation by linking it to misfortune. Apparently, his baleful tale of the character Lady Hermione contributed to a wariness if not rejection of opal among his wide readership in the dominant (British) empire of the time. Lady Hermione, of mysterious origins, wore a dazzling opal in her hair. This opal sparkled when she was happy, gleamed red when she was angry, and its radiance was quenched when sprinkled with holy water. After falling into a swoon she was carried to her chamber where, next day, just a heap of ashes remained on the bed on which she had been laid. The life of a mysterious stone (averse to holy fluid) was linked to the life of mysterious Hermione. This, published in 1829, really spooked the opal trade.

Despite the bad publicity, Queen Victoria liked opals. This helped sales of Australian material in England during the latter part of the 19th century.

Opal is relatively soft, fragile, and brittle for a gemstone. It can be difficult to fashion into jewellery. It is sensitive to heat, which causes fracturing and can result in loss of colour. Of course, miners and marketers of competing gems emphasise the negative features of its history and its physical properties. Hence its reputation as an unlucky stone.

Opal synthesis and treatment

Imitation opals were fabricated in the ancient world. Pliny (*NH*) 37.83 commented:

nullos magis fraus indiscreta similitudine vitro adulterat. experimentum in sole tantum, falsis enim contra radios libratis digito ac pollice unus atque idem tralucet colos in se consumptus, veri fulgor subinde variatur et modo ex hoc plus, modo ex illo spargit, fulgorque lucis in digitos funditur.

There is no stone more counterfeited by a fraudster than the glass imitations closely resembling opal. It can only be tested in sunlight. When fake opals are poised between thumb and finger against the sun's rays only one attenuated colour shines through. The flashing brightness of the true stone changes continually. At one moment, then another, there is more colour dispersion from different parts of the stone, and beautiful light diffuses onto the fingers.

Much later the polymath Athanasius Kircher (1678) in his *Mundus Subterraneus (MS)* discussed several glass synthetic gem-making techniques, *Opali Imitatio MS* 12.4:

Adulterari duplici vitro, vel colore, ut aliae gemmae Opalus non potest, Scribit tamen a Porta, calcem stanni in vitrum crystallinum excandens injectam illud obnubilare & colorare Opali instar: Sed oportet saepius ex igne eximere, & accommodare, donec quis voti compos fiat. Quercetanus a spiritu nitri alembicum vitreum intrinsecus ita tingi variis coloribus asserit, ut Opalus videatur.

Opal is not able to be counterfeited by coloured glass compounds as can other gems. Yet Porta writes that firing tin powder into crystal glass clouds and colours it in the manner of opal, but it ought often be removed from the fire and the procedure adjusted until such time as one's expectations are realised. Quercetanus claims that alkaline solution stains the inside of a glass still (alembic) with a variety of colours resembling opal.

It seems that the ancient technique of imitating opal with glass, as mentioned by Pliny, did not survive into the alchemy of Kircher's time.

Attractive manufactured opals, with similar chemistry and structure to natural opal, have been available since 1974 (Anderson and Jobbins, 1990). The Pierre Gilson process involves synthesis by chemical precipitation of silica under hydrostatic pressure. These opals have only slight differences in hardness (lower) and density (lower) when compared to true opal. They may be recognised by their mosaic patterns of colour inside which scaly or 'lizard skin' textures and columnar structures can occur.

Good looking plastic opals are also manufactured, from styrene spheres, but handling them gives an immediate clue to their origin as they are soft and very light in weight with densities approaching 1.0 g/cc.

Opal is often treated with smoke, dye, oil, wax, plastic, or silicone, to enhance the colour play and to hide flaws. Such adsorption improvement may not be long lasting, and may be difficult to recognise (see GIA, 1995).

Glass continues to be used in efforts to imitate opal. Glass so used is called paste. Usually it can be recognised as warm to the touch, compared to cool quartz, and by the bubbles it contains (Gübelin, 1974; Gübelin and Koivula, 2004). A particularly effective imitation, devised by J. Slocum, seems to be an anhydrous silica glass internally structured to produce an attractive iridescence. This is Slocum Stone, which is quite difficult to recognise by the naked eye. However it is denser (~2.45 g/cc) than true opal, and, under low magnification, the nature of the iridescent patches and zones, which can be quite variable, differ from true opal (Anderson and Jobbins, 1990).

When buying an opal, in the absence of an expert, a valid certificate of authenticity or special laboratory tests, a curious purchaser has to gauge a specimen's provenance and purity with a 10X hand lens, experience, and trust in the probity of the vendor. A density measurement if possible, and LWUV illumination, may be helpful in evaluating Australian opal. It is easy to be deceived, so *caveat emptor*: shopper take care.

Geoscience: Australian opal fields

Currently Drs Bruce Dickson and Phil Schmidt (pers. comm.) are investigating opal formation in Australia. They note that Australia produces most of the world's precious opal yet there is no accepted model for how or when it was formed. It is a most enigmatic substance, hiding clues to its formation. Instead of focusing on the opal itself they are looking at the chemistry, hydrology, geology and palaeomagnetism of the opal areas, testing out clues as to how and when it was formed. Sammut (2016) provides an interesting discussion on the make-up and genesis of opal and opal-like (imitation) materials.

On a regional scale, Merdith et al. (2013) have produced an opal prospectivity map for Australia's Great Artesian Basin by applying a spatial data mining methodology, using G Plates Paleo GIS software. This work has identified prospective opal areas and contributed to the understanding of opal formation.

At the local scale, geophysics has been usefully applied to opal environments. The occurrence of opal is associated with claystone structures underneath or within sandstone in NSW (e.g. Lightning Ridge), South Australia (e.g. Coober Pedy), and Queensland (e.g. Yowah). It occurs as thin seams and small concretions, so it is an unlikely candidate for direct geophysical exploration. Near surface geophysics has been usefully applied in studies of the lithology and structure of host and country rocks in the opal areas. This is attested by the work of Senior et al. (1977), Whiteley (1983), Leys et al. (2001), Moore et al. (2003), Zhe and Morris (2006), and others. A three electrical layer subsurface often approximates the opal host environments. At Lightning Ridge, for instance, there is a top layer of high resistivity silcrete, ~500 ohm m; an intermediate sandstone layer ~20 ohm m; and an underlying claystone, <2 ohm m. Resistivity would seem to be ideally suited for the investigation of the main strata even though complications could be expected in the form of variable moisture contents, and small structures such as joints, faults, and shears. Whiteley (1983) noted the possible use of seismic refraction to map weathering at Coober Pedy, and magnetics to help locate opal-hosting ferruginous zones at the sandstone-claystone boundary in southwestern Queensland fields.

Little has been published on the use of Ground Penetrating Radar in exploration for opal but recently it was reported to have been successfully applied in Queensland to identify ironstone boulder zones known to occur near opal bearing horizons, and to investigate opal bearing structures, in the shallow subsurface. Excavation of identified targets resulted in the recovery of opal-bearing material. This appears to be a promising development (http://www.opalhorizon.com/News/Company Announcements.aspx).

Some physical properties of opal

Although the direct geophysical detection of opal is unlikely, the physical properties of opaline materials are worth investigating, if only for the record, as little seems to be known of its physical properties beyond density and refractive index. Keller (1966) cited values of 7.15 and 7.43 for the permittivities (dielectric constants relative to free space) of two opals from Japan. Olhoeft (1981) recommended a DC conductivity of 3.9×10^{-7} S/m and a 1 MHz permittivity of 13.01 for opal. Xu et al. (1989) investigated the electrical properties of one natural and two synthetic opals at frequencies up to 100 kHz and temperatures to 485°C. They noted that the dielectric constant of the opals exceeded that of pure silica and attributed weak conductivity affects to impurity ion migration.

Some tests (see Emerson, 2015) were carried out mainly on common opal, as the price of precious opal samples of adequate size is prohibitively costly.

Mass, magnetic, electric, dielectric, and velocity measurements were made on a limited number of samples: common and white opal from Lightning Ridge NSW and Coober Pedy SA, and boulder opal from Yowah Qld. A recrystallised, pure, fine grained Devonian quartzite from north of Heathcote Victoria (used as a proxy in the absence of a suitable quartz crystal sample), chalcedony from north of Lismore NSW, and massive, vitreous, bluish-black cristobalite from Siskiyou County, California USA, were also tested (Figure 4). Cristobalite when microspherical is a constituent of many opals.

Opal water content was investigated by Smallwood (2014) using thermogravimetric, calorimetric, and other methods. Australian

Figure 4. *Some of the opaline materials used in the physical property tests prior to shaping for the measurement jigs: top left - Lightning Ridge NSW blue-black common opal, 13.57 g, top right - Coober Pedy SA white opal, 2.95, 5.63 g, bottom left – Coober Pedy SA milky blue common opal, 10.67, 6.50 g, bottom right, – Yowah Qld boulder opal, polished 19.40 g, rough 17.23 g. Photos by Lainie A Kalnins/CC BY-SA 3.0.*

sedimentary opal heated to 1000°C had significant mass losses in the middle temperature range (several hundred °C). The mass losses ranged from between 6 to 8%. This and other data were interpreted as showing that opal typically contains about 10% bound (silanol) water, 10% molecular water in voids (~50 nm diam.) and capillary pores (~5 nm diam.), and 80% molecular water trapped in silica cages.

In the tests carried out by the writer, fresh water could not be introduced into precious and common opal specimens whether by vacuum saturation or by boiling. Furthermore, prolonged oven drying to 105°C did not release any water. So effective (water-accessible) porosities are zero. However, the occluded porosities, as described by Smallwood, are certainly present, but the release of such water would have required grinding to powder and subjecting it to very high temperature. Water resides in opal, but, being occluded, it is immobile under ordinary conditions. Stevens (1998) noted that, contrary to popular belief, Australian opal is not porous in a way that will absorb liquids.

Table 3 summarises some results. Precious and common opal has no water accessible porosity, but the boulder opal (with goethite, sand and clay matrix) has 11% porosity. Densities are in the expected range for ironstone free opals, ~2.1 g/cc, but are higher for the boulder opal owing to its iron oxide content. This iron oxide contributes to a magnetic susceptibility, 66×10^{-5} SI, which, although low, is quite distinct from the other opals with virtually zero susceptibility (slightly negative, i.e. diamagnetic, in a couple of cases).

Galvanic resistivities were measured generally parallel to any foliation and at 1 kHz on shaped materials in the air dry state. The resistivities for the common and white opals are very high, average ≈450 000 ohm m. The resistivities of the non-hydrous quartzite, cristobalite, and chalcedony are even higher than the opals. These materials are dielectrics with large phase lags between voltage and current; displacement current is dominant. The boulder opal resistivity is lower on account of networked residual moisture in the porosity and clay components. Ohmic current dominates in this material for which resistivity diminishes by an order of magnitude when vacuum saturated with fresh water.

The dark common opal and the boulder opal did not fluoresce under long wave ultraviolet light; the others did.

Given the clearly dielectric or insulating nature of the opals, measurements of real and imaginary permittivity (dielectric constant relative to free space) were carried out generally normal to any foliation or lamination and at 1 MHz. Real or in phase permittivity (K′) reflects the polarisability of mobile, semi mobile, or bound charge, while the imaginary (quadrature, out of phase) permittivity (K″) reflects the energy loss from the charge movements (Maxwell-Wagner effects, dipole rotation etc.).

Table 3 and Figure 5 give the results of these limited tests. Clearly, the low density common opal has quite a high polarisability (K′ ≈ 10) when compared to literature values for

Table 3. Measured physical properties of some opal and other opaline materials

Material	Bulk density (g/cc) (air dry)	Porosity (%)	Magnetic susceptibility Si × 10^{-5}	Galvanic Res. 1 kHz, ohm m (air dry)	Response to Long Wave Ultraviolet	Permittivity 1MHz Real K′	Permittivity 1MHz Imaginary K′	Pwave Velocity 100 kHz (m/s)
Milk opal, white Coober Pedy SA (1 sample, precious)	2.15	→ 0	→ 0	403 268	✓	10.25	1.20	4655
Common opal, blue-black, Lightning Ridge NSW (average of 2 samples)	2.11	→ 0	→ 0	593 609	✓	10.38	2.14	4818
Common opal, white Coober Pedy SA (average of 2 samples)	2.11	→ 0	→ 0	348 310	✓	8.89	1.72	5000
Boulder opal goethite matrix Yowah, Qld (average of 3 samples)	2.48	11.2	66	25 215		11.76	2.56	4844
Quartzite, Heathcote, Vic	2.62	→ 0	→ 0	728 675		4.20	0.05	6164
Cristobalite, Siskiyou, California	2.36	→ 0	→ 0	623 896		5.00	0.03	6122
Chalcedony, Lismore, NSW	2.60	→ 0	→ 0	644 000		4.00	0.10	5241

crystal quartz (K′ = 4.4), and to the measured values for chalcedony (K′ = 4.0), quartzite (K′ = 4.2), or cristobalite (K′ = 5.0). This is to be expected from the aggregate complex of hydrous and hydrated minerals and mineraloids in the voids of the opal. The denser boulder opal has high polarisability and loss too, but this is due mainly to kaolinite, goethite, and residual moisture in the open-porosity matrix. Opals are quite lossy compared to other silicas. The opals' quadrature permittivities, K′ ≈ 1.8, are far higher than the quartzite, chalcedony, and cristobalite (K′ ≤ 0.1). Opal has a distinctive physical character when compared to other silicas.

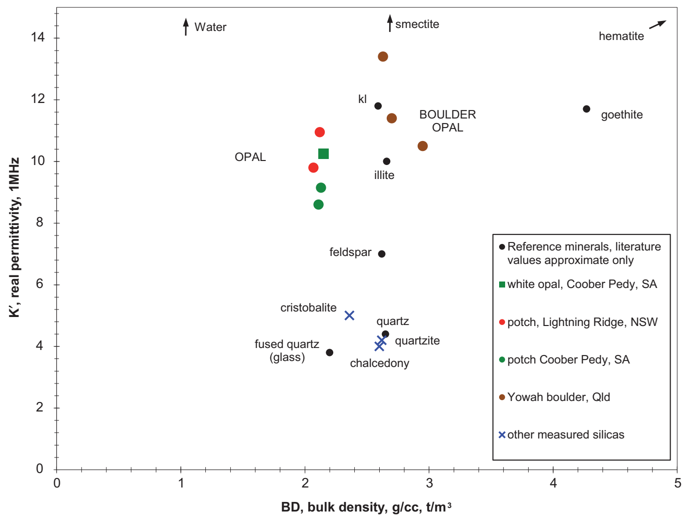

Figure 5. *A dielectric polarisability plot for real (in-phase) permittivity against bulk density measured air dry at 1MHz. The low density Australian common opal samples, owing to their hydrous nature, exhibit quite high polarisabilities compared to quartz and fused quartz. All these materials have virtually zero magnetic susceptibility. The Queensland boulder opal has a higher density and comparable polarisabilities but these arise from the iron oxide/clay matrix which holds only minor amounts of opal in seam and nodule form. The boulder opal has a magnetic susceptibility ~65 × 10^{-5} SI owing to its Fe oxide content. The reference mineral values are from Olhoeft (1981), kl = kaolinite.*

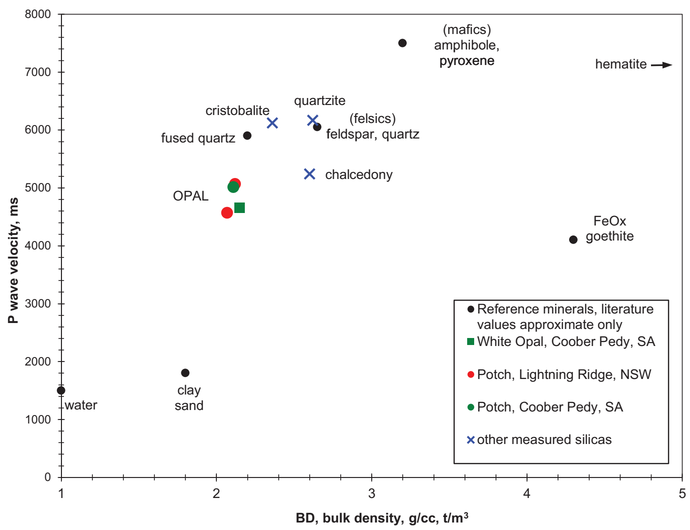

Figure 6. *A plot of compressional (P) wave ultrasonic velocity (100 kHz) against bulk density for common opal samples. The data are referenced to a notional weathered environment mineralogy. There are distinct differences in velocity and density between the opaline silicas and quartz.*

It seems that dielectric measurements could be usefully included in the suite of categorisation tests employed in opal studies.

Ultrasonic velocity measurements were carried out @ 100 kHz under 10 kN uniaxial load and generally subparallel to any foliation. The data are shown in Table 3 and Figure 6 in the perspective of the main minerals likely or possibly to be encountered in the weathered environment. Common opal is seen to have a fairly high velocity (~5000 m/s) but well below that of quartz and quartzite (~6100 m/s). The opal velocity is lower owing to its poor crystallinity, its porosity, and its mineraloid pore fill.

In addition to the mesoscale physical property indications presented here, any assessment of an opal environment's macroscale field character would need to consider energising frequencies, fracturing, and water saturation of the overall rock mass.

Remarks

The delightful sight of a beautiful iridescent opal has captured humankind from the earliest times. It is a mineral like no other. As the needle to the pole does swing, so the eye to the opal. An opal may not match a diamond in splendour, but it beats it in beauty. The abstract pleasure of an opal resides in the dynamism of its yellows, greens, blues, and reds that have no fixed form, no beginning, no end. Incomparably beautiful flashes of rainbow hues vary when viewed from different directions.

Opal's physical characteristics are distinctive, beyond its optical aesthetics. These include low density, a substantial porosity yet no permeability, quite hydrous yet very high resistivity, high dielectric polarisability compared to quartz, zero magnetic susceptibility (for the non-ironstone types), and a low compressional wave velocity compared to quartz. It is possible that the dielectric properties may be useful in the investigation of opal type and internal structure. In these quite limited tests there is not much difference between common and precious opal.

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