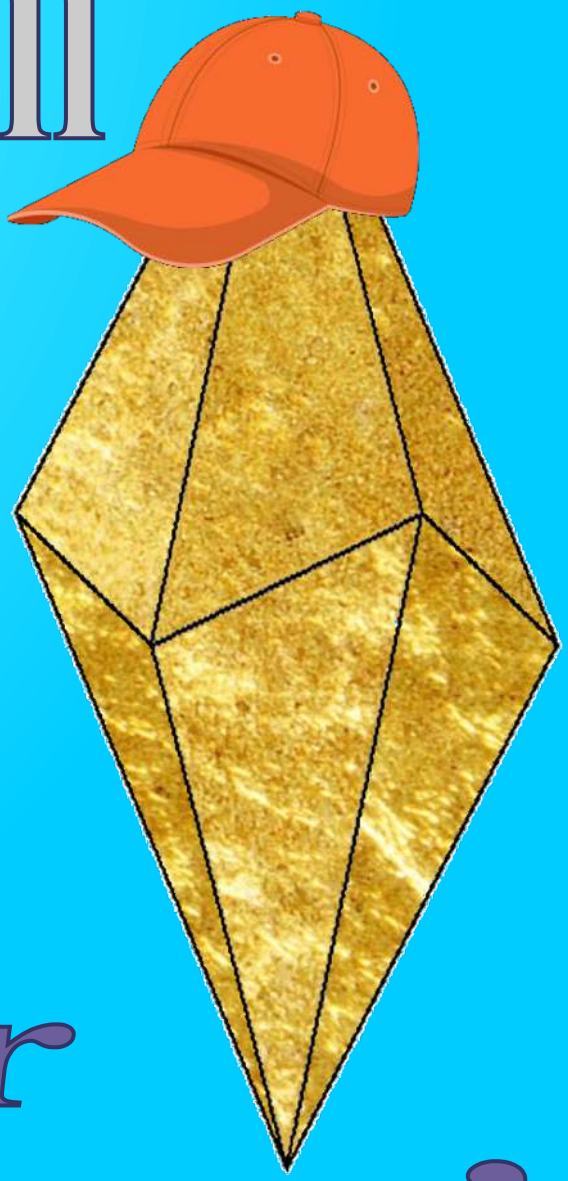
The Russell Society



Junior Members' Magazine

Issue No. 4 September 2026

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FROM THE EDITOR

Welcome to the Junior Members' Magazine

This is the fourth edition of the Juniors Members' Magazine (JMM) and we continue looking at the different aspects of mineral collecting that some people specialise in.

This edition focuses on those naturally occurring elements found in the native form that are considered to be minerals and collecting specimens of them. There are at least seventeen native elements that have been found occurring in the United Kingdom although many are exceptionally rare. This is a fascinating and popular aspect to the hobby but it is not without some warnings and precautions that you need to be aware of.

Alan Barnes continues his Introduction to Radioactive Minerals with Part 2 – The Minerals, Their Properties and Their Occurrence, looking at uranium and thorium minerals. This is a very in depth and interesting article that packs in a lot of information. Well worth the read.

Unfortunately, due to space and other restrictions, we have not been able to publish Part 4 of Phil Taylor's 'Rocks and Minerals Through Time and Space' looking at the key events in Earth history which have determined the variety of over 6,226 mineral species as of July 2026. This will be published in Issue 5, March 2027 – something to look forward to.

I welcome any feedback on articles in the JMM so please do not be afraid to comment. Without any feedback I do not know if what I and the others are providing is what you want. Send me your thoughts, suggestions and any items of interest to your fellow collectors of minerals.

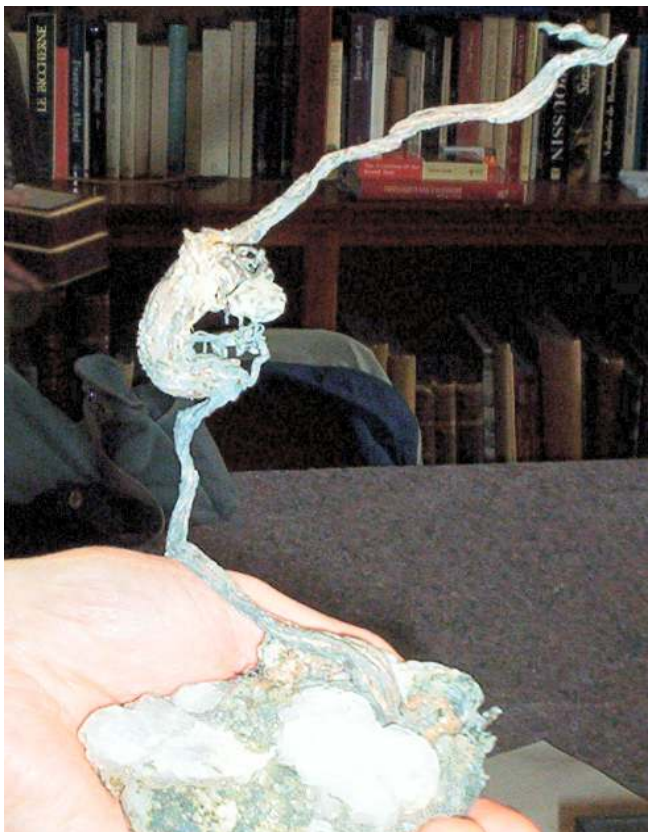
Finally although this publication is targetted at Junior Members of the Russell Society to help them develop their interest and knowledge in minerals the Society also publishes the biannual Newsletter and annual Journal both of which contain a considerable amount of interesting material. The Newsletter also contains listings of shows and events taking place throughout the year some of which should be a must for young mineral collectors and anybody with similar interests. The Newsletter can be downloaded from the Members' Page of the Russell Society web site. Take a look and visit some of the upcoming events.

Gary Morse, Editor.

Panning for gold in the United Kingdom is very unlikely to make you rich but it is great fun. This tiny speck is the result of panning for several hours on Dartmoor in 2007. Read more about native gold in the UK later and the largest gold nugget ever found that was some 720,000 times heavier than my little nugget.

Amazing Minerals

Some of the most attractive, and most sought after minerals specimens, are those termed as 'native elements'. Later there is an article on native elements and collecting them. Here are some of the various amazing forms that they can be found as.



Native silver from the famous Kongsberg Mines, Buskerud, Norway in the Collection of Georgiana, Duchess of Devonshire at Chatsworth House being held by the late Mick Cooper at the RS ASM 2006 visit to Chatsworth.
G. Morse photograph.

Dendritic gold 'ferns', with some calcite, from Hope's Nose, Torquay, Devon. Dimensions: 32 mm x 28 mm. From the collection of Shirley Adrian.
Photograph and specimen Richard Bell.

Shiny globules of native mercury on cinnabar from Almadén Mine, Almadén, Ciudad Real, Castile-La Mancha, Spain.
Photograph by Géry Parent – CC-BY-SA-4.0.

An exceptional twinned natural diamond crystal from South Africa. Size: 15 mm x 15 mm x 4 mm (9.94 carats).
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0

Cubic crystalline native platinum from Talnakh Cu-Ni Deposit, Noril'sk, Putoran Plateau, Taimyr Peninsula, Russia. Size: 8 mm x 7 mm x 5 mm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Sulphur crystals in situ at Ha'akulamanu (Sulphur Banks), Hawai'i Volcanoes National Park. FoV ≈ 18 cm. G. Morse photograph Nov. 2011.

Finely crystallised native copper from Botallack Mine, Botallack, St Just, Cornwall. Size: 60 mm x 32 mm x 16 mm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Graphite from the Borrowdale Graphite Mines, Seathwaite, Borrowdale, Cumbria. Size: 38 mm x 23 mm x 17 mm. Ex David Griffiths specimen acquired 1996.
G. Morse photograph and specimen GM0002.

Aspects of Mineral Collecting

We are continuing our series of looking at some of the specialist aspects of mineral collecting that are practised by many collectors worldwide. In this issue we will be considering the collecting of examples of naturally occurring native elements to give you an insight into this interesting option for specialisation in mineral collecting. We will also look at some of the pitfalls that you may encounter.

Collecting Native Elements

There are a large number of mineral collectors who attempt to acquire specimens of the naturally occurring elements that can be found worldwide. There are thirty-one recorded, International Mineralogical Association (IMA) approved, minerals that are found as native elements, some are doubtful and others have only been recorded from the Moon or in meteorites. Of the thirty-one IMA approved native element minerals seventeen have been recorded as occurring within the UK.

A very large plate of native copper from Wheal Unity (Ghostcroft Mine), Mullion, Cornwall in the collection of Camborne School of Mines. The plate is approximately 1.4 m wide. See below in Copper.
Scale = 1 m. G. Morse photograph, 2012.

Many of these specimens are exceptionally rare and are only found as very small examples but the challenge is to try and obtain representative specimens of these from the different locations where they occur. Some of these are the pure element, some are intermetallic compounds (an ordered solid-state compound, with a fixed chemical composition, of two or more metallic elements) or alloys (a variable mixture of two or more metals), some elements are what are termed metalloids (semi-metals) and other are non-metals some of which may have different allotropes (existing in different forms, in the same physical state). Here we shall be looking at what these native elements are, discussing their occurrence and how to identify them. This can be a very rewarding aspect to the hobby of mineral collecting but can be expensive for good and rare specimens.

What are Native Element Minerals?

Native element minerals are those naturally occurring elements that are found in nature in an uncombined form with a distinct crystal structure. The elemental class includes the metals, intermetallic compounds, some alloys, metalloids, and non-metals. Mercury is an exception as it is liquid between -38.83 °C and 356.73 °C yet it is an approved mineral, it readily forms amalgams (a metal alloy of mercury) with many other metals. Of course elemental atmospheric gases are, obviously, not included as minerals.

Two allotropes of carbon: graphite and diamond with an impure diamond called 'carbonado' ('black diamond').

The Nickel–Strunz classification system, which groups minerals based on their chemical composition, includes the naturally occurring phosphides, silicides, nitrides, carbides, and arsenides within its elements Class 1. Metals and intermetallic alloys are Class 1.A. (see Strunz-Mindat (2026) Classification — Elements (Metals and intermetallic alloys; metalloids and non-metals; carbides, silicides, nitrides, phosphides. https://www.mindat.org/strunz.php?a=1). We shall only be considering natives here but the rest are other groups that some collectors specialise in.

Below is a representation of the periodic table showing the elements that are IMA approved minerals forming native elements including intermetallics, metallic alloys, metalloids and non-metals. Those that are to be found within the United Kingdom (Tindle and Green, 2024) are highlighted in red although some are exceptionally rare or potentially anthropogenic (formed as a result of human processes). Gold (Au), and the six platinum group metals, (ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt)) are the native metals that occur naturally only in the elemental form. These are termed 'noble metals' due to their low reactivity with other elements and exist unreacted but they do form natural alloys with other metals. Copper (Cu) and silver (Ag) do commonly occur as native metals but they are also able to form different minerals by reaction with other non-metallic elements, notably sulphur (S).

The periodic table shows that the majority of the elements to be found occurring naturally fall within the d-block, groups 3 to 12, and are termed 'transition metals'. Simply this term arises from the property of having electrons that can participate in the formation of chemical bonds, in two electron shells instead of only one. The term transition[1] has no significance to chemistry and is just convenient name by which to distinguish the similarity of the elements within the d-block. This atomic arrangement gives the transition metals some unique chemical properties over other metals including their reactivity and ability to form coloured compounds. Low reactivity is why some are commonly found as the native element. None of the alkali metals (Group 1), alkaline earth metals (Group 2), or the fifteen rare-earth elements (REE), that are the lanthanide elements: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium and includes yttrium and scandium, do not occur as native minerals because they are more reactive.

G→ P↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	← D-block – Transition metals. →										13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Lanthanides:	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
Actinides:	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Key:	G = Group P = Period	Native metals	Native non-metals	Native metalloids	Reported from the UK	Synthetically produced

1 The term 'Transition' was introduced by the English physical chemist Charles Rugeley Bury (1890 – 1968) in 1921.

Native Alloys

Several metal alloys occur naturally. These include:

Brass (α-brass) – Alloy of copper and zinc.
Bronze (η-bronze) – Alloy of copper and tin.
Electrum – Alloy of principally gold and silver.
Gold-mercury amalgams.
Leadamalgam ($HgPb_2$) and others.
Lead-tin – As yet several unnamed Pb/Sn alloys.
Nickel-gold – Unnamed (UM2008-10-E:AuNi)
Nickel-iron – Both telluric and meteoric alloys.
Silver-mercury amalgam.
Unnamed nickel-copper alloys.

Where they form naturally occurring compounds with a fixed chemical composition they are classified as minerals. These are termed 'stoichiometric[2] alloys'. Where they have a variable chemical composition and contain varying percentages of metals in the alloy they are not generally classed as minerals but as 'non-stoichiometric alloys'. For example; the mercury-silver alloy (mercury alloys are usually called amalgams) moschellandsbergite has a fixed chemical composition with the formula Ag_2Hg_3 (contains (by mass) 26.39% Ag and 73.61% Hg) is accepted as a mineral yet the gold-silver-mercury amalgam known as 'goldamalgam', (Au,Ag)Hg has been rejected by the IMA as a mineral because the amounts of each component present can vary. Curiously, the amalgam mineral, weishanite, ((Au,Ag,Hg) (IMA), some references give $(Au,Ag)_3Hg_2$), from the type locality in the Weishancheng ore field, Henan Province, China is accepted as a mineral even though its composition is known to be variable. The whole aspect of naturally occurring 'native alloys' is rather confused and many were possibly formed as the result of pre-historical, anthropogenic metallurgical processes.

Metalloids

Native elements that are known as metalloids are antimony (Sb), arsenic (As), silicon (Si) and tellurium (Te). A metalloid is an element that exhibits some of the properties of metals and some of non-metals (www.chemicool.com). There is no agreed standard definition of a metalloid or which elements are classed as metalloids.

Non-metals

Naturally occurring elements that are non-metals are: Carbon (C), Selenium (Se) and Sulphur (S).

Carbon occurs as multiple allotropes. An allotrope is the property of some chemical elements to exist in two or more different forms, in the same physical state. There are five IMA approved naturally occurring allotropes of carbon (C) these are diamond (isometric), graphite (hexagonal), lonsdaleite (hexagonal), chaoite (hexagonal) and tartarosite (isometric). The last three allotropes are very rare.

Native elements in the UK

Below is a list of all the naturally occurring elemental native metals compiled from the IMA-CNMNC List of Mineral Names (July 2026). Those in **bold** text are ones that are recorded to have been found the UK.

Aluminium (Al)
Bismuth (Bi)
Cadmium (Cd)
Chromium (Cr)
Copper (Cu)
Gold (Au)
Indium (In)
Iron (Fe)
Iridium (Ir)
Lead (Pb)
Mercury (Hg)
Nickel (Ni)
Osmium (Os)
Palladium (Pd)
Platinum (Pt)
Rhodium (Rh)
Ruthenium (Ru)
Silver (Ag)
Tantalum (Ta)
Tin (Sn)
Titanium (Ti)
Tungsten (W)
Vanadium (V)
Zinc (Zn)

2 Stoichiometry is the relationship between the quantities of reagents involved in a chemical reaction and the compounds that are produced as a result of that chemical reaction with no excess of reagent remaining.

All of the noble metals occur as native minerals. The metals gold, silver, and copper occur in well distributed amounts in their native form in the UK yet the specimens are mostly very small. The table below lists all native elements and locations reported that have been found in the UK.

Element	Reported locations within the UK
Antimony	Allerdale, Patterdale and Caldbeck Fells in Cumbria. St Just, Cornwall. Okehampton, Devon.
Arsenic	Widespread locations throughout Cornwall and Devon.
Bismuth	Numerous locations throughout the UK.
Copper	Numerous locations throughout the UK.
Gold	Numerous locations throughout the UK.
Carbon (graphite)	Borrowdale, Allerdale, Cumbria and other locations mostly anthropogenic or meteoric.
Iridium	Unst, Shetland Islands. Isle of Rum.
Iron (Telluric)	Beinn Bhreac, Scotland and County Antrim, N. Ireland (both discredited). Other recorded occurrences are meteoric iron.
Lead	Probably all result from smelting operations.
Mercury	Caldbeck Fells, Cumbria. Matlock Bath, Derbyshire. Linlithgow, Scotland.
Osmium	Unst, Shetland Islands.
Platinum	Landewednack, Cornwall. Isle of Rum. South Ayrshire and Killin.
Silver	Numerous locations throughout the UK.
Sulphur	Numerous locations throughout the UK.
Tellurium	Aberfeldy, Perth and Kinross.
Tin	Isle of Mull, Argyll and Bute.
Zinc	Only found as a result of smelting operations.

Some of these reported native elements have only been found as single, very small single samples at just one location. For example; see the spherule of native tin that was found in analcime at Carsaig Bay, Carsaig, Isle of Mull, Argyll and Bute, Scotland. The only reported UK location for very rare native tin, see: https://www.mindat.org/gallery.php?loc=14281&min=3965&checkall=2.

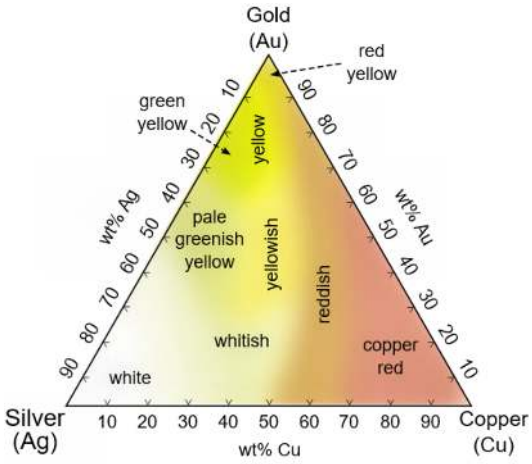
Gold

Despite its low reactivity, gold occurs not only in its native elemental form but as alloys with other metals and some very rare compounds. These are listed below.

Anyuiite, $AuPb_2$	Gachingite, $Au(Te_{1-x}Se_x)$	Native Gold, Au
Auricupride, Cu_3Au	Honeaite, Au_3TlTe_2	Novodneprite, $AuPb_3$
Aurihydrargyrumite, Au_6Hg_5	Hunchunite, Au_2Pb	Pampaloite, AuSbTe
Auropearceite, $[Ag_9AuS_4][Ag_6As_2S_7]$	Jaszczakite, $[Bi_3S_3][AuS_2]$	Penzhinite, $(Ag,Cu)_4Au(S,Se)_4$
Auropolybasite, $[Ag_9AuS_4][Ag_6Sb_2S_7]$	Jonassonite, $AuBi_5S_4$	Petrovskaite, AuAgS
Auroselenide, AuSe	Kostovite, $CuAuTe_4$	Petzite, Ag_3AuTe_2
Aurostibite, $AuSb_2$	Krennerite, Au_3AgTe_8	Rumoiite, $AuSn_2$
Bezsmertnovite, $(Au,Ag)_4Cu(Te,Pb)$	Makotoite, $Ag_{12}(Cu_3Au)S_8$	Sylvanite, $AgAuTe_4$
Bilibinskite, $PbCu_2Au_3Te_2$	Maldonite, Au_2Bi	Tetra-auricupride, AuCu
Bogdanovite, $(Au,Te,Pb)_3(Cu,Fe)$	Maletoyvayamite, $Au_3Se_4Te_6$	Thunderbayite, $TlAg_3Au_3Sb_7S_6$
Buckhornite, $AuPb_2BiTe_2S_3$	Montbrayite, $(Au,Ag,Sb,Bi,Pb)_{23}(Te,Sb,Bi,Pb)_{38}$	Tolstykhite, $Au_3S_4Te_6$
Calaverite, $AuTe_2$		Uytenbogaardtite, Ag_3AuS_2
Criddleite, $TlAg_2Au_3Sb_{10}S_{10}$	Museumite, $[Pb_2(Pb,Sb)_2S_8][(Te,Au)_2]$	Weishanite, (Au,Ag,Hg)
Cuproauride, Cu_3Au	Muthmannite, $AuAgTe_2$	Yuanjiangite, AuSn
Fischesserite, Ag_3AuSe_2	Nagyágite, $[Pb_3(Pb,Sb)_3S_6](Au,Te)_3$	

List of the 43 IMA recognised minerals containing gold, most are extremely rare and exist only as very small specimens. Note that the Au, Ag alloy known as electrum is not listed as it has a variable composition and thus is not a true mineral yet much 'native gold' could be electrum. List source Mindat: https://www.mindat.org/chemsearch.php?inc=Au%2C&exc=&ima=0&class=0&sub=Search+Minerals

Native gold is never found in an absolute pure form but normally contains some alloying metals. The carat (UK spelling) or karat (US spelling) is the fractional measure used to quantify the purity of gold and its alloys. 24 carat gold is 100% gold. This is not easily achieved, the purity of refined gold is measured by its fineness and the best purity that can be achieved is called 999.9 fine (parts per thousand, ppt). This means it is 99.99% pure gold. When one or more other metals are incorporated in gold they are expressed as fractions of 24. Thus 18 carat gold is 18/24 parts pure gold which is 75%. Alloying metals can change the colour of gold and gold panned from one river may have a different colour to that panned from a different location because the quantity and type of alloying metal is different. Pure gold is actually a reddish-yellow colour which is due to relativistic quantum chemistry. If you would like an explanation of that see: https://en.wikipedia.org/wiki/Relativistic_quantum_chemistry.



Approximate colours of Au–Ag–Cu alloys.

1 Troy ounce (31.1 g) of 999.9 fine gold.

One way to determine gold purity is to use the method discovered by Archimedes in his 'Eureka' moment and measure the density, https://scienceinfo.com/archimedes-principle. Pure gold has a density of 19.283 g cm^{-3}, anything lower than that is not pure. There are online tables of densities of different gold alloys, https://en.wikipedia.org/wiki/Fineness#Density.

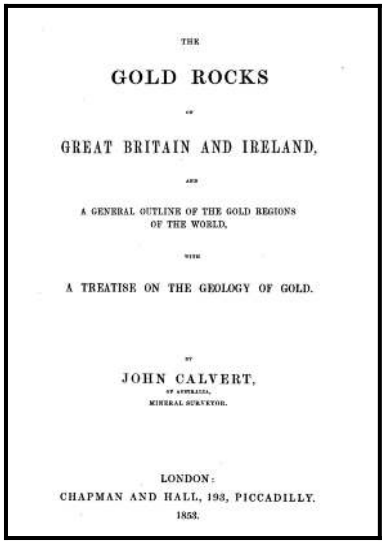
Electrum is a naturally occurring alloy of gold and silver, sometimes with trace amounts of copper and other metals. Its colour ranges from pale to bright yellow, depending on the proportions of gold silver and copper. Typically naturally occurring electrum has 30% – 45% silver (55% – 70% gold) it is classed as a native form of gold. Probably most of the early gold found and used was electrum.

Finding Gold

Gold, although mostly in small quantities, is found fairly widespread throughout the United Kingdom and with the right equipment can be found, with a bit of hard work. In his book *Gold Occurrences in the UK, A Gold Prospectors Guide (2023),* Lee Gary Palmer records over 750 gold occurring locations. Most of the gold found in the UK is found as alluvial grains, having been eroded out of its source rock and carried by streams and rivers to be deposited in the gravel beds. Specimens can be found by panning the river gravels. The second edition of Lee Palmers book book was updated in April 2023 and lists these locations.

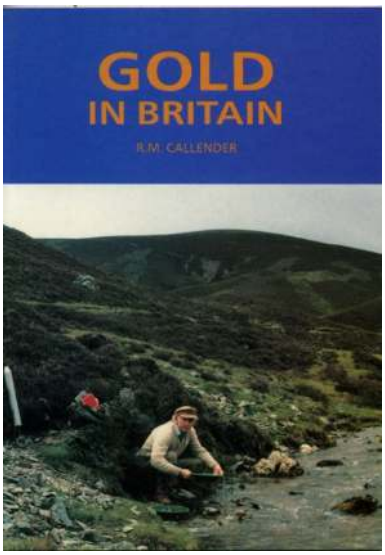
Gold Occurrences in the UK (2023) can be obtained from Lee Gary Palmer.
https://goldpublications.co.uk
Image used with permission.

A very early publication on UK gold was in 1853 by the notorious John Calvert (1825 – 1897) who was variously described at the time as "*A blackguard and a seducer of women.*" "*A wild Australian Bushman.*" Adam Sedgwick commented "*I never met a more perfect and transparent fraud.*" Calvert's book *The Gold Rocks of Great Britain and Ireland, and a general outline of the gold regions of the world, with a treatise on the geology of gold* lists many gold locations, some dubious. The book is freely available for download


THE
GOLD ROCKS
OF
GREAT BRITAIN AND IRELAND,
AND
A GENERAL OUTLINE OF THE GOLD REGIONS OF THE WORLD,
WITH
A TREATISE ON THE GEOLOGY OF GOLD.
BY
JOHN CALVERT,
OF ADELAIDE,
MINERAL SURVEYOR.
LONDON:
CHAPMAN AND HALL, 193, PICCADILLY.
1853.

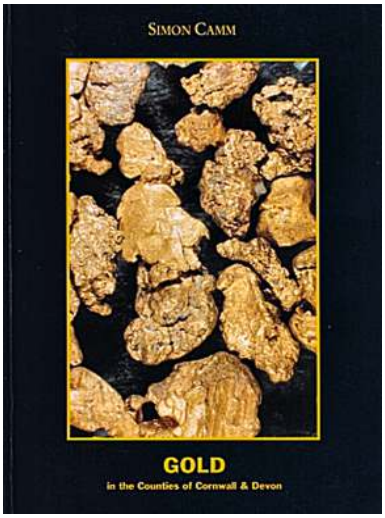
online and makes for good reading but the contents should be taken with some scepticism as he was renowned fraudster.

There are other books that have been published on gold in the UK. Some are out of print but do sometimes turn up on online sales sites. These are:



Gold in Britain by R. M. Callender, 1989. Pub. Goldspear (UK) Ltd. ISBN: 0951413422

Gold in the Counties of Cornwall and Devon by Simon Camm, 1995. Pub. Cornish Hillside Publications. ISBN: 0951941976. This was a very popular book and as it is now out of print, Simon Camm and the publishers have very kindly made a scanned PDF copy available for free download from:
https://www.researchgate.net/publication/286624030_Gold_in_the_Counties_of_Cornwall_and_Devon
[Accessed July 2026].



Another source of information on UK gold, and other minerals, is the British Geological Survey (BGS) and NORA the NERC (Natural Environment Research Council) Open Research Archive (https://nora.nerc.ac.uk). From there you can download the BGS 1999 publication for the DTi *Minerals in Britain: Gold* that covers the potential commercial locations for gold in the UK along with a map. https://nora.nerc.ac.uk/id/eprint/534494/1/mins_in_britain_gold.pdf. The site also has many other publications of interest.

The Law and Rules for UK Gold Prospecting

Under the Royal Mines Act 1693, all naturally occurring gold in the UK belongs to the Crown. In 2026 it is still in force in England and Wales, there are concessions for 'Tinners of Devon and Cornwall'. Currently the whole legislation situation and permit system is a confused disaster. The Crown Estate stopped issuing recreational licences some years ago, meaning that there is currently no formal route to take gold away from Crown land. You need to understand this legal position very clearly and make your own informed decisions. The best solution is to join legitimate organised groups who will have the relevant permissions and insurance. An internet search will find these groups Recreational panning for gold is generally allowed but the law differs by country.

Panning for gold on freezing cold Mennock Waters in April 2013, with a paid for licence.

In Scotland, statutory access rights under the Land Reform (Scotland) Act 2003 mean you can access most rivers without landowner permission, though Crown mineral rights still apply to the gold itself. The Museum of Lead Mining at Wanlockhead sell licences on behalf of Buccleuch Estate who own the area of Wanlockhead Waters and Mennock Waters and Hopetoun Estate who own Elvan Water, Short Clough and their tributaries, where gold can still be found. The museum also runs courses and sells panning equipment. See:
https://www.leadminingmuseum.co.uk/visit/gold-panning/gold-panning-courses

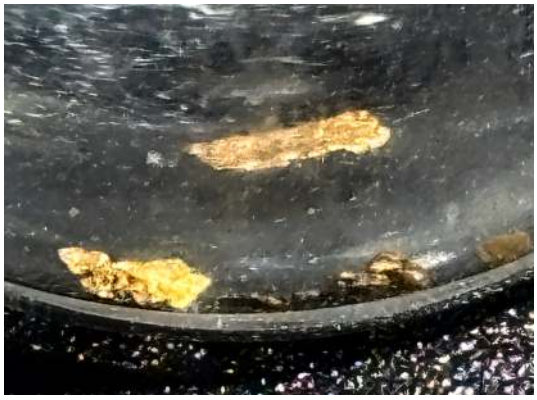
In England and Wales there is no right of access and landowner permission is essential everywhere, even in rivers. In Wales, many of the gold producing rivers are within Natural Resources Wales managed Sites of

Special Scientific Interest (SSSI) where panning is prohibited and this is rigorously enforced with prosecution if caught.

In summary to pan for gold legally requires: a known gold bearing location, the correct permissions (in writing), insurances against potential damage and, naturally, full respect for the collecting sites habitats and their flora and fauna.

Panning for 'gold' at Dolaucothi Gold Mines, Pumsaint, Carmarthenshire, Wales in 2005.

Some mining tourist locations have 'gold panning' activities where the public can pan for 'gold' and these are usually seeded with pyrite, 'fools gold', but it does allow for your panning techniques to be developed in a safe environment.



Native gold flakes, stored under water, panned from Dartmoor in 2010. Largest is ≈2 mm long.
G. Morse photograph and specimen GM0019.

Gold panning is a very satisfying hobby, you are very unlikely to get rich but the satisfaction achieved on finding those specks of gold in your pan is worth all the effort and you can also appreciate some of the stunning scenery where the gold is to be found.

There are a number of websites that give more information on UK gold and amateur prospecting and an online search will bring these up. Two that can be recommended are:

The British Gold Panning Association (BGA). The association in the UK that covers all aspects of the hobby of gold panning: https://britishgoldpanningassociation.com/ and the UK Gold Prospector: https://ukgoldprospector.co.uk.

Native gold is very easy to distinguish from other shiny, yellow minerals because it is ductile (able to deform plastically). If you press a pin into the surface of the specimen, using your hand lens or microscope, gold will just deform and move but pyrite, chalcopyrite and other golden coloured minerals, like micas, will just break up into pieces. If you drop a tiny gold nugget into a glass tube of water you will see that it sinks very rapidly due to its high density of 19.3 g cm^{-3}.

Silver

Native silver and acanthite from Wheal Ludcott, St Ives, Cornwall.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0

Native silver can be found within the UK and its occurrence is recorded from around 80 locations on the mainland (Mindat) but most specimens are very small. Native silver is not as common as native gold because silver does react with other elements, notably sulphur, to form what are called silver sulphosalt compounds. The IMA approved list of minerals (May 2026) records 243 silver containing minerals. Acanthite is the black silver sulphide, Ag_2S, that forms the tarnish on silver surfaces. Silver can also occur in other ore minerals such as the lead ore galena (PbS), probably as microscopic inclusions of silver sulphosalts. In Britain in the 19th century it was economically recovered from the lead after smelting and by selective crystallisation using the Pattinson process that was perfected by the English industrial chemist Hugh Lee Pattinson (1796 – 1858) in 1829 and patented by him in 1833. https://en.wikipedia.org/wiki/Pattinson%27s_process.

Sir Kingsley Dunham FRS FGS FRSE (1910 – 2001) in the publication *Geology of the Northern Pennine Orefield. Volume 1,* noted that silver recovery from galena by the London Lead Company's Nenthead mines was an average of 7 oz [presumably Troy oz] of silver per ton of lead [240 g/tonne] (Dunham, 1990) which considerably enhanced the profits from lead smelting. Galena that is rich in silver is termed 'argentiferous galena' or 'silver-bearing galena' but the only way to determine the actual silver content is by chemical analysis. Silver-bearing galena cannot be visually identified.

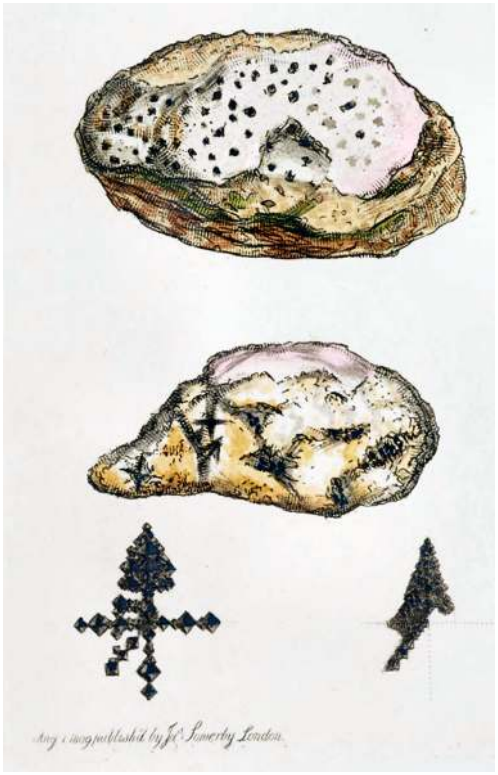
Native silver is found in various crystal habits and forms that can be very attractive and are eagerly sort after by collectors. Silver can occur as poorly formed cubic or octahedral crystals but it is more readily presented in parallel arborescent groups, tangled wiry masses, in flat lamellae (plates), as branched and dendritic (tree like) aggregates or as what are termed 'spongy' masses. Some examples of these are illustrated below.

Entrance of 'Kongens Gruve'; 'The Kings Mine', Kongsberg, Buskerud, Norway.
Image by Kjetil Bjørnsrud – CC BY-SA 3.0

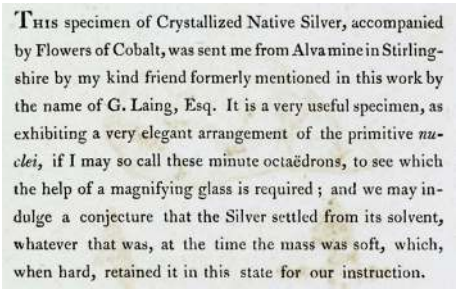
The most famous, and sought after, native silver specimens came from the famous Kongsberg mines, Buskerud, Norway. The mine closed in 1957 and has been preserved as part of the Norwegian Mining Museum in Kongsberg. The mine train takes visitors through some 2.3 km of the Christian VII Adit: https://norskbergverksmuseum.no/en/the-silver-mines [Accessed June 2026].

Most major national and private collections will contain at least one specimen of native silver from the Kongsberg mines. Take a look at 'The Famous Silver Mines of Kongsberg, Norway' on the Mineralogical Society of the District of Columbia web site to learn more about the mines, their history and to see some superb examples: https://news.mineralogicalsocietyofdc.org/kongsberg-silver [Accessed June 2026]. Such is the desirability of these specimens they are very much faked, see later.

A classic wiry native silver from Kongsberg, Norway. Size: 22 mm x 21 mm x 5 mm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0



As noted above there are some 80 locations recorded for native silver in the United Kingdom. A few of these have in the past produced some highly collectable specimens. If you would like to see some of the specimens that have been discovered take a browse around the photographs on Mindat at: https://www.mindat.org/gallery [Links to UK native silver search, accessed June 2026]. Some of the finest UK silver came from the Alva Silver Mine, Alva, Clackmannanshire, Scotland.



THIS specimen of Crystallized Native Silver, accompanied by Flowers of Cobalt, was sent me from Alva mine in Stirlingshire by my kind friend formerly mentioned in this work by the name of G. Laing, Esq. It is a very useful specimen, as exhibiting a very elegant arrangement of the primitive *nuclei*, if I may so call these minute octaëdrons, to see which the help of a magnifying glass is required; and we may indulge a conjecture that the Silver settled from its solvent, whatever that was, at the time the mass was soft, which, when hard, retained it in this state for our instruction.

Plate 327 native silver (Argentum Nativum) from Alva Mine illustrated in James Sowerby's (1757 – 1822) British Mineralogy or, Coloured figures intended to elucidate the mineralogy of Great Britain, Volume 4 with an extract of his accompanying text.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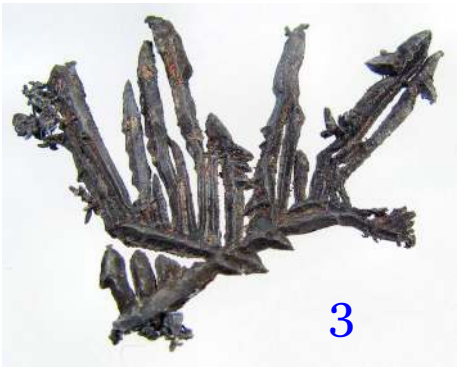
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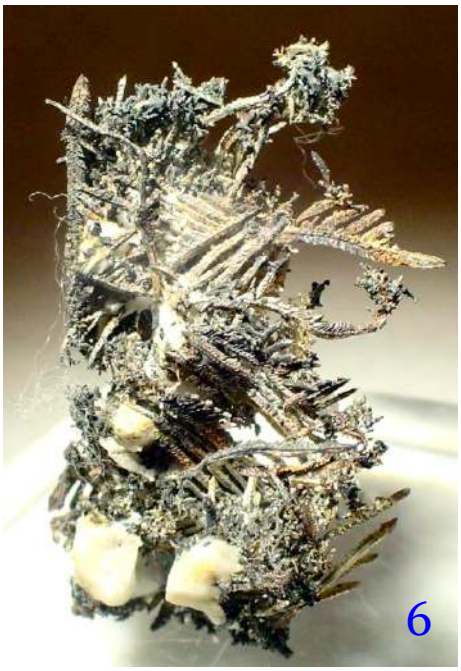
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Examples of Native Silver Habit

1. *Spongy mass of silver, with minor acanthite, from Balcoll Mine, Falset, Priorat, Tarragona, Catalonia, Spain. Size: 44 mm x 31 mm x 11 mm.* Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.
2. *An aesthetic group of silver crystals with a fine patina from the historic silver mines of Kongsberg, Buskerud, Norway, formally in the Smithsonian Collection. Size: 20 mm x 17 mm x 5 mm.* Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.
3. *Dendritic silver from Batopilas, Chihuahua, Mexico. Size: 30 mm x 30 mm x 5 mm.* Paul (Enschede) – CC-BY-SA-2.0.
4. *Contorted mass of parallel silver wires from the famous Kongsberg mines, Buskerud, Norway. Size: 14 mm x 10 mm x 9 mm.* Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.
5. *Fine mass of wiry and dendritic silver covering calcite from Balcoll Mine, Falset, Priorat, Tarragona, Catalonia, Spain. Size: 45 mm x 32 mm x 25 mm.* Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.
6. *Herringbone and arborescent silver comprised spinel-twinned crystals with minor calcite from New Nevada Mine, Cerro San Antonio, San Miguel, Batopilas, Chihuahua, Mexico. Size: 36 mm x 24 mm x 15 mm.* Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Copper

Native copper occurs fairly widespread throughout the United Kingdom. Mindat records (June 2026) show 151 locations in England with 121 of those being in Cornwall alone. Scotland has 17 reported locations and Wales 22. Some of the Cornish native copper specimens are quite spectacular but the majority of the copper specimens found now are small and very corroded. Some specimens from old mines have arisen from chemical reactions between the old mine iron structures and copper bearing solutions causing the copper to be deposited (reduced) replacing the iron. These should be considered to have formed as a result of post-mining, anthropogenic processes (man-made) and thus are not truly naturally occurring but they can be very attractive, interesting specimens.

Very fine crystalline mass of copper with cuprite from the 13 Level, Levant Section, Geevor Mine, St Just Cornwall. Possibly formed by reduction on old mine cart rails made from iron. Width ≈ 70 mm.
G. Morse specimen GM0012.

This method of precipitating copper from solution, using low value scrap iron, was employed at Parys Mountain Copper Mine on Anglesey, Wales to recover higher value copper from the very acidic waters draining from the mine containing high levels of dissolved copper salts. The old precipitation pits still exist and are barren, toxic areas of insoluble iron and copper contaminated waste.

The old copper precipitation pits at Parys Mountain Copper Mine.
G Morse photograph, September 2010.

Another Welsh occurrence of precipitated copper is one that happened naturally at the Dolfrwynog Turf Copper Mine, Coed y Brenin, Dolgellau, Gwynedd, Wales. The copper was so rich that the mine was worked from 1824 to 1847. Dissolved copper leached into the peat from the underlying Coed y Brenin copper porphyry deposit precipitated copper metal in the vegetation by a process of bioreduction. The peat was cut, ashed in a kiln to reduce the volume and to enrich the copper metal content. The ash was sent to Swansea for the refining of the copper metal. It was said that during one year in the 18th century 2,000 tons of peat ash was sold at a profit of £20,000 (Henwood, 1856). These processes of biological recovery and reduction are now being researched and studied as a low environmental impact method for the recovery of copper from mine wastes and low concentration sources by processes known as phytoextraction, or phytomining, using plants that can accumulate the metals within themselves.

The remains of a kiln used to ash the copper bearing peat at Turf Copper Mine.
G. Morse photograph, September 2010.

https://en.wikipedia.org/wiki/Hyperaccumulator#Phytomining

All of these Welsh sites are protected Sites of Special Scientific Interest and any collecting on the sites is forbidden unless permission has been granted.

For further information on Welsh copper occurrences visit the Amgueddfa Cymru – National Museum Wales mineral database at:
https://museum.wales/mineralogy-of-wales/database/?mineral=200&name=Copper

In Scotland the principle site where native copper could be found was, the now abandoned, Boyleston Quarry, Barrhead, Renfrewshire. Here native copper occurred as plates, nuggets and leaves plus small crystals were found disseminated within analcime, calcite and prehnite (Livingstone, 2003).

Native copper has been found at the Meadowfoot Smelter slag locality, Wanlockhead, Scotland as small, wiry aggregates and discreet blebs but as these are occurring at a former smelting site they cannot be considered to be naturally formed by geological processes.

Small pieces of native copper can be found in the rocks, as minor occurrences, throughout the Highlands and Islands of Scotland but do require some knowledge and hard work to find them. A search on Mindat.org for 'native copper from Scotland UK' will bring up a list of the Scottish locations and access to a few images of specimens.

Once again, the majority of these sites are now protected and any collecting, without written permission from land owners and regulatory authorities, is forbidden and if ignored can result in prosecution.

A very thin sheet of native copper from Boyleston Quarry, Barrhead, Renfrewshire. Size 160 mm x 120 mm. *Image © National Museums Scotland. Object No. G.1962.5. Out of copyright.*

Native Copper in Cornwall

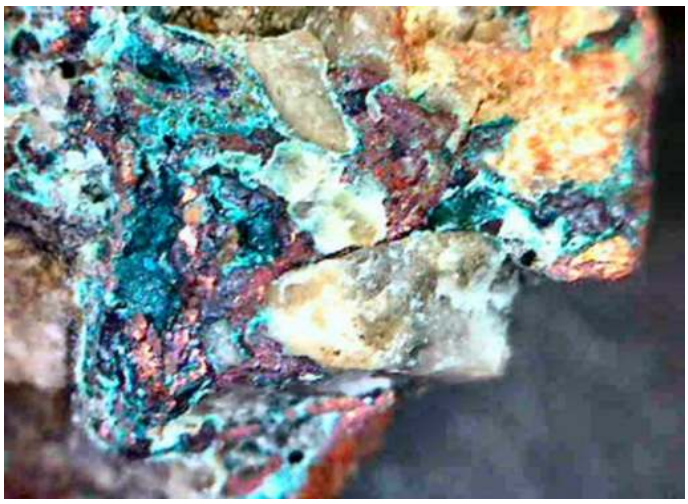
As had been remarked upon earlier the best place to find native copper on mainland Britain is in the county of Cornwall. The largest single piece of native copper ever discovered in Britain came from Ghostcroft Mine, (also known as Wheal Unity or Trenance Mine), Mullion, Cornwall (Embrey and Symes, 1987). A photograph of the specimen is shown in Embrey and Symes' book *Minerals of Cornwall and Devon* (Fig. 23) with the caption saying: '*Copper from the Ghostcroft Mine, Mullion Cornwall, a large mass, weighing 635 kg with a little cuprite and malachite. This specimen (BM.1985,MI11495) is 7 ft 6 in* [4 m] *long, up to 2 ft* [0.6 m] *wide and varies from 4 to 12 in* [102 mm to 305 mm] *in thickness.*'

Natural History Museum specimen (BM.1964,R142) of native copper from South Caradon Mine from the Russell Collection. CC-BY-SA-2.0.

In his publication *Mines and Miners of Cornwall,* Pt XIII, regarding Ghostcroft Mine, Mullion A. K. Hamilton Jenkin records: "*In 1848 a parcel of 15 tons of ore was sold, 9 tons of which fetched £19 per ton, the whole realising £200. Shortly after this another consignment of specimens from the mine reached London. Among these was a slab of malleable copper weighing 1568 lbs* [711 kg] *part of a slab of about 30 feet long, 4 feet wide and 6 inches thick* [9.1 m x 4.2 m x 0.2 m]. *This was broken from the main mass at a depth of only 14 fathoms from surface and special tackle had to be erected to raise it. As the largest specimen of native copper ever mined in England, the severed portion was sent to the Great Exhibition of 1851 and eventually found its way via the old Jermyn Street Museum to the present Museum of the Geological Survey. Other pieces of lesser size continued to be found as the work progressed, many of these having a dendritic or tree like formation.*" (Hamilton Jenkin, 1967).

The likes of that sample are very unlikely to ever be encountered again in Cornwall but on the old mine waste tips small samples can still be found.

The identification of native copper on specimens picked up in the field is not easy. Copper metal is very is prone to corrosion and oxidation giving rise to secondary copper minerals such as the red coloured copper oxide cuprite (Cu_2O), green coloured carbonate, malachite ($Cu_2(CO_3)(OH)_2$) or even more esoteric secondaries such as emerald green sulphate brochantite ($Cu_4(SO_4)(OH)_6$). Thus spotting the distinctive colour of metallic copper is virtually impossible unless these coatings are removed, either physically or chemically, to reveal the copper metal underneath. This practice can seriously affect a good specimen so proceed with care. The specimen of native copper and cuprite from Craddock Moor shown left was prepared using an ultrasonic cleaning bath to remove the adhering dirt and secondaries from the underlying copper showing the typical copper metal colour.



Native copper, cuprite with possible chalcocite, chalcopyrite and connellite, Craddock Moor Mine, Craddock Moor, St Cleer, Cornwall. FoV ≈10 mm.
G. Morse specimen GM0629. Collected 2018.

One way of finding a potentially copper bearing specimen is by feeling the weight (hefting) of the piece in your hand. Copper has a density of 8.9 g cm^{-3} so it should feel a little heavier than a similar sized piece of rock if a reasonable mass of copper is present. Scratching the surface with a sharp steel point may reveal underlying native copper. Some avid collectors of native copper specimens resort to the use of metal detectors on old dumps to locate possible pieces. Unfortunately old mine dumps can contain significant amounts of mining debris and other metallic waste that makes detecting a challenge. Some of the artifacts discovered can be of interest such as old, broken miner's tools, coins and brass buttons.

Corroded brass button found on the dumps of Golden Dagger Mine, Warren House, Teignbridge, Devon, in 2023.
G. Morse photograph.

Native copper can be found in the most unlikely of places so it is worth keeping your eyes peeled for the signs of heavy feeling specimens with red, blue and green coloured copper secondary mineralisation.

A conglomerate of iron oxide cemented sand (contains very small garnets) with two small patches of copper metal. Found in diggings in a lay-by off the B3306 at Pendeen, Cornwall, where a new bus shelter installation was being undertaken. Size: 4.1 cm x 2.2 cm x 1.7 cm.
Possibly anthropogenic?
G. Morse specimen GM0004 found 1982.

It is very unlikely that you will spot the presence of copper as the bright shiny copper coloured metal. There has been a long standing debate between mineral collectors as to whether or not specimens should be extensively cleaned to display the hidden minerals underneath the secondary mineralisation. I believe that a small amount of sympathetic cleaning is acceptable to show the full extent of the mineralisation within a specimen but I would draw the line at using chemicals to remove all the covering minerals and leave a bright and shiny specimen that is totally unnatural. The damage that overzealous 'specimen preparation' causes cannot be undone and it destroys the scientific value of the specimen.

Native copper and quartz, South Caradon Mine, St Cleer, Cornwall, England. Size: 70 mm x 45 mm x 25 mm. Specimen collected in 1988 by diving in sump shaft/engine shaft.
Barry Pitt specimen.

Specimen of quartz with sheet and massive native copper. Wheal Music, Porthtowan, St Agnes, Cornwall, England. Size: 75 mm x 20 mm x 35 mm. Barry Pitt specimen.

Mass of of loosely joined, small copper crystals with quartz and cuprite. Marke Valley Mine, Upton Cross, Linkinhorne, Cornwall, England Size: 80 mm x 50 mm x 35 mm.
Barry Pitt specimen.

Keweenaw County, Michigan, USA

By far the most famous locations for native copper specimens are within Keweenaw (pronounced: Kee-wi-naw), County, Michigan, USA. The Keweenaw Peninsula, located in Upper Peninsula of Michigan has the world's largest concentration of native copper deposits. So great was the quantity of native copper found in the area it earned the name of 'Copper Country'.

A 1960s postcard from 'Keweenawland" showing a map of 'Copper Country'.

The 19 ton mass of native copper on display in the Copper Pavilion of the A. E. Seaman Museum.

The world record holding, largest known native copper piece is the 19 ton 'Lake Copper' which was recovered from Great Sand Bay in Lake Superior. This 19 ton mass of Glacial Float Native Copper from the Keweenaw Peninsula is on display at the A. E. Seaman Museum in Houghton, Michigan, for more information and interesting reads on float copper and lake copper see: https://museum.mtu.edu/museum/copper-pavilion/lake_copper.

Three 'copper chips' from Cliff Mine, Keweenaw County, Michigan. Longest is approx. 10 cm.

Single masses of native copper, some weighing up to 527 tons, were found underground in mines such as in the Minesota Mine, Rockland, Ontonagon County, Michigan. These were so big that they could not be extracted whole but had to be cut up manually by chiselling progressively deepening grooves to divide them into manageable sizes underground just using hammers and cold chisels. This lead to resultant strips of copper similar in appearance to long wood shavings called 'Chisel chips'. These chips are mining artifacts that sometimes turn up in the spoil from the copper mines of the Keweenaw Peninsula.

Much of the shiny, 'native copper' found for sale in gift shops or online has originated from the Keweenaw region but it has been chemically cleaned or mechanically polished. They can also be be fakes formed during the smelting of and manufacture of copper metal artifacts. More of this later.

Native Sulphur

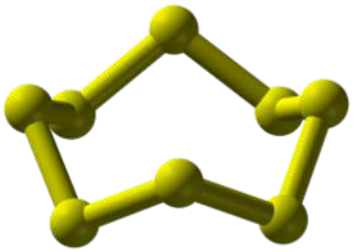
The last native element that we shall look at in detail here is sulphur. Firstly a short discussion on whether to use the word 'sulphur' or 'sulfur'. It's etymology goes back to Latin and not Greek as sometimes erroneously given. The oldest form of the word seems to be '*sulpur*' possibly derived from the proto-Indo-European **swépl̥* (genitive **sulplós*'), a nominal derivative of **swelp* 'to burn'. Over time this became sulphur. Only in English did the 'ph' remain for the 'f' sound, in other European languages the 'f' won through, for example *azufre* (Spanish), *schwefel* (German), *soufre* (French), *zolfo* (Italian). Interestingly, why the change from 'sulphur' to 'sulfur' occurred in the United States during the early part of the twentieth century is a mystery, as other 'ph' words are preserved in American English, it was possibly a German influence that initiated the change through their great involvement in the early chemical industry of the United States. The etymology of sulphur is still highly debated, an interesting article, 'Sulphur Or Sulfur? A Tale Of Two Spellings', in the *British Medical Journal* gives much more information (Michie and Langslow, 1988).

Since 1990 the International Union of Pure and Applied Chemistry, IUPAC, who make the rules for naming chemicals, have advocated the American spelling 'sulfur' as the preferred spelling to be used for the chemical, the commodity and its derivatives. The British English preference is still for 'sulphur'. Woe the day when we have to call the element with atomic number (*Z*) 15 'fosferous'! Perhaps we should return to old word of 'brimstone' (Middle English '*brinston*', probably from *birnen,* to burn and *ston,* stone).

The IMA still uses sulphur as the valid mineral name for the naturally occurring native element (The *New IMA List of Minerals – A Work in Progress,* July 2026) so we will continue to use the approved IMA name for native sulphur and the 'ph' in sulphur bearing compounds here, e.g. sulphate.

Sulphur is the fifth most common element on Earth (most is thought to be in the core combined with iron) and is 16th in abundance by mass in Earth's continental crust at 0.035% (350 g / tonne) it is also a very important biological element essential for life. Sulphur is capable of forming compounds with all other elements except the noble gases.

Sulphur can also exist as numerous solid allotropes but only three are stable, naturally occurring recognised forms. The orthorhombic polymorph, known as native sulphur, is the most common naturally occurring allotrope. Chemically it is called cyclo-octasulphur, (cyclo-S_8, α-sulphur or octathiocane) as it forms eight atom ring molecules. There are two other natural polymorphs that are are recognised, monoclinic clinosulphur (S_8) (β-sulphur) and monoclinic rosickýite (S) which is the densest form of natural sulphur.



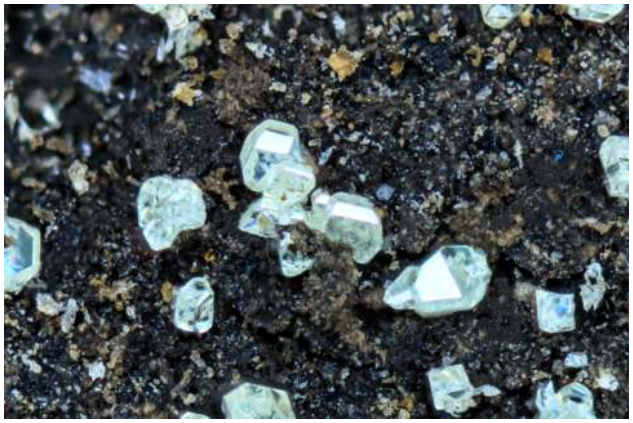
The most prevalent allotrope of sulphur in nature, cyclo-octasulphur (cyclo-S_8).

The greatest source of native sulphur are the sublimates[3] from volcanic fumaroles and solfataras, where hydrogen sulphide gas reacts with sulfur dioxide gas to liberate sulphur according to the following basic reaction:

1. $2H_2S + SO_2 = 3S + 2H_2O$

hydrogen sulphide + sulphur dioxide = sulphur + water

Yellow sulphur crystals on celestine from Agrigento, Agrigento Province, Sicily, Italy. Size: 99 mm x 56 mm x 52 mm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.



Almost colourless crystals of rosickýite on matrix. From an unspecified offshore drill hole, Ventura County, California, USA. Field of view: 1 mm.
Henk Smeets, tomeikminerals.com – CC-BY-SA-4.0.

Sulphur may also be found in sedimentary deposits associated with evaporites, salt domes, and petrochemical bearing rocks where it is often formed by the bio-reduction of sulphate minerals.

Southern Echo NOV 1973

The day the earth caught fire—and Mr Cole spotted it

IT may be chilly in city offices, but down in rural Dorset things are pretty hot.

At Clavell's Hard near the seaside village of Kimmeridge, smoke is rising through cracks in the cliffs, the ground is hot, and evil-smelling gases have killed off the grass.

Deep inside, the ground is actually on fire.

Phenomenon

The phenomenon was discovered by Douglas Cole, a 21-year-old geological research student, who was walking in the area.

Mr Cole, who lives in Church Lane, Southampton, said: 'There is a 2ft. 6in. layer of oil shale underneath the rock surface which has caught fire.

'This is an extremely rare occurrence — the last case noted in geological records was in 1826.

'There is a large area of dead grass on the cliff. Immediately under the loose stone the ground is red hot. If you thrust a stick into it, it would burn. I measured temperatures of just over 500deg. C.

'Once combustion like this starts nothing will stop it until the fuel is exhausted.'

By ANN KENT

Major John Mansel, of Smedmore House, Corfe Castle, who owns the burning cliff, said: 'There is a footpath running nearby and the cliffs are a popular beauty spot in the summer.'

Spontaneous

Mr Reginald Leonard, engineer for Wareham rural council, which covers the area, said: 'We often hear of spontaneous combustion in rubbish tips but this is the first I have heard of it happening in oil shale.'

Report of the burning cliff in the Southern Evening Echo, Nov. 1973.

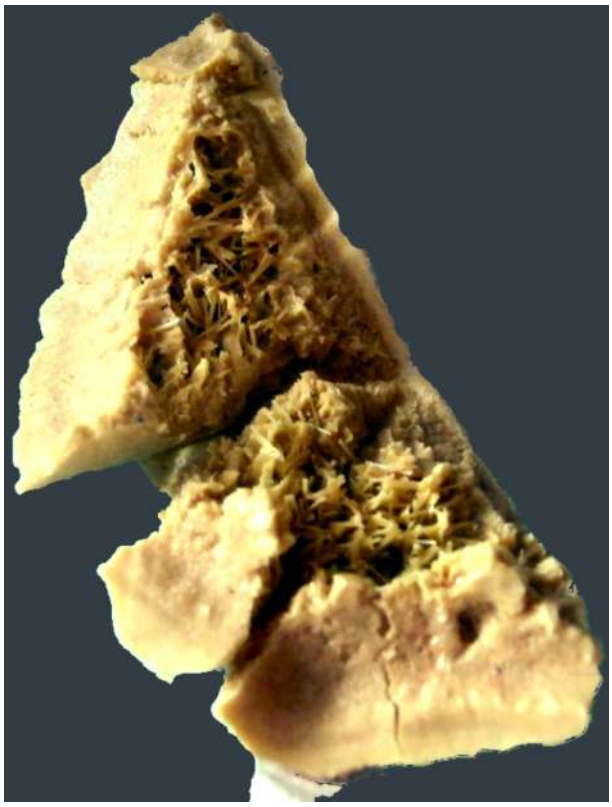
A search for native sulphur occurrences in the UK on Mindat reveals some 78 recorded locations for native sulphur in all three mainland countries though again many are small specimens and most are formed by reduction from sulphide or sulphate minerals.

One of the most unusual of the UK occurrences was in 1973 where natural burning of the oil shale in the cliffs at Clavell's Hard, Kimmeridge, Dorset caused sulphur to be

The burning cliff at Clavell's Hard 1973.
The late J. W. Thomas photograph.

3 Sublimation is the transition of a substance directly from a solid to the gaseous state, without passing through any intermediate liquid state. The products of sublimation are sublimates.

sublimed from fumaroles on the cliff top. Members of Southampton Mineral and Fossil Society visited the site and obtained some wonderful specimens by collecting the sublimate on layers of newspaper spread over the fumaroles.



Native sulphur, collected as sublimate on newspaper, from a fumarole on the cliff edge at Clavell's Hard, Kimmeridge in 1973. Remnants of the newspaper can be seen around the edges of the specimen. Length ≈ 12 cm.
The late J. W. Thomas specimen and photograph.

The majority of native sulphur found in the UK is found associated with sulphide minerals, notably pyrite and galena, where it has formed as a result of the oxidation of the sulphides. For example the decomposition of pyrite (FeS_2) and subsequent reaction with galena (PbS). The basic reactions are thus:

2. $4FeS_2 + 15O_2 + 10H_2O = 4FeO(OH) + 8H_2SO_4$

iron sulphide (pyrite) + oxygen + water = iron(III) oxide-hydroxide (goethite) + sulphuric acid

This reaction is what gives rise to the highly oxidised and weathered gossan (or iron-hat) of iron oxides that caps many ore deposits. The liberated sulphuric acid can react with other sulphides to form their sulphates thus:

3. $PbS + H_2SO_4 = PbSO_4 + H_2S$

lead sulphide (galena) + sulphuric acid = lead sulphate (anglesite) + hydrogen sulphide

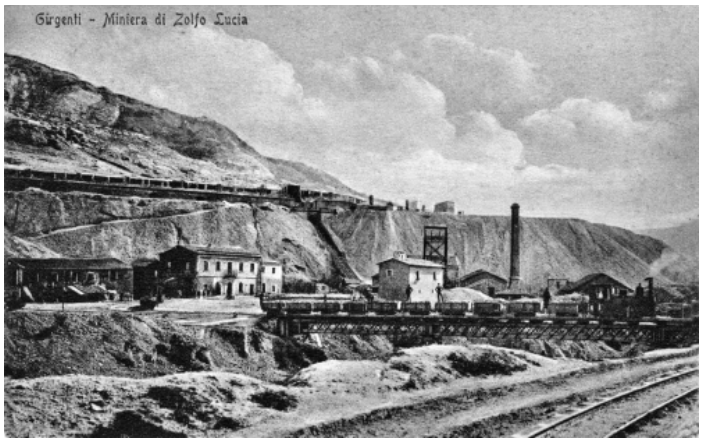
The liberated hydrogen sulphide gas can then undergo further reaction with atmospheric oxygen, possibly by biological processes, to liberate the native sulphur thus:

4. $2H_2S + O_2 = 2S + 2H_2O$

hydrogen sulphide + oxygen = sulphur + water.

This overall reaction (4) is the basis of the Claus Process which is important in the desulphurising process recovering elemental sulphur from waste gases containing hydrogen sulphide. It was patented in 1883 by the chemist Carl Friedrich Claus (1827 – 1900) and it is still the most important desulphurisation process used in the petrochemicals industry. For more details see: https://en.wikipedia.org/wiki/Claus_process.

Given that no spectacular sulphur specimens are to be found in the UK from where are the best specimens obtained? For many years some of the very best sulphur specimens came from Sicily, Italy. The island, in the Mediterranean, off the toe of Italy is the largest and most populous island in the Mediterranean, the home to Mount Etna, the largest active volcano in Europe and one of the most



The 'Lucia Sulpharus' or Lucia sulphur mine, Girgenti (Agrigento), c 1930.

active volcanoes in the world. It is this vulcanism that gave rise to huge economic deposits of sulphur and some magnificent specimens.

The principle sulphur mining area on Sicily from where the most sulphur was obtained was between the provinces of Caltanissetta, Enna and Agrigento. Geologically this area is given the name '*plató gessoso-solfifero*' (chalky-sulphur plateau) and had been mined for sulphur since around 200 BCE. Mining finally started to decline in the 1970s and no longer continues today. (https://en.wikipedia.org/wiki/Sulfur_mining_in_Sicily).

There are many specimens of sulphur and other minerals for sale, or in collections, that are just provenanced as 'Agrigento' (previously Girgenti) which encompasses the whole province and not the local municipal locality thus the specimens could have originated from one of very many mines over a very large area.

Celestine and sulphur from Agrigento, Agrigento Province, Sicily, Italy.
Size: 15 cm x 13 cm x 10 cm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Aragonite and sulphur from Agrigento, Agrigento Province, Sicily, Italy.
Size: 17.8 cm x 13.7 cm x 6.0 cm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Many Sicilian specimens are characterised by being on a white, crystalline matrix of aragonite (calcium carbonate, $CaCO_3$) celestine (strontium sulphate, $SrSO_4$) or sometimes gypsum (calcium sulphate, $CaSO_4 \cdot 2H_2O$) which makes for some very attractive specimens.

Some of the larger Sicilian native sulphur crystals may contain, or have minor surface coatings of the natural hydrocarbon bitumen that derives from bitumen-impregnated limestones present on the island. The bitumen can also be found on the matrix on some specimens. This property can be a diagnostic feature for native sulphurs that are from Sicily but the actual location cannot be ascertained.

Modified sulphur crystal with bitumen inclusions from Cozzodisi Mine, Casteltermini, Agrigento Province, Sicily, Italy.
Size : 8.0 cm x 6.5 cm x 5.8 cm.
Didier Descouens image, CCA-SA-4.0.

Organic inclusions and other impurities can modify the colour of sulphur crystals from the usual bright yellow to brownish or orange in the presence of bituminous inclusions or even greenish-yellow when some of the sulphur is replaced by trace amounts of elemental selenium.

As well as Italy there are other notable locations for good native sulphur specimens. These are Bolivia, Mexico, Poland, Russia, Spain, Ukraine and USA.

There is a very good 'Best of Sulphur' article on Mindat.org that shows the range of habits, forms and colours of the sulphurs from various locations. Take a look at the page at: https://www.mindat.org/a/best_sulphur.

Gypsum and sulphur from Cianciana, Agrigento Province, Sicily, Italy.
Size :32 cm x 18 cm x 10 cm.
Didier Descouens image, CCA-SA-4.0.

Native sulphur is a very easy mineral to identify from its various physical properties that can accessed online or from mineralogy books. There are many online references that claim sulphur has a 'rotten eggs' smell. This is totally incorrect as the small attributed to 'rotten eggs' is hydrogen sulphide, H_2S, the product of the reaction of sulphur with hydrogen. There is no available hydrogen in air for the reaction and the smell is actually the acrid odour of sulphur dioxide, SO_2, which is the gas liberated when sulphur combines with oxygen (burns) in the air. Very small crystals of sulphur can be readily identified by touching them with a very hot steel pin and noting the odour of sulphur dioxide liberated which is very similar to that of a burning match. Matches contain sulphur.

Native sulphur and the various allotropes can be rather unstable and are very prone to damage from small variations in temperature so, if you do collect native sulphur specimens keep them safely stored in a stable environment away from direct sunlight and thermal or humidity extremes.

Good quality, aesthetic specimens of native sulphur are highly sort after by collectors and thus command very high prices. This of course leads to widespread fakes being made. It is very easy to manufacture large sulphur crystals by growing them from solutions in solvents or by sublimation of massive, commercial lump sulphur. We will cover this later.

The Other Native Elements

Following on from the previous four relatively common native elements, the other remaining native elements are comparatively rare, especially in the United Kingdom.

Carbon in the form of graphite is found in the UK but there is only one main location in Cumbria at the Seathwaite Graphite Mines which are now a scheduled ancient monument under the Ancient Monuments and Archaeological Areas Act 1979 as amended, as it is considered by the Secretary of State to be of national importance, so any collecting is not allowed without permission. There is only one recorded occurrence of diamond in the UK and that is from Craigman 'Waud' [wad = graphite] Mine, New Cumnock, East Ayrshire, Scotland. This was reported to have occurred in graphite that had been formed by the contact of coal with intruded basalts (Smith, 1896). Smith records: "*In the Craigman Mine, the graphite close on the trap*[4] *contains minute particles which scratch rock-crystal, so that these particles are doubtless SMALL DIAMONDS, and this is the first time, so far as I know, that diamonds have been chronicled as having been found in the British Isles!*" Anecdotal diamonds have been reported that were found in the ash arising from peat used by crofters for fuel in the Caldbeck Fells, Cumbria these may have arisen from glacial deposits from the Baltic Shield during the ice age.

Native iron from Disko Island, Greenland.
Size: 49 mm x 29 mm x 15 mm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Native iron, also called telluric iron, is iron that originated on Earth, and is found in a metallic form rather than as an ore. Because iron is easily oxidised telluric iron is extremely rare, with only one known major deposit in the world located in Greenland. There is no recorded occurrence of telluric iron in the

4 The term trap has been used in geology since 1785 for basaltic rock formations. It is derived from the Swedish word for stairs (*trapp*) as an allusion to the step-like hills of volcanic landscapes.

UK and the only five records of iron are in meteorites. There were very early reports of native iron from Beinn Bhreac, Scotland, in granite with magnetite, and from County Antrim, Northern Ireland but these have now been discredited as probable misidentification (Tindle, 2008).

While iron is a native mineral, most is not really 'native' in the true sense as it probably originated from iron-nickel meteorites and will be alloys of iron and nickel. There are three recognised iron-nickel minerals, taenite, (Ni,Fe), awaruite, Ni_3Fe, and tetrataenite, FeNi. The nickel/iron ratio in taenite is variable.

True terrestrial native iron, Fe, is extremely rare, because it readily corrodes to the oxides (rust), but it does occur. The type locality, and most notable location for native iron, is Disko Island, Greenland where in 1870 the geologist, mineralogist and Arctic explorer Nils Adolf Erik Nordenskiöld (1832 – 1901) found boulders of iron along the shore of Uivfaq on the west coast of Disko Island, Western Greenland. The largest boulder found was a 22,700 kg mixture of native iron and the iron carbide cohenite, $(Fe,Ni,Co)_3C$ that was delivered to the Naturhistoriska Riksmuseet (National Museum of Natural History), Stockholm, Sweden. Other museums have very large specimens in their collections including the Statens Naturhistoriske Museum (National Museum for Natural History), Copenhagen, Denmark. The Disko Island iron has been determined as telluric and not being of meteoric origin (Bird and Weathers, 1977).

Part of the 6.6 ton block of Disko Island telluric iron that stands outside the Statens Naturhistoriske Museum in Copenhagen, Denmark.

There are other reported minor deposits of native iron around the world but many of these have been lost or worked out.

One location of telluric iron-nickel is Awarua Bay, South Island, New Zealand. This is the type locality for the mineral awaruite, Ni_3Fe, a naturally occurring alloy of nickel and iron. Another source of awaruite occurs in river placer deposits derived from serpentinised peridotites and ophiolites. It was first described in 1885 for an occurrence along the Gorge River near the locality it is named after.

Awaruite ('josephinite') from Josephine Creek, Josephine Co., Oregon, USA. Size: 22 mm x 12 mm x 9 mm. Mass: 13 g.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Another occurrence of a similar iron-nickel mineral was first reported in 1892 by W. H. Melville, (Melville, 1892) and the name "*josephinite is given in honor of the county, its locality, in accordance with the custom in use for naming analogous substances.*" This is after Josephine County, Oregon, USA where it is found as placer nuggets in stream channels and masses in serpentinised portions of the Josephine peridotite, these pieces are highly magnetic and could be recovered from the river bed with a magnet. The largest example reported was a 50 kg mass (Jamieson, 1905 and Palache *et al.*, 1944). The name josephinite has been discredited and it is now just classed as a synonym of awaruite although some authorities claim that its structure is substantially different to that of awaruite and thus it should be classed as a mineral in its own right (Bird and Weathers, 1975).

Josephinite, along with the iron-nickel arsenide oregonite, Ni_2FeAs_2, were designated the official twin minerals of Oregon in 2013 to promote education through the earth sciences, encouraging curiosity and study. Oregonite and josephinite are found only in Oregon in the United States.

Globules of shiny native mercury on matrix from Mayacamas Mountains, California, USA. Size: 3.8 cm x 2.4 cm x 2.1 cm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

The final native element to mention here is mercury. Native mercury occurs in deposits throughout the world mostly associated with the mercuric sulphide, cinnabar, HgS where it is liberated by the reaction of the sulphide with oxygen:

5: $HgS + O_2 = Hg + SO_2$

mercury(II) sulphide + oxygen = mercury (metal) + sulphur dioxide.

Mercury is a volatile toxic element. Metallic mercury is is not easily absorbed via ingestion or skin contact but breathing in mercury vapour is hazardous.

When inhaled mercury vapour is absorbed via the respiratory tract, enters the circulatory system and is distributed throughout the body. The UK long-term (8 hours) workplace exposure limit (EH40/2005) is 0.02 mg m^{-3} but it has been shown that chronic exposure by inhalation at very low concentrations in the range 0.7 – 42 µg m^{-3} can cause adverse effects (*British Journal of Industrial Medicine*. **49** (11): 782–90). Mercury is a cumulative poison and is not readily excreted from the body.

In light of toxicity of mercury it is not recommended that collectors keep specimens that contain native mercury in any quantity. If you do have small samples they should be sealed in airtight containers, properly stored in stable room temperatures and labelled as hazardous. Handling should be kept to minimum as the mercury globules are easily detached from specimens and can be spread into the environment. Common sense must be used. Although the amount of free mercury on a small specimen is quite low it is wise to take the best possible precautions, as you should with any potentially harmful specimens.

Native bismuth on quartz from St Ives Consols, St Ives, Cornwall, England. Size: 36 mm x 28 mm x 26 mm.
Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.

Native bismuth and arsenic are found throughout the United Kingdom, most notably from Cornwall. There are good specimens that sometimes turn up on mineral auction sites and dealers websites. Small specimens can still be found on old mine dumps but many of these sites now have very limited or no accessibility without written permission from the regulators and land owners. Identification of these two native elements is not easy as they are usually mixed in with other minerals such as sulphides and sulphosalts.

Arsenic and its compounds are toxic. Elemental arsenic is relatively safe but it does form toxic arsenic trioxide on its surface that can be transferred by handling. Dermal absorption is considered low and the principle route into the body is by ingestion so meticulous hygiene is required and use disposable gloves when handling specimens. Again keep small specimens securely enclosed in containers and well labelled. Store them in a locked display cabinet. There is some further information on the safe storage of mineral specimens available take a look at the Institute of Conservation web page on Geological Collections: https://www.icon.org.uk/conservation-hub/caring-for-your-collections/geological-collections.html.

Native Element Fakes and Fraud

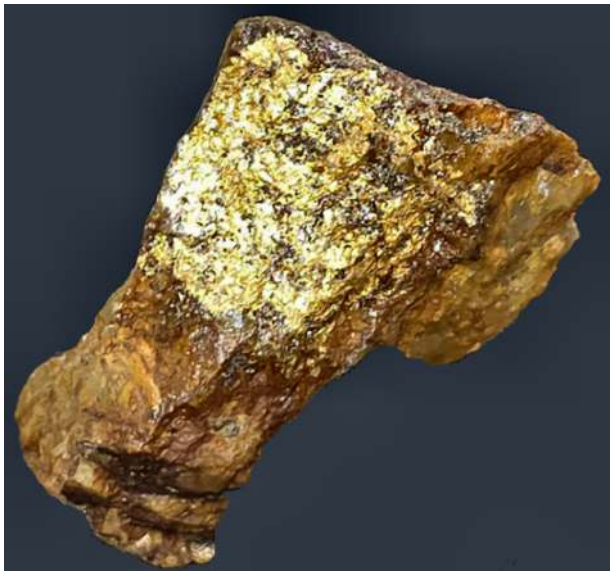
Good specimens of native elements are highly prized and sought after by the mineral collecting community. As they include precious metals and diamonds they can also be very expensive especially from rare locations. Native element specimens are also very easy to fake and be fraudulently provenanced. Below are examples of fakes and fraud that you should be aware of and if you are considering purchasing native element specimens please do so from reputable sources and research the items before parting with your hard earned cash. The photographs shown here have mostly been taken from sellers sites online. "*Caveat emptor.*"[5]

Real native gold nuggets or man-made? Impossible to tell from a photograph.

One of the commonest fraudulently sold native minerals is gold. Gold 'nuggets' can easily be manufactured from scrap, low value gold jewellery by melting it and pouring the melt into a bucket of water to produce random shaped solid pieces sometimes called 'cornflake gold'. This process of 'water casting' can be used for other low melting point metals and their alloys.

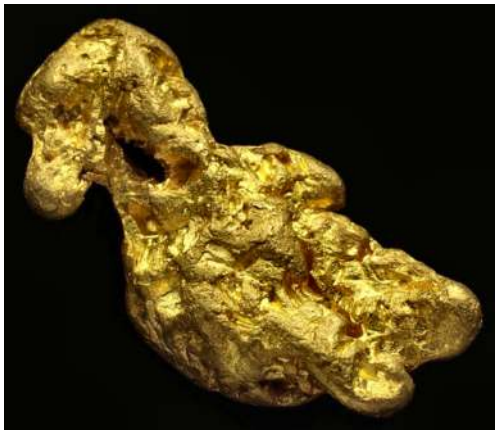
From the products of water casting small pieces are selected that resemble naturally occurring nuggets and they are sold for grossly inflated prices on dubious online sites. They are usually provenanced from rare locations, such as Wales, and the sellers may even provide you with a 'Certificate of Authenticity', (CoA) which is meaningless. Do not be fooled. Do your research on the site and the gold occurrences. There are instances of tumbled natural copper nuggets being electroplated with gold and passed off as real gold nuggets. See: https://www.goldfeverprospecting.com/fagonu.html

Another common method of faking native gold specimens is the attaching of gold leaf to the surface of a piece of rock. The give away is that the thin layer of gold is just on the surface and not disseminated throughout the matrix. It may be loose and can be removed easily with a gentle rub.



'A naturally occurring 24 g gold-bearing specimen from Valdez, Alaska, featuring dense native gold dispersed across an iron-oxidised host matrix' priced at £401.25 or is it just gold leaf stuck on a lump of ferruginous quartz?

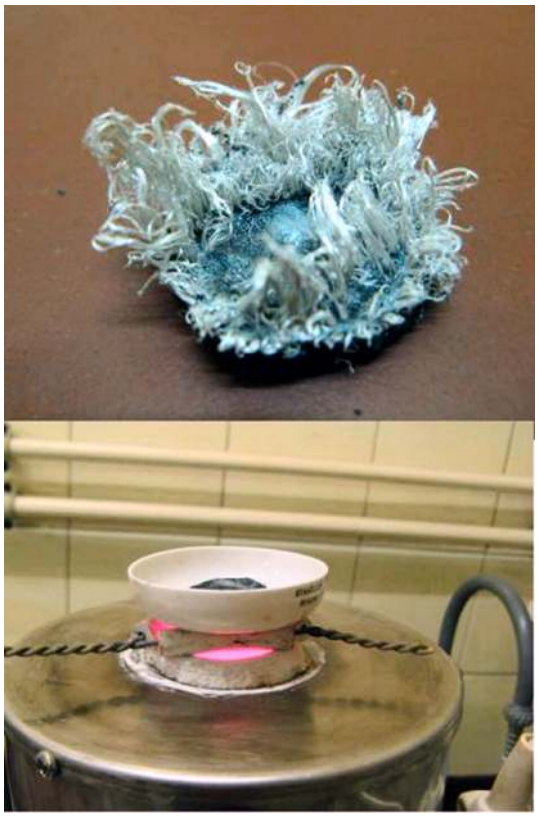
Another way fake gold nuggets are manufactured is by painting small pieces of rock or water cast base metal (e.g. lead) with a gold coloured paint. These are obvious fakes and simple to detect. The paint is easily removed with a solvent (acetone nail polish remover). Other rare examples for the creation of 'dendritic gold specimens' is by electrodeposition or by vapour deposition of gold. These are more specialist processes but the results are very convincing and can fool experienced collectors. You can grow your own metal crystals, see: https://sciencenotes.org/how-to-grow-metal-crystals.



A real gold nugget or gold painted base metal nugget? See: https://www.facebook.com/people/Fake-Gold-Nuggets/100070110570542

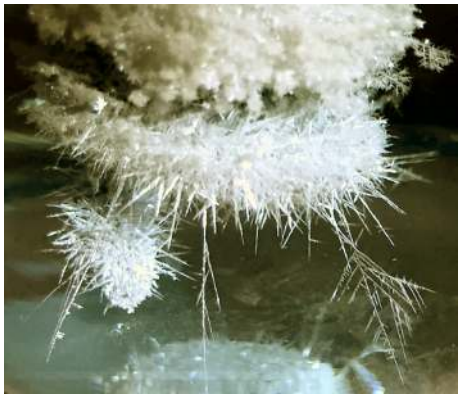
5 "Let a purchaser beware."

Native silver specimens are very easily forged from commercial silver, by water casting scrap silver, electrolysis and electrochemical reactions. The most desirable native silver specimens are the aesthetic wiry forms like those from Kongsburg and they can command a high price. Thus they are highly faked to the obtain the best return for little outlay.



Wiry silver grown from acanthite by heating.

Some very convincing wiry silver can be manufactured from the silver sulphide acanthite, Ag_2S, simply by heating it strongly in air in a crucible. The issue with these is that they are very bright silver and not naturally tarnished.

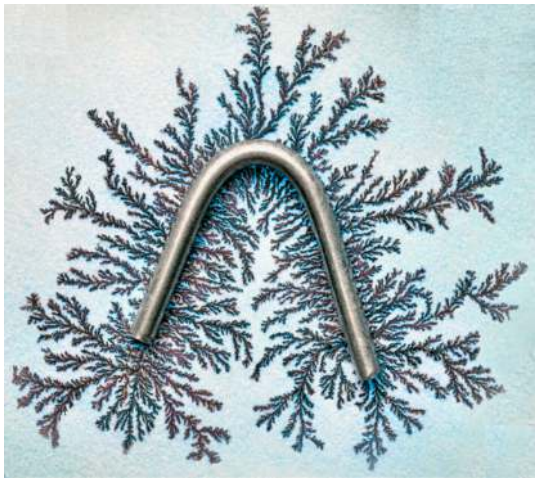


Silver crystals growing on a copper wire.

Silver crystals can be grown by a simple displacement reaction using a piece of copper wire immersed in a solution of silver nitrate, a chemical reaction takes place, causing crystals of silver metal to grow on the copper wire. These are very beautiful but very fragile. Electrolysis (passing a current through the silver solution) will promote growth of larger crystals. Electrolytic processes can be used to manufacture the arborescent or dendritic forms of silver but again they are very shiny and have none of the natural sulphide tarnish, associated minerals or attached matrix usually found with native silvers. Some natural specimens may have been cleaned by immersion in a cyanide solution to remove the black surface coating and reveal the underlying forms. This should ideally be declared by the seller and recorded on the label.

Frame from an online sale video showing a very bright, dendritic silver sample. Notice the large blob of adhesive used to join pieces together. Is it natural or man-made?

Copper is another native element that is routinely faked and passed off as natural. Copper is widely used in the metal-finishing industry and during the electroplating process dendritic copper forms can be created at sharp points where the current density is higher. These copper dendrites are very attractive and are sometimes sold as objects of interest but others are passed off unscrupulously as natural, native copper specimens (with extra magical healing powers!).



Beautiful dendritic copper growing from zinc wire placed on a filter paper soaked with copper sulphate solution. MEL Science.

Natural copper nuggets are very common on some online sale sites. Some of them may be provenanced as coming from Michigan but they can be

readily made from melting scrap copper and water casting. Some are sold as 'tumble polished' where they lose all surface features and develop a bright shiny finish. These may have been native copper nuggets but all scientific value has been destroyed. Many of the Keweenaw copper specimens are acid cleaned to remove all traces of matrix and any surface oxidation. They are not natural.

5 cm high copper dendrite formed by electrolysis of a copper solution.

A rather dubious 'natural healing copper crystal'. Man-made but nice

Sometimes a well cleaned specimen is acceptable if it enhances the appearance and reveals the hidden fine detail of the natural crystal structure. The choice is yours but make sure that the seller gives you all the facts on the origin and treatment of the specimen. This should be recorded on your label and in the catalogue record.

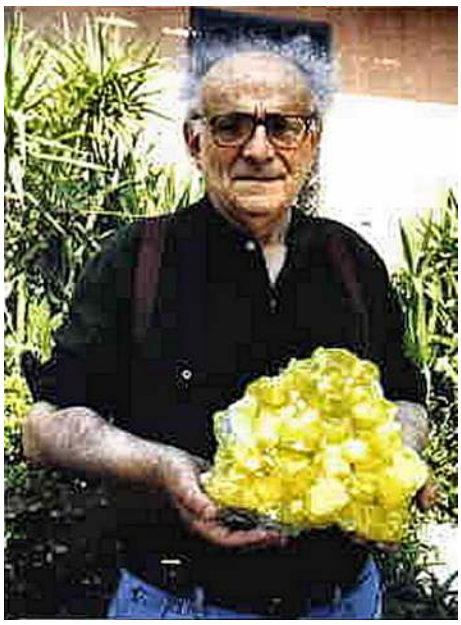
Finally one of the most easily faked and possibly least detectable forgeries are those of sulphur. Commercial sulphur is soluble in the inorganic liquid carbon disulphide, CS_2, a flammable, toxic compound with an unpleasant odour of that is described as being of rotting radishes. Carbon disulphide is capable of dissolving up to 22 g of sulphur per 100 g and when the solution is allowed to evaporate slowly, under controlled conditions it will yield perfect rhombohedral sulphur (S_8) crystals.

A copper dendrite glued to a quartz crystal. An obvious fake.

At the Turin Mineral Show in 2000 natural history enthusiast, chemist and entrepreneur, Dr Sergio Martinat, exhibited a showcase full of his artificial sulphur crystals alongside samples of natural specimens. In 2002 mineralogist Renato Pagano (1938 – 2023) reported an occurrence of laboratory grown sulphur crystals on a white Sicilian matrix being sold as natural specimens. Some of the specimens were very fine and indistinguishable from good natural specimens and they had been manufactured by Dr Martinat. Grown onto authentic aragonite, celestine and gypsum matrix material from solutions of sulphur dissolved in carbon disulphide these fakes fooled many dealers and institutions.

An example of Martinat's artificial sulphur grown on a white Sicilian matrix.

It was only when Pagano and others carried out close examination of the specimens and isotopic analysis of the sulphur that the fakes were exposed. The sulphurs did not show any of the normally expected inclusions for Sicilian specimens, especially the bitumen, and there was also detectable residues of the carbon disulphide solvent present in the specimens.



Dr Martinat with one of his artificial sulphur specimens. Giorgio Comollo photo.

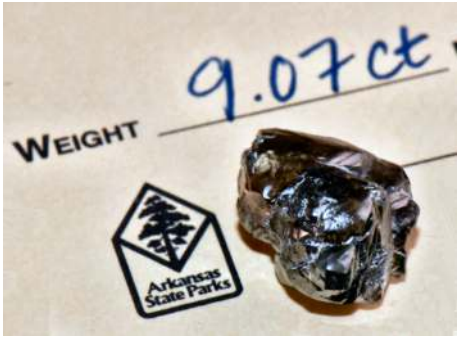
An obviously fake 'Large native sulphur on matrix from Sicily with amethyst crystal.' being sold online.

It is still happening today and there are dealers online peddling ridiculous combinations of sulphur crystals. If you have any doubt about the authenticity of a specimen leave it alone. Do your homework about the specimens from the location and sniff it to see if it it smells of rotting radishes.

To see some excellent photographs of both natural and man-made crystalline forms of the elements take a look at the Flickr page Paul's Lab at: https://www.flickr.com/photos/paulslab/albums.

The last scam that has been perpetrated on native element, and other mineral specimens, is the misrepresentation of provenance. This is where lower value specimens from a relatively common occurrence are passed off as coming from another, much rarer location with the subsequent increase in value. Only elemental and isotope analysis can possibly attribute a specimen to an actual location. It is very difficult to tell by visual examination where a single gold specimen originated from.

One of the most notorious of these provenance scams involved diamonds supposedly found at Crater of Diamonds (CoD) State Park in Murfreesboro, Arkansas, USA. This State Park allows the public to prospect for alluvial diamonds and keep their finds. The park offers free authentication at the Diamond Discovery Centre where the diamonds are weighed and certified free of charge for the finder. These diamonds attract premium prices because of their provenance and rarity. Can you spot the potential for a scam?



A nine carat brown diamond discovered in the park in 2020.

A 3.69 carat white diamond found at the State Park of unknown worth (park officials do not appraise them) but a genuine 3.85 carat diamond found at the park the previous year sold for $20,000.

In 2007 American Eric Blake with three assistants 'found' over 16.5 carats[6] of diamonds at the State Park, including one 3.92 carat stone. All were certified by the park. These diamonds were sold at very high prices online. This apparent remarkable good luck and quantity of diamonds being found raised some suspicions and Blake was investigated. Initially it was shown that out of all of his recorded finds 60% of them were brown! Usually only around 20% of the finds at the CoD are brown in colour. Further investigation later uncovered invoices for numerous natural loose diamonds used in the fraud. Photographs of the diamonds supplied by the seller were matched to diamonds fraudulently sold by Blake. Blake had been been buying loose diamonds, at relatively low prices, from the commercial Panna Diamond Mine in Madhya Pradesh, India for around $100 per carat, taking them to the CoD, pretending to have found them there to get them certified and then selling them as CoD diamonds for around $2000 per carat. A very healthy profit. Blake was convicted of fraud. The Smithsonian Magazine has an article by Brendan Borrell, from January 2009, that gives more details: https://www.smithsonianmag.com/history/the-curious-case-of-the-arkansas-diamonds-43575867

6 When used for gemstones carat is a unit of mass. 1 carat = 200 mg (0.2 g) so 16.5 carats = 3.3 g.

Described online as: 'Natural Rainbow Bismuth Ore Metal Crystal.'

The final warning should be an obvious one. Many online sites, gift shops and stores sell man-made, highly iridescent and very attractive bismuth crystals. These have been discussed in a previous issue. Some sites sell them as naturally occurring or 'bismuth ore' specimens. They are man-made on an industrial scale and many tons must be sold all over the world. I have a nice example in my collection of interesting objects as it exhibits the wonderful hopper crystal structure to good effect. It is not included in my mineral collection and is labelled as man-made.

Be alert to fraud. Remain sceptical, do your homework and identify reputable sources before parting with your money. If in any doubt or if it looks to good a bargain walk away. Native element collecting is a very rewarding aspect of the hobby that has some spectacular specimens and the challenge is to find genuine good examples.

Acknowledgments

Many of the mineral specimen images presented in the above two articles are made freely available for use by Robert M. Lavinsky who has donated his entire collection of photographs that are on mindat.org and all of the pictures from his own Arkenstone Fine Minerals business web pages https://www.irocks.com for use on Wikimedia Commons with Creative Commons (CC) licenses that make it possible for everyone around the world to share them legally and freely. They are an invaluable resource for authors and all persons interested in minerals.

I must also thank Mr Barry Pitt (Russell Society and Southampton Mineral & Fossil Society member) for allowing use of his Cornish copper specimen images from Mindat.

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Welcome Stranger – the world's largest gold nugget

On Friday 5th February 1869 two Cornish miners, John Deason and Richard Oates, found the huge nugget which was named 'Welcome Stranger' when they were prospecting around Moliagul in the gold fields of Victoria, Australia. The nugget was found buried just below the surface near the base of a tree on a slope leading to what was then known as Bulldog Gully, the nugget had a gross weight of 109.6 kg (3,523 troy oz). As there were no suitable scales available for weighing such a large nugget it was broken into three pieces for weighing The final weight after cleaning and removal of any attached matrix was 72.02 kg (2,315.5 troy oz).

'Welcome Stranger' gold nugget (1869) replica. Source: Museums Victoria [M 20314].CC BY (Licensed as Attribution 4.0 International) Photographer Rodney Start.

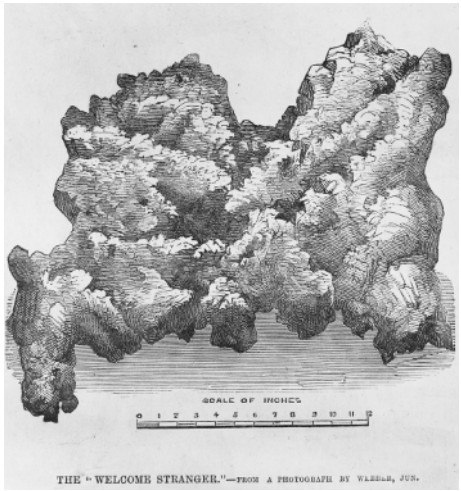
Deason and Oates were paid an estimated £9,381 for their nugget, At August 2026 gold prices, 72 kg would be worth approximately £7.5 million.

In 2019 the descendants of the two discoverers gathered to celebrate the 150th anniversary of the discovery with re-enactments of the finding of the nugget. There is a statue in the former mining town of Redruth in Cornwall that commemorates the two Cornish men Deason and Oates and their lucky find.

Statue in the car park of Cornwall Gold, New Portreath Road, Redruth, Cornwall that commemorates the discovery by John Deason and Richard Oats.

See also: BBC News – Welcome Stranger: World's largest gold nugget remembered:

https://www.bbc.co.uk/news/uk-england-cornwall-47041314. [Accessed July 2026]



A wood engraving print made from the only known photograph of the complete nugget before breaking. State Library Victoria.

Radioactive Minerals Part 2 – The Minerals, Their Properties and Their Occurrence

Alan Barnes

Thorium and Uranium Minerals

In Part 1 of this three-part series of papers on radioactive minerals, the discovery of radioactivity, radioactive elements and their chemistry was discussed along with a guide to the geological formations in which radioactive minerals can be found, how to set about collecting them and the hazards associated with the handling and storage of these minerals. In this second paper, a broad overview of some of the more commonly encountered and some of the chemically more interesting or unusual secondary uranium and thorium minerals. In this paper, the oxides, carbonates, phosphate and arsenates and finally the silicate minerals are described, whilst in Part 3 the sulphates, arsenites, selenites, tellurites, tellurates, molybdates, tungstates and vanadates will be described along with some of the very rare uranium secondary minerals such as oxalates. Obviously, it is not possible to describe every radioactive mineral because there are far too many, so the objective of this and the subsequent paper is to give a broad overview of the many interesting and highly collectible radioactive secondary minerals that exist along with some photographs and descriptions of the minerals that will help you to identify any unknown minerals that you may have (or wish to have!). Some of the minerals shown here are exceptionally rare and hence, regrettably, almost impossible to obtain, but some of these are shown to highlight the sometimes unusual chemistries that uranium – and even thorium – minerals can possess. A glossary of some of the more technical and descriptive terms used in this article is given at the end.

Thorium Minerals

Although thorium is 2 – 3 times more abundant in the earth's crust than uranium (Refs 1 – 3), currently there are only 39 thorium minerals that have been approved by the IMA, although there are a further 9 minerals that pass the criteria for being new minerals, but which have not yet been formally named. Yet another 23 thorium containing minerals are still in the earlier stages of the process to determine whether these are new minerals or not, but which have varying degrees of chemical differences from similar, already approved minerals. The remainder are thorium containing varieties of other minerals in which thorium is only a minor constituent. To be approved as a new mineral, the potential new mineral has to meet specific criteria and has to have a chemical composition that is different from any other mineral.

The chemistry of thorium minerals is limited to that in which the thorium is present as the tetravalent Th^{4+} ion and in nature it occurs with other tetravalent metal ions such as uranium (U^{4+}), zirconium (Zr^{4+}), hafnium (Hf^{4+}) and cerium (Ce^{4+}). However, it also occurs with some trivalent elements such as scandium (Sc^{3+}), yttrium (Y^{3+}) and the trivalent lanthanide elements (Ce^{3+} – Lu^{3+}). The reason why thorium can do this is because it has a similar ionic radius of 94 picometre (pm, 10^{-12} m, or one trillionth (1/1000000000000) of a metre) to these elements. Zirconium, for example, has an ionic radius of 80 pm whilst that of hafnium is 83 pm, scandium is 74.5 pm, yttrium is 90 pm and cerium is 103 pm.

Thorium minerals, like those of many of the other elements, cannot be further oxidised and so Th^{4+} is the only stable oxidation state of thorium. Whilst tetravalent uranium can lose up to two further electrons by oxidation to give hexavalent uranium, thorium cannot be further oxidised because it has no more electrons that it can readily lose.

The most commonly encountered thorium minerals are thorianite, thorite and monazite, the latter of which is a thorium phosphate which forms a solid solution with cerium(III) phosphate, $CePO_4$, and all of the other rare earth element phosphates.

Thorite ($ThSiO_4$) was discovered and named in 1829 by Jöns Jakob Berzelius as it was the mineral in which he found the new element thorium (Ref. 4). It nearly always contains significant amounts of

uranium and analysis shows that the chemical formula of thorite should be written as $(Th,U)SiO_4$ to reflect the considerable uranium content which can be up to 25% of the thorium content. Some thorite specimens can also have up to about 13% of the silicate anions replaced by phosphate anions. Thorite frequently occurs associated with other thorium containing minerals such as zircon, uraninite, gadolinite, fergusonite, yttrialite, pyrochlore and, of course, monazite. When nicely crystallised, thorite it crystallises in the tetragonal system as square prismatic crystals (Figure 1) that can reach up to 8cm in size and which are isomorphous with zircon and hafnon, but it can also occur massive and compact. It has a distinct cleavage, a conchoidal fracture, a brittle tenacity, a hardness of 4.5 – 5 on the Mohs scale and a density of 6.63 – 7.20 g cm^{-3}. The streak can be pale green, pale orange, or dark brown and the lustre ranges from being vitreous when fresh to resinous or greasy. There are seven varieties of thorite, one of which is 'ferrithorite' which has the slightly different composition of $(Th,Fe^{3+})[Si(O,OH)_4]$; crystals of 'ferrithorite' are orange and can reach up to 50cm in size such as the ones found at the Aq-tuyz REE deposit, Aq-tyuz ore field, Talas region, Kyrgyzstan (Refs 5 & 6).

Figure 1. Thorite crystal measuring 19 mm x 7 mm x 7 mm from Mogok Township, Pyin-Oo-Lwin District, Mandalay region, Myanmar.
Pavel Kartashov photo edited by author. Use of photograph and editing both permitted by Pavel Kartashov.

Thorite crystals, like all thorium minerals, are frequently metamict because the strong α radiation emitted by thorium damages the surrounding crystal lattice. This is because when thorium decays by α-decay, the radiation travels though the crystal lattice not only causing ionisation, but also causing atoms within the crystal lattice to move giving rise to crystal defects which damage the crystal structure. To the naked eye, metamict minerals appear to be crystals, but their physical properties are more like those of glasses (which are amorphous). It is because of this that they are usually glassy and are brittle with a fracture like that of glass. Thorite shows a range of colours and whilst black or brownish black are by far the most common, it can also be yellow, brownish yellow, reddish brown, green or orange. The orange and green colours of thorite are both due to the presence of uranium.

Thorianite, ThO_2

Thorianite is the only other primary thorium mineral and is a common accessory mineral that always forms a solid solution with uraninite. It was identified as a new species by Wyndham R. Dunstan in 1904 (Ref. 7). It occurs either as small, rounded grains and as cubic, or slightly elongated cubic crystals that often have slightly rounded, or rough, edges. The crystal faces also tend to be somewhat rough. Twinning is common on the {111} crystal face, although interpenetrant twins are also relatively common (Figure 2). Crystals can reach up to 9cm in size and are usually black or brownish black, but can also be dark grey or dark reddish brown. It has a poor cleavage on the {001} crystal face and an uneven to sub-conchoidal fracture. The mineral is brittle with a hardness of 6.5 to 7 when unaltered with a relatively high specific gravity of 9.9. It shows a poor cleavage on the {001} crystal face and has a sub-metallic lustre when fresh, but on weathering changes to being resinous. It is always opaque, except in thin sections where it appears transparent and dark brown in colour. A streak test gives a grey to greenish grey streak. It occurs as an accessory mineral in granite pegmatites and less so in carbonatites or serpentinites, but is commonly found as a detrital

Figure 2. Interpenetrant twinned crystals of thorianite, the larger of the two crystals is elongated and measures 11 mm x 7 mm x 7 mm. The specimen is from the Andranondambo Phlogopite deposit, Maromby, Amboasary Sud district, Anosy, Madagascar.
Alan Barnes specimen and photograph.

mineral in detrital heavy mineral concentrates, such as those occurring in stream gravels in Galle district and Balangoda district of Sri Lanka. Large crystals of thorianite occur at Taolanaro, Fort Dauphin in Madagascar. Associated minerals are commonly thorite, zircon, cassiterite, the allanite group of minerals and ilmenite, although in Andolobe, Madagascar it is associated with phlogopite, spinel and diopside. Thorianite is found in many countries, with several important deposits being found in Madagascar, South Africa, Russia, USA, Canada, Brazil and China. In the UK, thorianite occurs in Presteigne, Powys where it occurs associated with thorite as minute inclusions, some 2 – 5 µm across, in spherical bitumen nodules in the Folly Sandstone (Ref. 8).

Cheralite, $CaTh(PO_4)_2$

Cheralite is the only other primary thorium mineral. It is the dimorph of huttonite and is isomorphous with monazite (Ref. 9). It should not be confused with the now discredited mineral cheralite-(Ce) which is identical to calcium-rich monazite-(Ce). Cheralite itself was redefined as a species (at the expense of brabantite) in 2007 by Linthout (Ref. 10). It crystallises in the monoclinic system and although it can form subhedral crystals reaching up to 5cm in size, it is most commonly found as metamict subhedral to anhedral massive aggregates (Figure 3) and is often associated with black euxenite, tourmaline, quartz, zircon, chrysoberyl and very rarely siderite (Ref. 11). Very small, well-formed crystals of cheralite do occur, but are rare. Good quality green to olive-green microcrystals to about 0.05cm can be found in an albite pegmatite at Pizzo Marcio in Piedmont, Italy where it is associated with spessartine and dark red columbite-(Mn). Cheralite has a hardness of 5 on the Mohs scale with a specific gravity that ranges from 4.7 – 5 and shows a greasy or resinous to vitreous lustre. It can be pale yellow, reddish brown, brownish green or greyish brown, the latter often showing a reddish brown colour on the crystal edges. The streak is white. It possesses several cleavages, some of which are distinct whilst others are difficult to see, and distinct to difficult cleavages, and a poor parting. The fracture is uneven and the tenacity is brittle. It can be found is kaolinised pegmatite dikes and the surrounding kaolinised granite gneiss, or in alluvial deposits such as those at Kuttankuli, India. It also occurs in a carbonatite at Mount Weld, Western Australia. The Uranium King Mine in Wyoming is well-known locality amongst collectors for its cheralite specimens.

Figure 3. Crystalline mass of brownish red cheralite from the Uranium King Mine, Encampment, Carbon County, Wyoming, USA. *Dr. Alexander Matthies photograph used with permission.*

Figure 4. Yellow crust of extremely small althupite crystals on matrix measuring 2.3 cm × 2.3 cm × 1.4 cm from the type locality for the species, Kobokobo Pegmatite, Mwenga, Sud-Kivu, Democratic Republic of Congo. *Photograph used with permission of Persson Rare Minerals.*

Althupite, $AlTh(UO_2)_7(PO_4)_4(OH)_5O_2{\cdot}15H_2O$

Whilst there are only six approved minerals that contain both aluminium and thorium and a further seven minerals which may be approved as new minerals, althupite is one of only two approved minerals that have aluminium and thorium as the dominant cations (Ref. 9). The other is eylettersite, $Th_{0.75}Al_3(PO_4)_2(OH)_6$. Both are phosphate hydroxides and both are very rare. Althupite gets its name from its chemical composition of an ALuminium, THorium, Uranium Phosphate. It is a member of the phosphuranylite group of minerals which also includes the more commonly available minerals phosphuranylite, $KCa(H_3O)3(UO_2)7(PO_4)_4O_4{\cdot}8H_2O$, bergenite, $Ca_2Ba_4(UO_2)_9(PO_4)_6O_6{\cdot}16H_2O$ and the significantly rarer minerals including vanmeersscheite, $U^{6+}(UO_2)_3(PO_4)_2(OH)_6{\cdot}4H_2O$, yingjiangite, $K_2Ca(UO_2)_7(PO_4)_4(OH)_6{\cdot}6H_2O$ and dumontite, $Pb_2(UO_2)_3O_2(PO_4)_2{\cdot}5H_2O$.

Althupite occurs as yellow, thin, tabular, trigonal crystals with a maximum length of 0.1 mm that are flattened on {100} and which

usually occur in groups of parallel crystals that show a vitreous or sub-vitreous lustre (Figure 4). The specific gravity is 3.91 and the hardness is 3.5 – 4. Crystals are usually transparent and the tenacity is flexible. It is not fluorescent (Ref. 12).

It occurs as a secondary mineral in the uraniferous zone of an altered granite pegmatite at the Kobokobo Pegmatite in the Democratic Republic of Congo where it is found associated with columbite and beryl. It also occurs at Intragna, Onsernone Valley, Centovalli, Locarno, Ticino, Switzerland.

Thorutite, $(Th,U,Ca)Ti_2(O,OH)_6$

Thorutite forms monoclinic crystals that show prismatic terminations with crystals reaching up to 2cm in size. It occurs only in the metamict state and forms translucent, black crystals with a resinous lustre, but is brown on thin edges (Ref. 13). It has a hardness of 5 – 6, a specific gravity of 5.8 and a pale brown streak. Thorutite forms a series with brannerite and occurs in veins of microcline and sericitised nepheline, in a syenite massif and is commonly associated with microcline, thorite, zircon, calcite, baryte and galena (Ref. 13). This rare species occurs at fifteen locations including Australia, Brazil, China, India, Kyrgyzstan, Namibia, Russia, Sri Lanka and the USA.

Tuliokite, $Na_6BaTh(CO_3)_6 \cdot 6H_2O$

Figure 5. A group of very well-formed white to pale greyish crystals of extremely rare tuliokite from Kirovskii Apatite Mine, Kukisvumchorr Mt, Khibiny Massif, Mirmansk Oblast, Russia. *Carsten Slotta specimen and photograph used with permission.*

This is an unusual mineral compositionally because it is the only thorium mineral in which the anions are solely carbonate anions. It is a very rare mineral that crystallises in the hexagonal crystal class and forms brittle, prismatic or rhombohedral crystals that reach up to about 4 mm in size (Figure 5). It is typically pale to dark grey or brownish in colour with a white streak and vitreous lustre; the dark grey colour is due to the inclusion of organic impurities. The hardness is 3 – 4 on the Mohs scale and the specific gravity is 3.1 whilst the lustre is vitreous and the streak is white (Ref. 14). Tuliokite occurs in hydrothermal veins in syenite pegmatites associated with nepheline, sidorenkite, vinogradovite, villiaumite, microcline, pirssonite, shortite, trona, thermonatrite, natron, natrolite and aegirine at the Kirovskii Apatite Mine, Kukisvumchorr Mt, Khibiny Massif, Mirmansk Oblast, Russia. This is the only known locality for this species and only about twelve specimens have been found.

Ichnusaite, $Th(MoO_4)_2 \cdot 3H_2O$

Ichnusaite was the first thorium molybdate mineral species to be discovered and is almost certainly formed as an alteration product of molybdenite under alkaline conditions (Ref. 15). It crystallises in the monoclinic system and forms aggregates of thin, transparent, colourless to very rarely pale pink, tabular crystals that reach up to 0.2 mm in size and which show a pearly to adamantine lustre. Aggregates of ichnusaite can sometimes have a rosette-like habit with the aggregates reaching up to 0.5 mm in size (Figure 6).

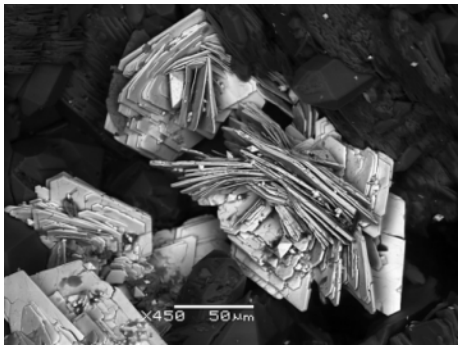


Figure 6. BSE-SEM image of a rosette-like aggregate of ichnusaite showing crystals up to 0.05mm with the largest crystal aggregate measuring 200 µm. *Italo Campostrini image used with permission.*

Ichnusaite is unusual not only because of its chemistry, in that it is one of only two known minerals that are thorium molybdates, but also because it has a pure chemistry (i.e. no other elements substitute for either thorium or molybdenum). The streak is colourless and there is one perfect cleavage. Whilst the tenacity is brittle, the hardness and specific gravity have not been determined, although the specific gravity has been calculated to be 4.262 (Ref. 15). It is always found intimately associated with nuragheite in

vughs in quartz veins where it is also associated with muscovite and xenotime-(Y) at the Mo-Bi deposit at Su Seinargiu, Cagliari, Sardinia, Italy. More recently, ichnusaite has been found at the Old 25 Pipe in Kingsgate, New South Wales, Australia where it is associated with kingsgateite, and at Punta de Su Seinargiu, Sardinia, Italy. It is impossible to distinguish between ichnusaite and nuragheite without destroying the crystals because the only difference between these two minerals in the amount of water present in the crystal structure. This can only be determined using a technique known as thermogravimetric analysis which involves heating the sample to high temperatures leading to destruction of the mineral by dehydration.

Nuragheite, $Th(MoO_4)_2 \cdot H_2O$

Nuragheite is the second of the two known thorium molybdate minerals in Nature (Refs 16, 17). Unlike the chemically similar ichnusaite which crystallises in the monoclinic crystal class, nuragheite crystallises in the orthorhombic system and forms minute, thin, colourless to very rarely pale pink, tabular crystals that reach up to 0.2mm in size and which show a pearly to adamantine lustre. The crystals are brittle and show a perfect cleavage. As is the case with ichnusaite, it is formed as an alteration product of molybdenite ore under alkaline conditions. At the Mo-Bi deposit at Su Seinargiu, Cagliari, Sardinia, Italy, nuragheite occurs associated with muscovite, xenotime-(Y) and intimately with ichnusaite. It also possibly occurs at Rainbach Valley, Salzburg, Austria (Ref. 18).

Cabvinite, $Th_2F_7(OH) \cdot 3H_2O$

Cabvinite is the only known thorium halide mineral and is formed by the low temperature hydrothermal alteration of molybdenum-bismuth mineralisation which also leads to a number of other very rare minerals including suseinargiuite [$NaBi(MoO_4)_2$] and mambertiite [$BiMo_{2.85}O_8(OH)$] (Ref. 19). Cabvinite is named after two Italian mineral collectors, Fernando Caboni (1941 -) and Antonello Vinci (1944 -) for their contribution to the knowledge of the extensive mineralogy of Su Seinargiu which is the type locality for nine extremely rare minerals. Cabvinite crystallises in the tetragonal system and occurs as microscopic, white square prismatic crystals that reach up to 100 µm in length that are elongated along [100] in length and which are up to 40 µm thick (Figure 7). SEM images suggest that there is either cleavage or parting on {001}. The streak is white and whilst the hardness and density have not been measured, calculations show that the hardness is 5.5. Crystals of cabvinite show a vitreous lustre. It occurs in a quartz vein at Punta de Su Seinargiu, Sarroch, Metropolitan City of Cagliari, Sardinia, Italy where it is associated with brookite and iron hydroxy-oxide minerals such as 'limonite'.

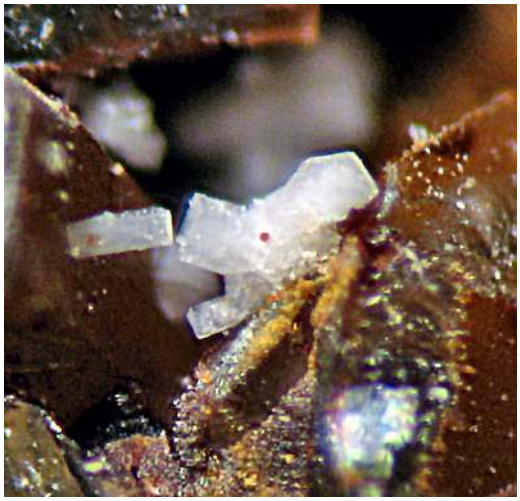


Figure 7. SEM image of an aggregate of tetragonal cabvinite crystals, the largest of which measures approximately 100 µm. This specimen is from the type and only known locality for the species; Punta de Su Seinargiu, Sarroch, Metropolitan City of Cagliari, Sardinia, Italy.
Prof. Cristian Biagioni image used with permission.

Some crystals, such as the cabvinite crystals shown, are far too small to have their hardness determined by the Mohs hardness test described in our Editor, Gary's, excellent article on how to determine the properties of minerals (see Junior Members' Magazine, Volume 2, pages 5 – 23, September 2025). It is, however, possible to calculate the hardness of such a mineral if its crystal structure is known. If so, the first step is to assess the bond strengths between the atoms because the higher the bond strength, the harder the mineral will be. From there, crystal defects and the extent of them need to be considered because these will lower the hardness. Once this has been completed, a hardness can be calculated. Finally, the Mohs scale is used to compare the mineral's hardness with that of known values to determine the hardness. Hence, by understanding the crystal structure and the strength of all of the chemical bonds in it, mineralogists can accurately calculate the hardness of a mineral.

Ekanite, $Ca_2ThSi_8O_{20}$

Ekanite is a relatively rare mineral that crystallises in the tetragonal system and which forms poorly developed pyramidal crystals reaching up to 1 cm in size and which are usually striated parallel to the [100] crystal face (Ref. 20). Although several different crystal habits are known, ekanite also occurs massive and as clusters of granular crystals. Crystals show two cleavages, one of which is distinct on {101} and another which is indistinct on {001}. The hardness is 4.5 – 5.0 and the specific gravity ranges from 2.95 – 3.28. Crystals are transparent to translucent and are either colourless, pale to dark green, yellowish green to yellowish brown, yellow or red (due to inclusions). The streak is white, the lustre is vitreous, the fracture is irregular and the tenacity is brittle. Although ekanite occurs in twenty three localities, the best-known to collectors are the Tombstone Mountains in Yukon, Canada where it is found non-metamict and it is from specimens collected in a glacial syenite boulder at this locality that it was possible to elucidate the crystal structure of ekanite (Ref. 21). Here, ekanite is found associated with fluorite, garnet, quartz, microcline, clinopyroxene, apatite, sodic plagioclase, hematite, thorogummite, zircon and titanite. Very small, but beautiful green crystals (Figure 8) come from, amongst other places, Case Collina, Tuscany, Italy where it is associated with quartz, feldspar and pyroxene.

Figure 8. Aggregate of pale green ekanite crystals on a quartz matrix from Case Collina, Pitigliano, Grosseto Province, Tuscany, Italy. *Dr. Alexander Matthies photo used with permission.*

Huttonite, $ThSiO_4$

Huttonite is the dimorph of thorite and crystallises in the monoclinic system (Refs 22, 23) and was first discovered in samples of beach sands from the West Coast of New Zealand by the mineralogist Colin Osborne Hutton (1910 – 1971 (Ref. 23). It is transparent to translucent and fluoresces dull white with a pinkish tinge under SW-UV (254 nm) illumination. Huttonite forms flattened anhedral grains that do not exceed 0.2mm in size and which are colourless or cream to pale yellow-green. Unlike thorite, huttonite is rarely metamict because it is isostructural with monazite which is resistant to metamictisation. Huttonite shows two cleavage planes, one of which is distinct whilst another is poor. The hardness is 4.5 and the specific gravity is 7.1; the fracture is conchoidal. These properties can help in distinguishing huttonite from thorite, although x-ray crystallography is a useful technique for determining the identity with a good degree of certainty. Huttonite is known from a variety of locations with New Zealand, Finland, Italy, Poland, Australia, Germany, Czech Republic, Sweden, USA and Russia being the most well-known locations for specimens.

Uranium Minerals

Thorium forms just 39 approved minerals (although there are potentially 25 new thorium minerals that are in various stages of the IMA new mineral approval process and a further 14 minerals that contain only very small amounts of thorium, or which are varieties of other approved minerals). At the time of writing [July 2026], uranium, on the other hand, forms 317 minerals with an additional 27 minerals that are either varieties of other minerals containing additional metals such as Pb, Fe or rare earth elements (e.g. 'gilpinite'), or are dehydrated varieties of approved minerals (e.g. dehydrated wyartite), or are doubtful varieties (e.g. 'cuprozippeite'), or are anthropogenic (e.g. 'chernobylite'), or are now considered to be mixtures of minerals (e.g. alpha-wiikite), or which were once approved minerals but new data has led to their discreditation as a distinct species (e.g. 'bismutopyrochlore'), or which may eventually be approved as new minerals (e.g. 'fluorplumbopyrochlore'). The reason why uranium has the ability to form so many more minerals than thorium is due to its ability to exist in more than one oxidation state and the dependence on the species formed on the pH of the fluids from which a mineral was formed as well as the availability of suitable anions in that solution that will

precipitate a different mineral when the hot water cools. (see the Chemistry of Uranium and Thorium Section in Part 1, published on 1st March 2026).

Primary Uranium Minerals

All primary uranium minerals exist with uranium in its lowest naturally occurring oxidation state of +4. There are only two groups of primary uranium minerals; oxides and silicates. The former includes uraninite (UO_2) and pitchblende which is essentially uraninite with variable amounts of U_3O_8 that are formed due to oxidation of uraninite. Included in the oxides group are mixed oxides such as brannerite, UTi_2O_6 and davidite $(REE)(Y,U)Fe_2(Ti,Fe,Cr,V)_{18}(O,OH,F)_{38}$ in which the REE component is the fifteen rare earth elements. There are three davidite minerals: davidite-(Y), davidite-(Ce) and davidite-(La) all of which occasionally occur in deposits in high enough concentration to be a commercially viable ore of both the rare earth elements and uranium. Uraninite also forms a complete solid solution with thorianite, all members of which crystallise in the cubic system. In nature, ratios of Th:U of 1:1, or close to that, are relatively rare.

Uranium Oxides

Uranium oxide minerals are limited to uraninite, UO_2, and 'pitchblende', which is a variety of uraninite. Uraninite occurs in four geological settings: as well-formed crystals or dendritic growths in pegmatites where it occurs in association with the columbite-tantalite series, monazite and zircon; in high temperature hydrothermal veins, where 'pitchblende' occurs associated with cassiterite, arsenopyrite and Co-Ni-Bi-As minerals; in moderate temperature hydrothermal veins with galena and other sulphide minerals; in sandstone deposits with vanadium, copper and ores of other metals.

In pegmatites, uraninite crystals usually contain up to 10% of thorium as thorianite (which forms a complete solid solution with uraninite) and up to 15% of rare earth elements, along with a host of other impurities, largely because the size of these ions prevent them from entering into the main rock-forming silicates as they crystallise on cooling. On the other hand, 'pitchblende' usually occurs in a fairly pure state because it has crystallised out of hydrothermal fluids that do not contain such impurities due to their very poor solubility.

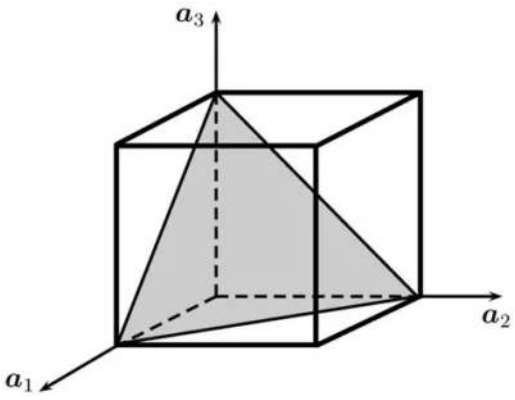


Figure 9. Diagram of a cubic crystal with the shaded section showing the (111) crystal plane on which twinning in uraninite can occur.Figure used with the permission of Daniel Leidermark.

Uraninite crystallises in the cubic system and forms black to brownish black cubic crystals that reach up to 11cm in size. Modifications of the cubic crystal, such as octahedra and dodecahedra are known, but are nowhere near as common as the simple cubic crystals. Other habits of uraninite are botryoidal to reniform, colloform banded, columnar, massive and dendritic, although the latter of these habits is rare. Twinning is rare in uraninite crystals, but when it does occur the twinning is always on the (111) crystal plane (Figure 9).

Uraninite has a hardness of 5 – 6 on the Mohs scale. The density is typically 10.63 – 10.95 g cm^{-3} but decreases very noticeably with oxidation to as low as 6.5 g cm^{-3}. Due to the high uranium content of 50% – 88%, uraninite is highly radioactive. The reason why the uranium content is so variable is due to the presence not only of thorium, but also the inclusions of lesser amounts of the decay products of uranium, other impurities such as the rare earths, for example, and oxidation of UO_2 to pitchblende, U_3O_8. Uraninite shows an uneven to conchoidal fracture and the tenacity is brittle. It is very commonly black to brownish black in colour, but can also be pale grey or pale green. It gives a brownish black streak in specimens of the same colour, but pale grey and pale green specimens give a grey or lustrous olive-green, grey, olive-green streak respectively. It occurs in granite and syenite pegmatites, in high-temperature hydrothermal tin and tungsten veins and in moderate-temperature Co–Ni–Bi–Ag–As and other sulphide veins. In pegmatite deposits, it is usually associated with zircon, monazite, tourmaline, mica group minerals and the feldspar group

whilst in hydrothermal veins it is found associated with pyrite, chalcopyrite, galena, bismuth, silver, gold, nickeline, baryte, fluorite and carbonates. It also occurs in quartz-pebble conglomerates.

Figure 10. Group of intergrown crystals of uraninite to 1.5 cm from Trebilcock Pit, Topsham, Sagadahoc County, Maine, USA. Specimen dimensions are 2.7 cm x 2.4 cm x 1.4 cm.
Rob Lavinsky (www.irocks.com) photograph taken from Wikimedia.com and used under a CC-BY-SA-3.0 copyright licence.

Uraninite is very widely distributed, occurring in 87 countries. Good quality, well-crystallised specimens of cubic crystals, such as the one shown in Figure 10, come from the Shinkolobwe Mine in the Democratic Republic of Congo, the Swamp #1 Quarry in Topsham, Maine, USA and the Cardiff Uranium Mine in Ontario, Canada, amongst others.

Octahedral crystals are those that crystallise in the cubic system and can be imagined to being formed from a cubic crystals by squeezing the finger and thumb of each hand on the top and bottom faces of the crystal and then pulling up or down from the crystal. This generates eight crystal faces whereas a cubic crystal has just six. In reality though, crystals cannot be stretch and the octahedral habit is formed Good quality octahedral crystals can be found at Råde in Østfold, Norway and from Rock Landing Quarry in Connecticut, USA and at the Chaput-Payne Minein Québec, Canada.

Intermediates between the cubic and octahedral forms are called cubo-octahedral crystals, good examples of which are found at the Swamp #1 Quarry in Topsham, Maine, USA.

Figure 11. Botryoidal aggregates of uraninite from Bytíz, Příbram, Příbram District, Central Bohemian Region, Czech Republic. Associated with the uraninite and shown in the bottom right hand side of the photograph is white calcite. FoV is 1.5 cm.
Alan Barnes collection and photograph.

Botryoidal aggregates of uraninite, such as the one shown in Figure 11, occur at Bytíz in the Czech Republic.

Other well-known localities to the ones already listed for uraninite specimens are South Terras Mine in Cornwall where it is possible to find very small crystals. Massive uraninite occurs at many more mines in Cornwall than coffinite does, with some of the most important Cornish localities being Wheal Edward (Ref. 24), Wheal Trenwith (Ref. 25), South Terras Mine (Ref. 26) and Carn Brea Mine (Ref. 27). In Devon, the Merrivale Quarry is the best-known site amongst collectors of radioactive minerals and from where quite rich specimens of autunite can be found that are closely associated with small botryoidal aggregates of earthy, black 'pitchblende'. In Scotland, the Needle's Eye Mine in Dumfries & Galloway is well-known for its interesting mineralogy including specimens of massive uraninite and a small group of secondary uranium minerals including boltwoodite, walpurgite, uranophane and vandendriesscheite.

Secondary Uranium Minerals

Secondary uranium minerals are formed from the oxidation of uraninite in arsenic-bearing uranium deposits. Almost all secondary uranium minerals have uranium in the U^{6+} oxidation state and most of these occur as the $(UO_2)^{2+}$ cation. Exceptions to this are vysokýite, štěpite, lermontovite, vyacheslavite, umohoite, ningyoite and běhounekite in which the uranium has an oxidation state of +4 (the same as uraninite).

Hydrated Uranyl Oxides

Some secondary hydrated uranyl oxides also contain other metal ions, whilst others do not. Examples of minerals in the latter of these two groups include the common minerals schoepite, studtite and metastudtite, but the rare mineral ianthinite is also a member of this group. It is only stable in mildly

reducing conditions and contains uranium in both the +4 and +6 oxidation states; the +4 oxidation state is liable to oxidation whereas schoepite, studtite and metastudtite all contain uranium solely in the +6 oxidation state which cannot be further oxidised. All of these minerals form either on, or very close to uraninite, from which they are derived.

Ianthinite, $U^{4+}(UO_2)_5O_7 \cdot 10H_2O$

Ianthinite (Refs 28, 29) gets its name from the Greek word *ιάνθινος* (i.e. 'ianthinos') meaning violet coloured, alluding to its dark purple colour.

Figure 12. Very dark purple ianthinite crystals to 1.6 mm showing initial alteration to brown-coloured and then slowly turning yellow as schoepite is formed. Alan Barnes collection and photo.

Ianthinite is only stable in mildly reducing environments that, whilst stabilising U^{4+}, are not strongly reducing enough to reduce the UO_2^{2+} cation. Ideally, to preserve specimens of this species without alteration, they should be stored under an inert gas such as nitrogen, but this is rarely possible in private collections meaning that the oxidation of the U^{4+} cation is unavoidable resulting in the formation of bright yellow schoepite under normal atmospheric conditions. Indeed, almost all commercially available specimens show at least some alteration to schoepite, as shown in Figure 12. This alteration occurs in four stages. In the first stage, the very dark purple crystals turn violet-brown in colour, whilst in the second stage, the crystals turn pale brown. In the third stage, the colour change is from pale brown to greenish yellow whilst in the fourth and final stage they turn bright yellow as schoepite is formed. Two of these stages are clearly visible in Figure 12.

Unaltered ianthinite crystallises in the orthorhombic system and occurs most commonly as very dark purple plates or more commonly as lath-like crystals, but can also occur as acicular or prismatic crystals that reach up to 2mm in length. The streak is dull violet-brown and the lustre is vitreous to sub-metallic when fresh. Crystals show two cleavages, one of which is perfect and the other of which is good. The fracture is conchoidal and the tenacity shows flexible lamellae. The hardness is 2 – 3 on the Mohs scale. Ianthinite does not fluoresce, but the alteration product, schoepite does fluoresce on UV illumination. It occurs associated with uraninite, schoepite, kasolite, dewindtite, parsonsite, becquerelite and fourmarierite.

Notable localities for ianthinite include the Shinkolobwe Mine in the Democratic Republic of Congo and the Krunkelbach Valley Uranium deposit in Baden-Württemberg, Germany although it occurs at a further 33 localities worldwide. The two locations given here provide the best examples of the species.

Schoepite, $(UO_2)_8O_2(OH)_{12} \cdot 12H_2O$

Schoepite is named for Alfred Schoep (1881 – 1966), Professor of Mineralogy at the University of Ghent, Belgium. Whilst schoepite may well occur as a dehydration product of ianthinite, it can also be formed directly from uraninite by chemical reaction with hydrogen peroxide, H_2O_2, generated from the alpha-radiolysis of water. At moderate H_2O_2 concentrations, schoepite is the most stable uranium phase, whilst at increasingly higher H_2O_2 concentrations, the most stable minerals are studtite, schoepite, metaschoepite and finally becquerelite Schoepite itself, however, is not immune from further dehydration, initially forming metaschoepite, $(UO_2)_8O_2(OH)_{12} \cdot 10H_2O$ with the final dehydration step yielding paulscherrerite, $(UO_2)(OH)_2$, as the final product.

Schoepite crystallises in the orthorhombic system and commonly occurs as tabular crystals parallel to {001}, as equant crystals or as short prismatic crystals that do not exceed 1.5mm in length (Ref. 30). Over twenty different crystal forms of schoepite have been recorded. It rarely occurs in microcrystalline aggregates (Figure 13). It is most commonly bright yellow in colour, but can also be amber-coloured or brownish yellow. It gives a yellow streak and an adamantine, sub-adamantine, or more rarely a vitreous lustre. Crystals show one perfect cleavage, are brittle with a hardness of about

2.5 and are frequently transparent. The density is 4.80 – 4.96 g cm^{-3}. Under UV illumination, schoepite exhibits a green fluorescence.

Figure 13. Aggregates of thin, yellow bladed crystals of schoepite to 0.7 mm across from Krunkelbach Valley Uranium Deposit, Menzenschwand, St Blasien, Waldshut, Freiburg Region, Baden-Württemberg, Germany. Carsten Slotta photograph used with permission.

Schoepite occurs associated with uraninite (where it occurs as a surface coating) and with a range of other secondary uranium minerals including ianthinite, uranophane, soddyite, becquerelite, billietite, fourmarierite, curite, rutherfordine and vandendriesscheite at the Shinkolobwe Mine in the Democratic Republic of Congo; with cuprosklodowskite at the Musonoi Mine in the Democratic Republic of Congo, and with paraschoepite, arsenuranylite, metazeunerite, uranospinite, nováčekite at the Cherkasar deposit in Uzbekistan. In the United Kingdom, schoepite is, somewhat surprisingly, very rare and occurs only at two localities in Scotland; Sandyhills Bay (Ref. 31) and at Needle's Eye Mine (Ref. 31). Other notable localities are the Krunkelbach Valley Uranium Deposit and the Clara Mine, both in Baden-Württemberg, Germany and the Jomac Mine in Arizona, USA. Pseudomorphs of schoepite after uraninite occur at Beryl Mountain, New Hampshire, USA.

Studtite, $(UO_2)(O_2)(H_2O)_2 \cdot H_2O$ and Metastudtite, $(UO_2)(O_2)(H_2O)_2$

Studtite and, by default, metastudtite are named after Franz Edward Studt (1873 – 1953), a British geologist who worked for Tanganyika Concessions Ltd. He was a mineral prospector and prepared the first geological map of Katanga in 1913.

Geochemically, studtite and metastudtite are interesting minerals because they are the only two minerals that contain a peroxide (O-O) group. It has been reported that the peroxide group is generated from the alpha-radiolysis of water by high energy alpha particles and it appears that these are the only two minerals that require a radioactive environment for them to form (Refs 32, 33).

Figure 14. Divergent spray of bright yellow studtite crystals 2 mm in width with the largest crystal measuring 3 mm in length associated with yellow bladed crystals of uranophane to almost 1 mm from Shinkolobwe Mine, Shinkolobwe, Haut-Katanga, Democratic Republic of Congo. FoV is 4 mm. Alan Barnes specimen and photo.

Studtite was first found at the Shinkolobwe Mine in the Democratic of Congo, a locality famous amongst collectors of radioactive minerals as an excellent source of high quality, rare to extremely rare, radioactive specimens. It crystallises in the monoclinic system where it may form pseudohexagonal crystals. It commonly occurs as small, yellow to pale yellow acicular crystals that reach up to 1mm in length, as divergent sprays or stellate aggregates, or as microcrystalline crusts. The hardness is very soft, the tenacity is flexible and the lustre is vitreous. The density is 3.58 g cm^{-3} on a synthetically prepared sample. Studtite does not fluoresce under UV illumination.

It is often found associated with other radioactive minerals including uranophane, rutherfordine and lepersonnite-(Gd) at the Shinkolobwe Mine, Democratic Republic of Congo, with billietite, uranophane, rutherfordine, heisenbergite, baryte, quartz, hematite and 'limonite' at Menzenschwand, Germany, with sklodowskite, cuprosklodowskite and heterogenite-3R at the Musonoi Mine, Democratic Republic of Congo, and with tengchongite, calcurmolite and kivuite at Tengchong County, People's Republic of China.

The prime locality for high quality specimens is the Shinkolobwe Mine (Figure 14), but well-crystallised specimens

are also found at Musonoi Mine, Democratic Republic of Congo and in the Krunkelbach Valley in Germany. There are no reports of studtite being found in the UK.

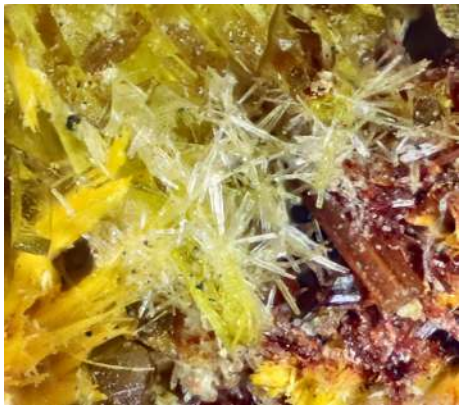


Figure 15. Aggregate of colourless to white metastudtite crystals with associated uranophane from the Shinkolobwe Mine, Shinkolobwe, Kambove Territory, Haut-Katanga, Democratic Republic of Congo. FoV 1 mm. Alan Barnes specimen and photo.

Metastudtite is a very rare mineral and is a partially dehydrated version of studtite (Refs 34, 35). It crystallises in the orthorhombic system as fibrous or acicular crystals (Figure 15), as elongated tablet-like crystals, or as nodules. Similarly to studtite, the crystals are flexible and can be bent without breaking them meaning that the tenacity is flexible. Due to its softness and flexibility, the hardness of metastudtite (along with studtite) has not been able to be determined. The density has also not been measured, but using software entitled 'Crystal Density Calculator' the density of a mineral (or any other solid material) can be calculated based on the molecular structure and unit cell parameters. Using this technique, the density of metastudtite has been calculated to be 4.67 g cm^{-3}. Crystals are colourless to pale yellow and are semi-transparent. The streak is yellowish-white and the crystals show a silky lustre. Metastudtite dissolves in hot hydrochloric acid solution. Interestingly, studtite does not dissolve in hot hydrochloric acid and so this test can be used to distinguish between the two species (although it is not recommended that this be attempted).

Minerals associated with metastudtite often include uraninite, uranophane, soddyite, uranopilite, fourmarierite, wölsendorfite, rutherfordine, becquerelite, masuyite, kasolite and extremely rarely, wulfenite at the Shinkolobwe Mine, Democratic Republic of Congo.

Metastudtite also occurs at Kamoto, Democratic Republic of Congo, in Daweb, Namibia and in Hundholmen, Norway. There are no reports of metastudtite being found in the UK.

Hydrated Uranyl Oxides Containing Other Metal Ions

Hydrated uranyl oxides containing lead are important in understanding the oxidation zones of geologically old uranium deposits. In such deposits, the half-life of uranium means that since its formation, some of the uranium and its daughter nuclides have decayed giving rise to radiogenic lead. This lead can then form secondary minerals with uranium giving rise to a series of brightly coloured minerals that are desirable additions in mineral collections. There are currently forty two approved minerals containing lead and uranium, with some of the more better-known examples amongst collectors of radioactive minerals being curite (Refs 36, 37), fourmarierite (Ref. 38), masuyite (Refs 35, 39), richetite (Refs 35, 40, 41)], sayrite (Refs 42, 43), spriggite (Ref. 44), vandendriesscheite (Refs 6, 45) and metavandendriesscheite (Ref. 46). There is one other mineral that has been discredited and further one that was published without official approval, two further minerals that do not meet the criteria defining a new species and a further ten minerals that may be approved as new species in due course. Other metals that form minerals with uranium include calcium (which forms becquerelite, $Ca(UO_2)_6O_4(OH)_6{\cdot}8H_2O$, (Ref. 47), barium (which forms the barium analogue of becquerelite, billietite, $Ba(UO_2)_6O_4(OH)_6{\cdot}4\text{-}8H_2O$) (Ref. 35) and copper, which forms vandenbrandeite, $Cu(UO_2)(OH)_4$, (Ref. 48).

Curite, $Pb_3(H_2O)_2[(UO_2)_4O_4(OH)_3]_2$

Curite is named after Pierre Curie, the French physicist and chemist who was a pioneer in the fields of crystallography and magnetism. With his wife, Marie, he shared the 1903 Nobel Prize in Physics for their pioneering work on radioactivity.

Curite is one of the most aesthetic secondary uranium minerals and crystallises in the orthorhombic system as semi-transparent, deep to pale reddish-orange, orange or scarlet-coloured, long prismatic to acicular crystals that are striated parallel to [001], as porous aggregates of fine acicular crystals, as fine-granular aggregates, as opaline crusts, and in the massive state (Refs 36, 37). Crystals show one

perfect cleavage on {100}. The hardness is 4 – 5, the density is 7 – 7.4 g cm^{-3} and the tenacity is brittle.

Figure 16. Curite crystals associated with green metatorbernite from the Shinkolobwe Mine, Haut-Katanga, Democratic Republic of Congo. *Elmar Lackner specimen and photograph. Photograph used with permission.*

Curite is commonly associated with uraninite, soddyite, schoepite, kasolite, fourmarierite, (meta)torbernite, rutherfordine, sklodowskite, vandendriesscheite and dewindtite at the Shinkolobwe Mine, Democratic Republic of Congo (Figure 16) and with a similar type of assemblage at Swambo Hill, Democratic Republic of Congo. At the Strel'tsovskoe Mo-U orefield, Russia, it is associated with becquerelite, schoepite and uraninite, whilst at the Johannesschacht Mine in Germany it is found associated with baryte and uranophane. In total, it occurs at sixty three localities in twenty one countries.

Vandendriesscheite, $PbU_7O_{22}·12H_2O$ and Metavandendriesscheite, $PbU_7O_{22}·nH_2O$ (where n<12).

Vandendriesscheite is named after Adriaan Vandendriessche (1914 – 1940), who was professor of geology and mineralogy at the University of Ghent (Belgium). He was killed as a soldier in WWII on 27th May 1940.

Vandendriesscheite crystallises in the orthorhombic system and forms crystals that are flattened on {001} (Ref. 45). Crystals can also be pseudohexagonal, diamond or barrel-shaped, or, more rarely, tabular crystals reaching up to 1.5 mm in size and showing the family of crystallographic planes {001}, {011}, {111} and {010}. It is structurally related to gauthierite. It also occurs as composite aggregates or in sub-parallel aggregates and in dense microcrystalline aggregates. It is very commonly intimately intergrown with metavandendriesscheite (Ref. 46). There is one perfect cleavage on {001}. The hardness is 3 and the density is 5.45 – 5.46 g cm^{-3}. Crystals are transparent and are orange to yellowish orange or amber-orange in colour and show a waxy lustre.

Figure 17. Spherical aggregates of orange-yellow acicular crystals of vandendriesscheite to 1.34mm from Novazza Mine, Lombardy, Italy. *Dominico Preite Collection. Matteo Chinellato photograph used with permission.*

It is commonly associated with metavandendriesscheite, fourmarierite, becquerelite, metatorbernite, uranophane, rutherfordine, uraninite at the Shinkolobwe Mine, Democratic Republic of Congo. At the Ruggles Mine in New Hampshire, USA it is associated with uraninite, phosphuranylite, schoepite, paulscherrerite and zircon. Other notable localities for vandendriesscheite are the Rabejac Est Mine in France. In the UK, vandendriesscheite is not common with only four known localities; Loe Warren Zawn (Ref. 49), Dalbeattie (Ref. 31), Sandyhills Bay, Dumfries & Galloway, Scotland (Ref. 31), Needle's Eye Mine, Dumfries & Galloway, Scotland (Ref. 31) and Novazza Mine, Lombardy, Italy (Figure 17).

Masuyite, $Pb(UO_2)_3O_3(OH)_2·3H_2O$

Masuyite is named after the Belgian geologist Gustave Masuy (1905 – 1945) for his extensive contributions to the study of uranium minerals.

It crystallises in the orthorhombic system forming pseudohexagonal crystals that are tabular on {001} and which reach up to 3 mm in size (Ref. 39). It can also form scaly crystals (Figure 18) and rosettes. Twinning is very common {110} or {130} as twin and composition planes. The colour ranges from orange to brownish orange. Crystals show two cleavages, one {001} is perfect whilst the other {010} is good. The density is 5.08 g cm^{-3}.

Figure 18. Orange scaly aggregates of masuyite surrounded by yellow studtite and colourless (appearing white in the photograph) metastudtite. At the edges are darker yellow uranophane crystals. The masuyite aggregate measures 1.5 mm and the FoV is 2.7 mm. Specimen is from the Shinkolobwe Mine, Shinkolobwe, Haut-Katanga, Democratic Republic of Congo.
Alan Barnes specimen and photo.

Minerals commonly associated with masuyite include becquerelite, fourmarierite, kasolite, studtite, metastudtite, rutherfordine, uraninite, uranophane, richetite and wyartite at the Shinkolobwe Mine. Elsewhere, masuyite is associated with uraninite, kamotoite-(Y) and pendevilleite-(Y) at the Kamoto East Open Cut in the Democratic Republic of Congo, with uranophane and sklodowskite at the Rabbit Lake Mine in Saskatchewan, Canada and with wölsendorfite at the Giftkries Mine in Jáchymov, Czech Republic.

Additional localities for masuyite not listed above include, but are not limited to, the Mas d'Alary opencast Mine in Lodève, France and the Schneeberg area of Saxony, Germany.

Becquerelite, $Ca(UO_2)_6O_4(OH)_6 \cdot 8H_2O$

Becquerelite is named after Antoine Henri Becquerel (1852 – 1908), the physicist who discovered radioactivity in 1896 and after whom the bequerel (one of the units of radioactivity, denoted by Bq) was named. Among many of the honours he won, he was awarded the 1903 Nobel Prize in Physics, along with Marie and Pierre Curie for their pioneering work on radioactivity.

Becquerelite crystallises in the orthorhombic system usually as tabular on {001} that have a hexagonal outline, but crystals can also be prismatic, elongated along [010] into thick laths (Refs 50, 51). Crystals can reach up to an impressive 3 cm in length, although these are exceedingly rare. Crystals are commonly amber yellow (Figure 19), but can also be golden to lemon-yellow, yellowish orange or brownish yellow. There are four cleavages, of which only one is perfect; the other three are imperfect. The hardness is 2.5, the density is 5.09 – 5.2 g cm^{-3} and the tenacity is brittle. Samples of becquerelite give a yellow streak and show an adamantine to greasy lustre.

Figure 19. Dark amber coloured, flat-terminated crystals of becquerelite to 5 mm with very pale yellow uranophane from Shinkolobwe Mine, Shinkolobwe, Kambove Territory, Democratic Republic of Congo. *Photo Rob Lavinsky, www.irocks.com photograph taken from Wikimedia.com used under a CC-BY-SA-3.0 copyright licence.*

Minerals commonly associated with becquerelite include uraninite, rutherfordine, schoepite, soddyite, kasolite, curite, fourmarierite, dewindtite, ianthinite, wölsendorfite, masuyite at the Shinkolobwe Mine, Democratic Republic of Congo and johannite, uranopilite and zippeite at the Happy Jack Mine, Utah, USA.

Becquerelite is quite widely distributed, occurring at 115 sites in 28 countries. The Shinkolobwe Mine is the best-known among collectors for producing high quality specimens, but other significant localities for it include the Happy Jack Mine in Utah, USA and the Urcal deposit in La Rioja Province, Argentina. In the UK, it occurs at Geevor Mine in Cornwall (Ref. 52) and possibly at West Wheal Owles in Cornwall and Foggintor Quarry in Devon.

Billietite, $Ba(UO_2)_6O_4(OH)_6 \cdot 4\text{-}8H_2O$

Billietite is named after Valère Louis Billiet (1903 – 1945), a crystallographer from the University of Ghent, Belgium.

Figure 20. Billietite crystals, each about 1 mm in size from Krunkelbach Valley Uranium deposit, Menzenschwand, St Blasien, Waldshut, Freiburg Region, Baden-Württemberg, Germany. Carsten Slotta photo edited and used with permission.

It crystallises in the orthorhombic system as pseudo-hexagonal crystals, tabular on {001}, which may be elongated along {110} and which can reach up to 5mm in size (Refs 53, 54). Twinning is very common on both {110} and {111}. Crystals show three cleavages, one of which is perfect {001} whilst the other two, {110} and {010}, are imperfect. Crystals are transparent to translucent and are either yellow, golden yellow, or amber yellow to orange and show an adamantine lustre (Figure 20). The tenacity of billietite is brittle and the density ranges from 5.28 – 5.36 g cm^{-3}. To the author's knowledge, the hardness of billietite has not been determined, presumably due to the brittleness of the crystals.

Minerals commonly associated with billietite are uraninite, rutherfordine, becquerelite, studtite, metatorbernite, uranophane, fourmarierite, wölsendorfite, metaschoepite and soddyite at the Shinkolobwe Mine, Democratic Republic of Congo. At the Musonoi Mine, Democratic Republic of Congo, billietite occurs associated with malachite, rutherfordine, torbernite, kasolite, vandenbrandeite and cuprosklodowskite, whilst at Rabejac Est it occurs associated with vandendriesscheite, uraninite and masuyite.

The best-known localities for billietite are the Shinkolobwe Mine, Democratic Republic of Congo and the Musonoi Mine, Democratic Republic of Congo, but the Krunkelbach Valley Uranium deposit produces some very unusual star-like polycyclic twinned crystals.

Uranyl Carbonates

Secondary uranyl carbonates can be split up into four groups: uranyl monocarbonates; uranyl di- and tricarbonates that contain other metal cations; uranyl carbonates that contain rare earth elements; uranyl carbonates that may also contain other anions.

Uranyl monocarbonates that contain no other metal cations

This group is limited to just three minerals; blatonite (Refs 55, 56), joliotite (Refs 57, 58) and rutherfordine (Refs 59 – 62), the latter of which is by far the most common of the three. It occurs quite frequently as the outermost alteration layers on uraninite that is pseudomorphed by 'gummite' and uranyl silicates. Blatonite is very rare, occurring at only eight localities worldwide with the Jomac Uranium Mine in Utah, USA being the best-known amongst collectors. Chemically, it is a monohydrate version of rutherfordine and occurs as distorted, pale yellow, acicular crystals that do not exceed 1mm in size. Again, from a chemical perspective, joliotite is also a hydrated version of rutherfordine except that this time there are two molecules of water per unit cell rather than one in blatonite. Joliotite occurs at just five localities worldwide, three of which are in Germany with the Krunkelbach Valley Uranium Deposit being the best-known amongst collectors.

Rutherfordine, $(UO_2)CO_3$

Rutherfordine is the simplest and most abundant of the three uranyl carbonate minerals that do not contain any other anions or metal ions. It is named after Professor Ernest Rutherford (1871 – 1937) for his contributions to nuclear chemistry including the discovery of the concept of radioactive half-life, proving that radioactivity involves the change of one element into another, differentiating between alpha and beta radiation and the naming thereof, discovering and naming the proton, and developing the Rutherford model of the atom. He was awarded the Nobel Prize for Chemistry in 1908 for his endeavours and the element rutherfordium (atomic number 104) is named in his honour.

Rutherfordine crystallises in the orthorhombic system as lath-like crystals that are often elongated along [001] (Refs 59 – 62). Crystals can reach up to 3 mm in length. It commonly occurs in radiating groups of crystals, as fibrous or matted aggregates or in very fine grained masses. Crystals are semi-transparent or translucent but can also be transparent and show two cleavages, one of which is perfect whilst the other of which is nearly-so. It occurs in a range of colours from pale yellow to straw yellow or greenish yellow but can also be orange or brownish amber or pale brownish (Figure 21). Zoned crystals are also known. The lustre is usually dull or earthy, but fibrous crystals can have a silky lustre. To the best of the author's knowledge, the hardness has not been determined. Rutherfordine crystals can be susceptible to alteration to schoepite.

Figure 21. Lath-like crystals of pale brownish rutherfordine to about 2 mm from the Shinkolobwe Mine, Shinkolobwe, Haut-Katanga, Democratic Republic of Congo. *Elmar Lackner photo used with permission.*

It commonly occurs associated with uraninite, metatorbernite, schoepite, billietite, becquerelite, studtite, kasolite, boltwoodite, soddyite, masuyite, curite, vandendriesscheite, fourmarierite and sklodowskite.

Rutherfordine can be found in 66 locations in 24 countries. The best known localities are the Shinkolobwe Mine in the Democratic Republic of Congo, the Musonoi Mine in the Democratic Republic of Congo, the Johannesschacht Mine in Germany and the Bel Air Mine in France, all of which produce very nice crystals, or aggregates thereof. In the UK, rutherfordine is known from Loe Warren Zawn (Ref 49) and South Terras Mine (Ref. 79), both of which are in Cornwall.

Uranyl Dicarbonates and Tricarbonates

Both uranyl dicarbonates and tricarbonates contain other metal ions including sodium, potassium, calcium, magnesium, lead and zinc. Minerals in this group include andersonite, čejkaite, bayleyite, liebigite, zellerite, metazellerite, rabbittite, grimselite, znucalite, swartzite and widenmannite. Andersonite and bayleyite are both water-soluble minerals, the former of which occurs as an efflorescent mineral on mine walls in moderately dry locations. All of these minerals are fluorescent under UV illumination with the exception of metazellerite, grimselite and widenmannite. Quite often, minerals of these two sub-classes occur with other members of the same class. For example, andersonite is often associated with bayleyite and/or swartzite as well as with other uranyl carbonate minerals containing other anions such as schröckingerite.

Figure 22. Widenmannite crystals to approximately 0.45 mm from the Prokop Mine, Březové Hory deposit, Březové Hory, Příbram, Příbram District, Central Bohemian Region, Czech Republic. *Pavel Škácha photo used with permission.*

Widenmannite, $Pb_2(OH)_2[(UO_2)(CO_3)_2]$

Widenmannite is an example of a very rare lead uranyl dicarbonate that occurs in the oxidised zones of some Pb-As bearing deposits, such as the Michael Mine in Germany, or as an alteration product of sulphide minerals by seawater, such as at Loe Warren Zawn, England. It is named after Johann Friedrich Wilhelm Widenmann (1764 – 1798) who discovered uranium in the Black Forest of Germany (from where widenmannite was first discovered in 1961) (Ref. 63).

It crystallises in the orthorhombic system as lath-like crystals that are tabular on {010} and are elongated on [001] (Refs 63, 64). Crystals are colourless to whitish, very pale greenish yellow or yellow and reach up to 0.5 mm in size (Figure 22); they are often aggregated into tufts of mats. There is just one perfect cleavage on {010}. The streak is pale yellow, the lustre is silky or pearly and the density is 6.89 g cm^{-3}. It is not fluorescent under UV illumination.

Associated minerals are quartz, galena, cerussite, hallimondite and hügelite at the Michael Mine in Germany and with dewindtite and uraninite at Loe Warren Zawn where it occurs as thin crusts of the massive mineral (Refs 49, 65). Minerals associated with widenmannite at other localities include kasolite, sklodowskite and erythrite.

Apart from the two mentioned localities above, widenmannite also occurs at the Uranus Mine in Germany, at the Giftkies adit in Jáchymov and the Jánská vein in the Březové deposit both of which are in the Czech Republic and at the Needle's Eye Mine in Dumfries & Galloway, Scotland.

Andersonite, $Na_2Ca(UO_2)(CO_3)_3 \cdot 6H_2O$

Figure 23. Gemmy green andersonite crystals to 0.7 mm with brighter, yellowish green schröckingerite from 17 Level, Peath Lode, Geevor Mine, Cornwall. Steve Rust photo used with permission.

Andersonite is a uranyl tricarbonate that is named after Charles A. Anderson (1902 – 1990) who was a geologist with the United States Geological Survey and who collected the minerals from the zone that produced the first andersonite specimens.

It is an uncommon secondary mineral that forms in the oxidised zones of uranium-containing hydrothermal polymetallic sandstone deposits and often occurs as a coating on the walls of mines that produce it, suggesting that its formation may be post-mining. It crystallises in the trigonal system (Ref. 66), frequently as rhombohedral crystals, but also shows either flattened or pseudo-cubic habits. It can also occur as granular or crystalline coatings such as those found at the Atomic King Mine in Utah, USA. Crystals are generally transparent to translucent and are bright green to yellowish green in colour. It is a fluorescent mineral and fluoresces a bright pale green to yellow-green colour under under SW and LW-UV (365 nm) illumination. The hardness is 2.5 and the density is 2.8 g cm^{-3}. The lustre is vitreous to more frequently pearly. Specimens should not be cleaned with water because andersonite is soluble in water and should be stored in dry conditions to prevent slow dissolution.

Minerals commonly associated with andersonite are schröckingerite, bayleyite, boltwoodite, liebigite, swartzite and gypsum.

The Atomic King Mine in Utah, USA is the best-known source of andersonite amongst collectors, but better crystals can be acquired from the Kővágószőlős Uranium Mine, Hungary and the Lower Kane Creek Mining District, Utah, USA and from the 17 Level, Peath Lode at Geevor Mine (Figure 23).

Uranyl Carbonates Containing Rare Earth Elements

All of the minerals in this small sub-group of uranyl carbonates are very rare and none contain solely the carbonate anion. Astrocyanite-(Ce) and shabaite-(Nd) both contain carbonate and hydroxide anions whilst lepersonnite-(Gd) and lepersonnite-(Nd) both contain silicate, carbonate and hydroxide ions. All of these species occur only in the Democratic Republic of Congo; astrocyanite-(Ce) and shabaite-(Nd) both occur at the Kamoto East Open Cut whilst lepersonnite-(Gd) and lepersonnite-(Nd) both occur at the Shinkolobwe Mine; lepersonnite-(Nd) occurs at Swambo Hill. Bijvoetite-(Y), kamotoite-(Y) and pendevilleite-(Y) (Ref. 67) are the only three uranyl carbonates that contain yttrium as an essential rare earth element (although technically yttrium is not a rare earth element; it is normally considered along with the rare earth minerals because it has a very similar chemistry to them).

Astrocyanite-(Ce) $Cu_2(Ce,Nd,La)_2(UO_2)(CO_3)_5 \cdot 1.5H_2O$

The name of this mineral is derived from the Greek word *ἀστρον* ("astron") for "star" and *κυανός* ("kyanos") for "blue" due to the appearance of the mineral which occurs as blue stellate aggregates of platy crystals where it occurs in the oxidation zone of the uranium-bearing portion of a Cu–Co deposit at the Kamoto East Open Cut. The -(Ce) suffix represents the dominant rare earth element.

Figure 24. Radial aggregates of pale blue astrocyanite-(Ce) with yellow crystals of kamotoite-(Y) from Kamoto East Open Cut, Kamoto, Mutshatsha, Democratic Republic of Congo. FoV 2 mm. Alan Barnes collection and photo.

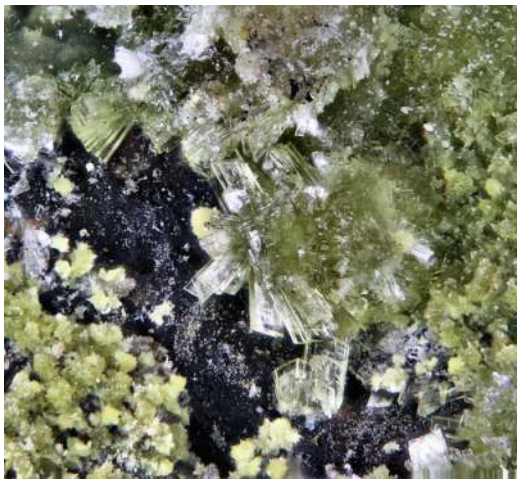


Figure 25. Group of green tabular crystals of shabaite-(Nd) associated with a yellow-green unidentified mineral from Kamoto East Open Cut, Kamoto, Mutshatsha, Lualaba, Democratic Republic of Congo. Carsten Slotta photo used with permission.

It crystallises in the hexagonal system as very small, tabular crystals that reach up to 1mm in size and occurs either as single crystals or as stellate aggregates (Figure 24). There is a single cleavage on {001} (Refs 68, 69). The colour ranges from pale blue, bright blue to greenish blue and the crystals show a vitreous or earthy lustre. The hardness is 2 – 3 on the Mohs scale, the density is 3.80 g cm^{-3} and the streak is white, or sometimes bluish.

Associated minerals are uraninite, kamotoite-(Y), shabaite-(Nd), uranophane, masuyite, schuilingite-(Nd) and françoisite-(Nd).

This very rare mineral occurs only at the Kamoto East Open Cut in the Democratic Republic of Congo.

Fifty five approved minerals contain neodymium, but only six of these contain both neodymium and uranium.

Shabaite-(Nd) is named after the Shaba Province of the Democratic Republic of Congo where it was first found. It was identified as a new mineral in 1989 (Ref. 70).

It crystallises in the monoclinic system and occurs as rounded micaceous plates, flattened on {010} and elongated along [100] and in rosettes that can reach up to 5 mm in size. Crystals may be twinned on {001} and show one perfect cleavage on {010}. The hardness is 3.5 and the density is 3.03 – 3.23 g cm^{-3}. Crystals are often pale greenish yellow to pale green in colour and show a pearly lustre (Figure 25).

It occurs as a very rare secondary mineral in the oxidised zone of the Kamoto East Open Cut in the Democratic Republic of Congo where it is found associated with uraninite, kamotoite-(Y), astrocyanite-(Ce), françoisite-(Nd), schuilingite-(Nd), uranophane and masuyite.

Kamotoite-(Y). $Y_2(UO_2)_4(CO_3)_3O_4{\cdot}14H_2O$

Kamotoite-(Y) is one of four currently known naturally occurring minerals containing both yttrium and uranyl cations, the others being bijvoetite-(Y), alwilkinsite-(Y) and sejkoraite-(Y), the latter two of which are both sulphates rather than a carbonate like bijvoetite-(Y). Kamotoite-(Y) is named after the Kamoto East Open Cut in the Democratic Republic of Congo where it was first discovered (Refs 72, 72).

It crystallises in the monoclinic system and occurs as single crystals and commonly as divergent sprays or stellate aggregates of wedge-shaped bladed crystals that reach up to 2 cm in length; crystals are striated perpendicular to elongation [100] (Ref. 73). It also occurs as crusts of granular or very small crystals. Crystals show two cleavages on {010} and {001), both of which are good. The hardness has not been determined, but the density is 3.93 g cm^{-3} and the tenacity is sectile. Crystals are transparent to translucent and are bright yellow in colour. It effervesces strongly in dilute hydrochloric acid.

It occurs as a very rare secondary mineral in the oxidised zone of the Kamoto East Open Cut where it is commonly associated with uraninite, uranophane, rutherfordine, schoepite, kasolite, soddyite, curite, becquerelite, schuilingite-(Nd), françoisite-(Nd), shabaite-(Nd), astrocyanite-(Ce), masuyite,

malachite and pendevilleite-(Y) (Figure 26, this photograph was published in *Mineralogical Record*, Volume 20, Number 4, July-August 1989, page 281.).

Figure 26 Superb example of radiating sprays of lustrous yellow crystals of kamotoite-(Y) up to associated with small, white, spherical aggregates of extremely rare pendevilleite-(Y) from the Kamoto East Open cut, Kamoto, Mutshatsha, Lualaba, Democratic Republic of Congo. FoV 136 mm. *Paul de Bondt specimen and photo used with permission.*

Apart from the Kamoto East Open Cut, which produces the best crystals of this rare species, kamotoite-(Y) has also been found at the J. G. Gole Quarry in Canada, in Jáchymov in the Czech Republic, at the Sophia Mine in Germany, at the Bjertnes Pegmatite in Norway and at Les Esserts Gorges in Switzerland.

Uranyl Carbonates Containing Other Anions

This sub-group of carbonates includes a range of rare to very rare minerals including albrechtschraufite, schröckingerite, szilagyiite, lepersonnite-(Gd) and lepersonnite-(Nd). Of these, schröckingerite is the most abundant and best-known, but lepersonnite-(Gd) – and perhaps its neodymium analogue lepersonnite-(Nd), are well-known amongst collectors of rare uranium minerals because they are minerals in which usually less dominant rare earth elements are dominant.

Schröckingerite. $NaCa_3(UO_2)(CO_3)_3(SO_4)F{\cdot}10H_2O$

Schröckingerite is a hydrated sodium calcium uranyl fluoride, sulphate carbonate and is named for Baron Julius von Schröckinger (1813 – 1882) who first found the mineral as an alteration product of uraninite. It is related to the very rare mineral szilagyiite both chemically and structurally (Ref. 74).

Figure 27. Aggregate of superbly formed, pale yellowish green, transparent, pseudohexagonal crystals of schröckingerite. FoV is 2.7 mm.
Dr Travis Olds specimen and photograph used with permission.

It crystallises in the triclinic system as pseudo-hexagonal crystals (Figure 27) that reach up to 6 cm in size, but also occurs as micaceous or scaly crystals, as rosettes and globular aggregates and in crusts. The tenacity is flexible and the crystals show a perfect cleavage on {001}. The hardness is 2.5 on the Mohs scale and specimens show a strong greenish yellow fluorescence under UV illumination. Crystals are greenish yellow in colour and show a sub-vitreous lustre. It is an uncommon alteration product of uraninite in the oxidised zone of uranium deposits, and, like andersonite, it may be of post-mining origin.

Minerals that are commonly associated with schröckingerite include uraninite, dolomite, gypsum, andersonite, bayleyite, liebigite, swartzite and albrechtschraufite.

It is quite widespread in its occurrences, although the mines in Utah, USA and, to a lesser extent, several of the uranium mines in the Czech Republic, most notably the Svornost Mine, host nicely crystallised specimens of it. In the UK, it occurs at the Geevor Mine in Cornwall.

Lepersonnite-(Gd) $Ca(Gd,Dy)_2(UO_2)_{24}(SiO_4)_4(CO_3)_8(OH)_{24}{\cdot}48H_2O$ and Lepersonnite-(Nd) $Nd_4(UO_2)_{24}(SiO_4)_4(CO_3)_8(OH)_{28}{\cdot}48H_2O$

Lepersonnite-(Gd) (Ref. 75) and its neodymium analogue, lepersonnite-(Nd) (Refs 76, 77), are the only two known uranium minerals containing both carbonate and silicate anions and so are unique minerals. They are named for Jacques Lepersonne (1909 – 1997) from the Royal Belgian Museum for Central Africa. He was honorary head of the Department of Geology and Mineralogy at the museum

where the type specimens are preserved. The -(Gd) suffix was added in 1987 to be in line with the Levinson rules (Ref. 78) with the –(Nd) suffix for the neodymium-dominant analogue being adopted at the time the mineral was first described in 2025.

Both minerals crystallise in the orthorhombic system as mammillary crusts or spherical aggregates of radiating or acicular aggregates of long, thin, prismatic crystals that are formed from the hydration and oxidative weathering uraninite. Spherules of lepersonnite-(Gd) can reach up to 5 mm in diameter whilst those of lepersonnite-(Nd) are smaller. Often, broken spherules are found that comprise beautiful, radiating sprays of crystals. The hardness has not been determined, but the density is 3.92 – 4.02 g cm^{-3}. Crystals are transparent to translucent and are bright yellow in colour and commonly occur as radial to acicular aggregates composed of long prismatic, thin crystals (Figure 28 & Figure 29), as the products of hydration–oxidation weathering of uraninite.

Figure 28. Spherical and stellate aggregates of lepersonnite-(Gd) with small, bladed crystals of bijvoetite-(Y). FoV 13 mm. *Carsten Slotta photograph used with permission.*

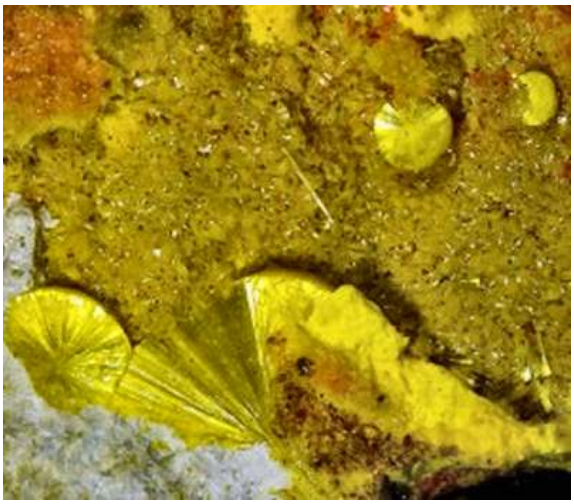


Figure 29. Radiating sprays of bright yellow, acicular crystals of lepersonnite-(Nd) associated with darker yellow soddyite, orange curite and white schoepite from Swambo Hill, Kambove Territory, Haut-Katanga, Democratic Republic of Congo. FoV 8.9 mm. *Eddy Van der Meersche photo used with permission.*

Associated minerals occurring with lepersonnite-(Gd) are uraninite, studtite, curite, becquerelite, fourmarierite, bijvoetite-(Y), uranophane and 'gummite', whilst other minerals associated with lepersonnite-(Nd) are curite and schoepite.

Lepersonnite-(Gd) occurs in the lower portion of the oxidation zone developed above uraninite-bearing dolomitic rocks at the Shinkolobwe Mine in the Democratic Republic of Congo, which is the only known location for it whilst lepersonnite-(Nd) occurs on a dolostone matrix at Swambo Hill, Kambove Territory, Haut-Katanga, Democratic Republic of Congo where it is associated with soddyite, swamboite-(Nd), curite, studtite, gold and quartz.

Szilagyiite, $NaCa_3(UO_2)(CO_3)_3(SeO_3)F(H_2O)_6$ and Borzęckiite, $Pb(UO_2)_3(SeO_3)_2O_2{\cdot}3H_2O$

Szilagyiite (Ref. 79) and borzęckiite (Ref. 80) are two of only nine known uranyl carbonate selenites. The former is named after Paul Szilagyi who helped collect the type material used for analysis and who also provided access to the Blue Streak mining complex. It occurs as rather dense yellow-green rosettes of transparent, tabular crystals that reach up to 1mm in size in which the individual tablets reach up to ~200 μm in size. The selenite anion is formed from the oxidation of ferroselite ($FeSe_2$) that occurs as small but dense areas of very small, grainy crystals in an asphaltite[7]-laden sandstone lens richly coated by andersonite [$Na_2Ca(UO_2)(CO_3)_3{\cdot}6H_2O$]. Szilagyiite crystallises in the trigonal system and is closely related to schröckingerite both chemically and structurally. It also shows some

7 A rock rich in bitumen.

chemical similarity to albrechtschraufite, $Ca_4Mg(UO_2)_2(CO_3)_6F_2{\cdot}17\text{-}18H_2O$. Crystals show one perfect cleavage on {001} and a vitreous lustre. It shows a pale yellow-green streak, has a density of 3.16 g cm^{-3}, a Mohs hardness of 2 – 3, the tenacity is brittle and the fracture is uneven/irregular.

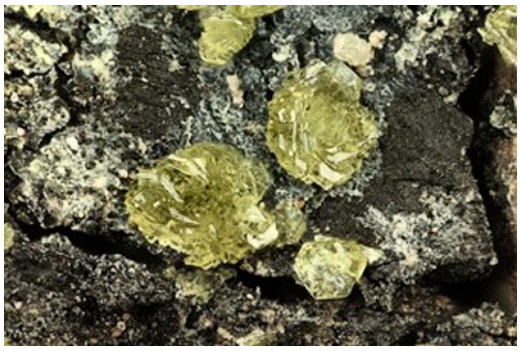


Figure 30. Yellow-green tablets and rosettes of szilagyiite to approximately 0.6 mm on an asphaltite coating on sandstone matrix from the Pickett Corral Mine, Montrose County, Colorado, USA. Dr Travis Olds photograph used with permission.

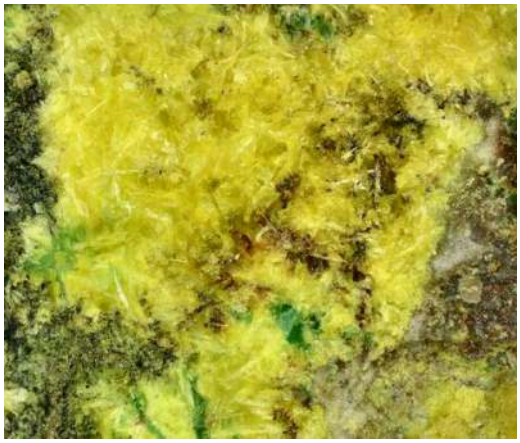


Figure 31. Aggregates of thin, yellow, bladed crystals of borzęckiite with white, acicular crystals of olsacherite from Burro Mine, San Miguel County, Colorado, USA. FoV is 1.2 mm. Dr. Alexander Matthies photo used with permission.

Szilagyiite is a very rare mineral and occurs only at the Pickett Corral Mine in Colorado, USA (Figure 30) where it is found associated with andersonite and magselite, $[Mg(H_2O)_6](SeO_3)$.

Borzęckiite is the Pb analogue of guilleminite, $Ba(UO_2)_3(SeO_3)_2O_2{\cdot}3H_2O$ and is named after Robert 'Redbor' Borzęcki, a well-known Polish mineral collector, museologist and an expert in the mining history of the Sudetes Mountains, where the type locality for the species is located. It was found on dumps near the No. 16 shaft of the Miedzianka Mine and crystallises in the orthorhombic system as translucent, pale orange-yellow crystals that show a vitreous lustre. Individual crystals are intergrown and lath-like reaching up to 6 µm in length and about 0.3 µm thick that form crusts and botryoidal aggregates up to 500 µm in diameter. It also occurs as veinlets that cut through oxidised uraninite-clausthalite masses. Structurally, it is related to marthozite, guilleminite and larisaite. The streak is pale yellow, the Mohs hardness is 2, the density is 5.277 g cm^{-3}, the tenacity is brittle and the fracture is irregular/uneven. It is non-fluorescent in both SW-UV (254 nm) and LW-UV (365 nm) illumination.

Associated minerals at the type locality include a chlorite group mineral, clausthalite, fourmarierite, native selenium, trögerite, uraninite, uranophane, olsacherite and digenite. Borzęckiite is somewhat more widespread than szilagyiite, occurring at four localities worldwide with the type locality being at Miedzianka, Gmina Janowice Wielkie, Karkonosze County, Lower Silesian Voivodeship, Poland. The other localities where it occurs at the Musonoi Mine in the Democratic Republic of Congo, La Creusaz Uranium Prospect in Switzerland and the Burro Mine in Colorado, USA (Figure 31).

Uranyl Phosphates & Arsenates

Of all the different anions, most collectors of radioactive minerals will have at least some uranyl phosphates and arsenates in their collection. Torbernite and metatorbernite are certainly amongst the best-known of the uranyl phosphates, whilst autunite and meta-autunite are the best-known of the uranyl arsenates. Uranyl phosphate minerals are formed through a combination of two mechanisms: precipitation and sorption. In the first of these processes, both uranyl cations and phosphate anions are required in the hydrothermal fluids, the combination of the two results in the formation of stable minerals. In the precipitation phase, when positively charged uranyl cations react with negatively charged phosphate anions under specific conditions, the lower solubility of the product causes precipitation, although there are a number of factors including temperature, pH and the presence of other minerals that govern at what point precipitation occurs. The resulting mineral then becomes sorbed onto nearby rock. In the sorption process. While native phosphorus does not occur in Nature, native arsenic does and this leads to a slightly different process for the generation of uranyl arsenate minerals than for uranyl phosphate minerals. In the case of uranyl arsenates, under oxidising conditions, arsenic is oxidised initially to arsenite (AsO_3^{3-}) anions which are then further oxidised to arsenate anions (AsO_4^{3-}). Under these oxidising conditions uraninite is also oxidised to the uranyl

cation, UO_2^{2+}. The two ions combine with hydroxide ions formed from water resulting in the formation of uranyl arsenate minerals. These minerals are only found in oxidising environments due to the oxidation processes required to generate the respective mobile cations and anions. Some of these minerals are widely distributed in Nature whereas other only occur at a single location. Due to its size, it is convenient to divide this group of minerals into four sub-groups; the autunite group, the phosphuranylite group; a group whose members are structurally related to walpurgite; a group whose members do not appear to be closely related to any of the three former groups. The autunite group is itself divided into two groups based on differences in crystal structure related to the degree of hydration. The most hydrated state remains as the autunite group whilst the lower hydration state is called the meta-autunite group. In cases where there is just a single lower hydration state, the 'meta-' prefix is used to differentiate the lower hydration state from the higher one. Some cases, however, are not quite so simple because there are several hydration states. Such minerals are identified by Roman numbers, an example of which is meta-uranocircite I and meta-uranocircite II.

Torbernite, $Cu(UO_2)_2(PO_4)_2{\cdot}12H_2O$ and Metatorbernite, $Cu(UO_2)_2(PO_4)_2{\cdot}8H_2O$

Torbernite and metatorbernite are, not surprisingly, named for the same person, Torbern Olof Bergmann [1735 – 1784). Bergmann was a Professor of Chemistry and Physics at the University of Uppsala, Sweden. Torbernite was discovered first in 1793, but it was not until 1916 that it was discovered that torbernite lost some of its water of crystallisation over time resulting in a mineral with the same chemical composition but a lower water content. This mineral became known as metatorbernite. The 'meta' prefix is an abbreviation of metamorphosed which indicates that a mineral has undergone a change, in this case the loss of some water.

Figure 32. Group of platy green torbernite/metatorbernite crystals from Old Gunnislake Mine, Clitters United Mines, Gunnislake, Calstock, Cornwall, England. The group as a whole measures 2.5 cm x 1.4 cm.
Alan Barnes collection and photo.

Torbernite (Ref. 81) is a member of the autunite group whereas metatorbernite is a member of the meta-autunite group. It crystallises in the tetragonal system as thin to thick, tabular crystals that can be square or octagonal with crystals reaching up to about 2.5 cm in size. It typically occurs in sub-parallel aggregates and also as foliated, micaceous or scaly aggregates. Twining is rare, but when it does occur, it is on {110}. Crystals are always green but can range from bottle green to pale green. The lustre can be vitreous, sub-adamantine, or waxy on cleavages. As dehydration progresses, the lustre becomes duller. Crystals show one perfect cleavage on {001}. The tenacity is brittle becoming more with increasing dehydration. The hardness is 2 – 2.5 on the Mohs scale and the density is 3.22 g cm^{-3}. The exact water content of torbernite varies with the relative humidity where it is stored. Torbernite does not fluoresce under UV illumination.

Minerals that are associated with torbernite include autunite, cuprosklodowskite, kasolite, malachite, metatorbernite, parsonsite, quartz, uraninite, uranophane, wulfenite and zeunerite.

Metatorbernite also crystallises in the tetragonal system (Refs 83, 84) and typically forms pseudomorphs after torbernite by a stepped dehydration process (Ref. 84). Square tabular crystals that are flattened on {001} and modified by {011} are well-known, but it can also occur as lamellar or sheaf-like aggregates, or as rosettes of crystals that can reach up to 2cm in diameter. There are two cleavages, one of which is perfect on {001} and one of which is indistinct on {010}. The tenacity is brittle and the hardness is 2.5 on the Mohs scale. The density is 3.52 – 3.70 g cm^{-3}. Crystals are pale to dark green in colour and transparent to translucent with a vitreous, sub-vitreous, sub-adamantine, resinous, pearly or waxy lustre. It does not fluoresce under UV illumination.

Minerals frequently associated with metatorbernite are albite, curite, heterogenite, kasolite, malachite, meta-autunite, parsonsite, phosphuranylite, quartz and torbernite.

Torbernite and metatorbernite are two of the most common of the secondary uranium minerals, along with autunite and meta-autunite. Torbernite (and metatorbernite) occur in 45 countries with the Democratic Republic of Congo and the United Kingdom producing the most desirable specimens for collectors. In the UK, the classic locality for torbernite is the Old Gunnislake Mine in Cornwall from which large, lustrous, platy green crystals can be acquired (Figure 32).

Autunite, $Ca(UO_2)_2(PO_4)_2{\cdot}10\text{-}12H_2O$ and Meta-autunite, $Ca(UO_2)_2(PO_4)_2{\cdot}2\text{-}6H_2O$

Autunite (Refs 85, 86) and meta-autunite (Ref. 87) are both formed under oxidising conditions in arsenic and uranium-bearing hydrothermal veins and in granitic pegmatites, autunite forming first and then slowly dehydrating to meta-autunite over time. Autunite was named by Henry James Brooke (1771 – 1857) and William Hallowes Miller (1801 – 1880) in 1852 for the type locality for the species at Saint Symphorien near Autun, France. Both species can occur in the same crystal form because the dehydration process involves the loss of water from the surface of the crystal leading to the inner parts of the crystal comprising autunite and the surface comprising meta-autunite. Given the striking similarity in the chemical formulae of torbernite and autunite (and their meta-derivatives), it is not surprising that they show similar physical properties.

Autunite crystallises in the tetragonal system transparent to translucent yellow to greenish yellow, thin to thick platy crystals that are tabular on [001] and with either a rectangular or octagonal outline. Crystals can reach up to 2 cm in size. It often occurs as sub-parallel growths, as foliated or scaly aggregates or as crusts. Crystals show one perfect cleavage on {001} and a second one on {100} that is indistinct. The hardness is 2 – 2.5 on the Mohs scale and the density varies with the degree of hydration, ranging from 3.05 – 3.2 g cm^{-3}. The lustre is vitreous but becomes duller on dehydration and the streak is yellow. Specimens show strong yellow-green fluorescence when illuminated with either SW-UV (254 nm) or LW-UV (365 nm) light.

The water content of meta-autunite has, in the past, resulted in a proposal to redefine the nomenclature of it because the water content (unlike meta-torbernite) is quite variable and ranges from 2 – 6 molecules of water per molecule of meta-autunite. There was a proposal to name $Ca(UO_2)_2(PO_4)_2{\cdot}6H_2O$ and $Ca(UO_2)_2(PO_4)_2{\cdot}2H_2O$ as meta-autunite-I and meta-autunite II respectively. To collectors wanting to label their specimens accurately, this generated a problem because the hydration of meta-autunite depends on humidity, Consequently, if a sample was analysed and found to contain 5 molecules of water per molecule of meta-autunite, how should it be labelled? Should it be labelled as 'meta-autunite I with some meta-autunite II', or 'meta-autunite pseudomorphing autunite', or just simply as 'meta-autunite'? What do you think? Bear in mind that because the water content of the specimen can vary with humidity levels, the composition is very likely to change throughout the year with varying humidity levels. Because of this, it would never be possible to accurately label a specimen based on this proposed nomenclature system and because of this, this proposal never really made any progress with being adopted by collectors. After all, who would want to have to change the mineral name for a specimen several times a year? Very few, the author suspects!

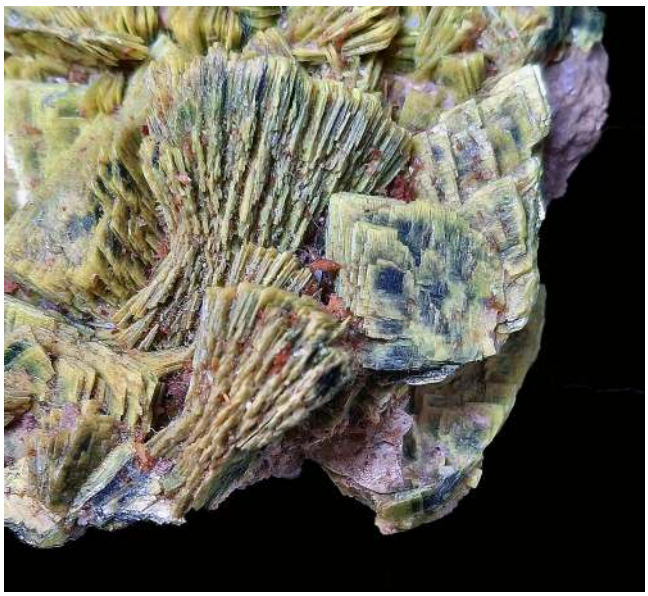


Figure 33. Wheat-sheath and platy aggregates of greenish yellow crystals of meta-autunite to 1.6 cm in size from Les Oudots Quarry, Marly-sous-Issy, Charolles, Saône-et-Loire, Bourgogne-Franche-Comté, France. Alan Barnes Collection and photo.

Would you do it? Consequently, the nomenclature for meta-autunite has remained at just 'meta-autunite' because it covers all possibilities for the varying degrees of hydration.

Minerals commonly associated with it include albite, 'gummite', meta-autunite, muscovite, phosphuranylite, quartz, sabugalite, saléeite, torbernite, uraninite, uranophane and uranophane-beta.

Autunite and meta-autunite are two of the most common uranium minerals and are very widely distributed, occurring in several hundred localities in fifty five countries. Whilst well-crystallised, good quality specimens can be obtained from many of these localities, Les Oudots Quarry and the Margnac II Mine in France and the Daybreak Mine in Washington, USA both respected amongst collectors for producing very high quality, rich specimens. Other classic localities include the Mounana Mine in Gabon, the Assunção Mine in Portugal and the Hagendorf South Pegmatite in Germany also giving high quality specimens, but there are many others too. In the UK, Merrivale Quarry in Devon, Wheal Basset in Cornwall are the two localities from where specimens are most highly sought after, but in total, autunite and meta-autunite occur at twenty localities in England and one in Scotland.

Bassetite, $Fe(UO_2)_2(PO_4)_2{\cdot}10H_2O$

Bassetite is an uncommon mineral that is found in the oxidised zones of uranium-bearing hydrothermal deposits. The classic, and type locality, for the species is Wheal Basset in Cornwall, England which has produced some very high quality specimens that are highly desirable to collectors and which consequently demand high prices. It is isostructural with other uranium minerals such as autunite, novacekite and saleeite and is a member of the autunite group of minerals.

Figure 34. Brownish orange to brown tabular crystals of bassetite crystals to 2 mm from Wheal Basset, Carnkie, Carn Brea, Cornwall, England.
Alan Barnes collection and photo.

Bassetite crystallises in the monoclinic system forming pseudotetragonal crystals that have a square or rectangular outline occurring as thin tablets that frequently form parallel or fan-like aggregates of crystals, the individual crystals of which do not generally exceed 3mm in size. Twinning is quite common in bassetite with two crystals growing at 90° with [001] of one crystal being parallel to [110] of the other.

Crystals show three cleavages, of which {010} is perfect and {100} and {001} both being distinct. The hardness is 2.5 and the density is in the range 3.40 – 3.63 g cm^{-3}. The density calculated from x-ray crystallography is 3.63 g cm^{-3}. The colour of bassetite crystals most commonly yellowish brown to brownish orange, yellow, or more rarely olive green, the lustre is typically waxy or sub-vitreous and the streak is pale yellow to greenish white. The tenacity is brittle and the fracture is micaceous.

Minerals commonly found associated with bassetite include uranospathite, torbernite, uraninite and pyrite at the type locality whereas at other localities it is associated with meta-autunite, torbernite, saléeite and metanováčekite.

Bassetite occurs at two British localities, Wheal Basset in Carnkie and South Terras Mine in St. Stephen-in-Brannel. It may also occur at Foggintor Quarry, Princetown, Devon. Other localities noted for producing high quality specimens include the Hagendorf South Pegmatite in Germany and Arcu su Linarbu in Italy.

Zeunerite, $Cu(UO_2)_2(AsO_4)_2{\cdot}12H_2O$ and Metazeunerite, $Cu(UO_2)_2(AsO_4)_2{\cdot}8H_2O$

Zeunerite (Ref. 88) is named after Gustav Anton Zeuner (1828 – 1907), a physicist and engineer who was working as the Director of the School of Mines, Freiberg, Germany when the mineral was first described. It is a member of the autunite group of minerals which have the generic chemical formula $A_{1\text{-}2}(UO_2)_2(BO_4)_2{\cdot}5\text{-}10H_2O$ where A = Cu^{2+}, Ca^{2+}, Ba^{2+}, Ni^{2+}, Mn^{2+}, Fe^{2+} or $(HAl)^{4+}$ and B = P or As. It is formed in the oxidised weathering zones of hydrothermal uranium deposits containing arsenic and primary uranium minerals such as uraninite. The crystal structure of zeunerite shows that the unit cell of zeunerite is made up of AsO_4^{3-} tetrahedra that are bonded to uranium-oxygen groups giving distorted octahedra. When many of these unit cells come together to give a highly ordered structure, the platy crystal habit of zeunerite becomes apparent along with the perfect cleavage on one crystal face and a distinct cleavage on another crystal face. Chemical analysis of zeunerite shows that there are twelve molecules of water for every unit cell of zeunerite, whilst the crystal structure shows that these water molecules are located in the interstices between neighbouring unit cells of zeunerite. However, because the water molecules are located in these interstices, they are not strongly bonded to any of the other atoms in the crystal structure. Consequently, they are easily lost and soon after a zeunerite specimen is collected, it starts to lose water and continues to do so over time leading to the formation of metazeunerite which is a member of the meta-autunite group that has the generic formula $A_{1\text{-}2}(UO_2)_2(BO_4)_2{\cdot}5\text{-}10H_2O$ where A and B are the same as for the autunite group. Specimens that were collected a long time ago are almost certainly metazeunerite, but by storing a zeunerite specimen in a sealed container it is possible to extend the time that it takes for it to completely change into metazeunerite. Both species crystallise in the tetragonal crystal system as square tabular to pseudo-cubic crystal or in sub-parallel aggregates. Whilst zeunerite crystals are usually transparent (Figure 35) to translucent and are emerald green to yellowish green in colour with a sub-vitreous, resinous or waxy lustre, metazeunerite crystals are almost always translucent to opaque (Figure 36) and range in colour from pale green to medium green with a vitreous, or more commonly, pearly lustre.

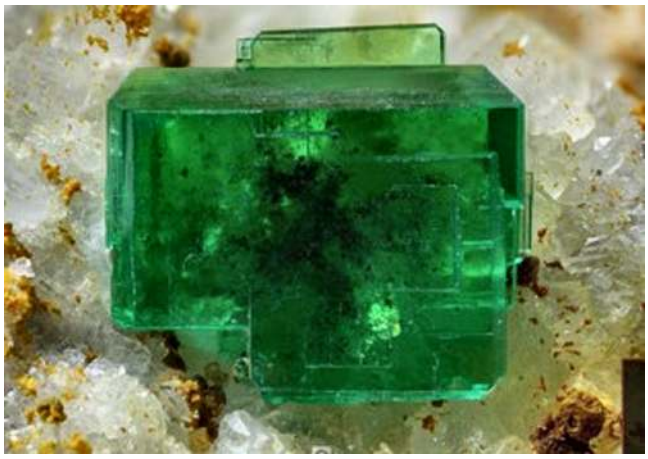


Figure 35. Transparent, green tabular crystal of zeunerite partially covered by blackish goethite measuring 2.8 mm x 2.0 mm across from Rocche Grana Quarry, Montoso Quarries, Bagnolo Piemonte, Cuneo Province, Piedmont, Italy.
Pasquale Antonazzo specimen and photograph used with permission.

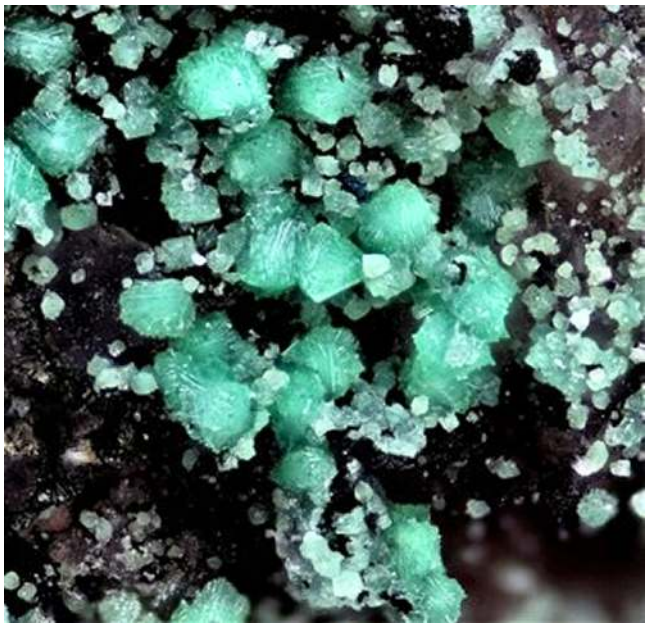


Figure 36. Pale green aggregates of metazeunerite showing sub-parallel growth of crystals associated with asbolane, quartz and pyrite from South Terras Mine, St. Stephen-in-Brannel, Cornwall, England.
Steve Rust specimen and photo used with permission.

However, crystal clarity can never be used as a definitive means of distinguishing between the two species because zeunerite can sometimes be translucent to opaque whilst metazeunerite can occasionally be transparent (Figure 37). Zeunerite crystals can reach up to 4 cm in size, but this is very rare; more commonly the crystals are 1-5mm in size. Both zeunerite and metazeunerite show a pale yellow-green fluorescence in both long wave and shortwave UV and both are soluble in acids.

Figure 37. Unusually partially transparent, flat, tabular green transparent metazeunerite crystals to approximately 1 mm from the Schmiedestollen dump, Wittichen, Black Forest, Baden-Württemberg, Germany.
Carsten Slotta photo used with permission.

Whilst zeunerite is a member of the autunite group of minerals, metazeunerite is a member of the meta-autunite group. Other examples of the autunite group include:
autunite [$Ca(UO_2)_2(PO_4)_2.10\text{-}12H_2O$,
uranospinite [$Ca(UO_2)_2(AsO_4)_2.10H_2O$],
uranocircite [$Ba(UO_2)_2(PO_4)_2.10H_2O$)],
rauchite [$Ni(UO_2)_2(AsO_4)_2.10H_2O$] and
torbernite [$Cu(UO_2)_2(PO_4)_2.12H_2O$] to name but a few of this group of thirteen minerals.

The meta-autunite group, includes:
metazeunerite [$Cu(UO_2)_2(AsO_4)_2{\cdot}8H_2O$],
meta-uranocircite [$Ba(UO_2)_2(PO_4)_2{\cdot}7H_2O$],
metarauchite [$Ni(UO_2)_2(AsO_4)_2{\cdot}8H_2O$] and
metatorbernite [$Cu(UO_2)_2(PO_4)_2{\cdot}8H_2O$]. The term 'meta' is used to indicate 'less water'.

Both zeunerite and metazeunerite can be found associated with other arsenate minerals such as olivenite, scorodite, heinrichite and mansfieldite as well as with other copper minerals such as azurite and malachite or iron minerals such as hematite and goethite. Quartz, and baryte are all common gangue mineral associated with (meta)zeunerite.

Zeunerite and metazeunerite sometimes described as being rare minerals, but they are found at over 230 localities worldwide. Some of the most important localities for specimens of these minerals are the Schmiedestollen dump in the Black Forest of Germany (Ref. 89), the Majuba Hill Mine in Nevada (Ref. 90), USA and the Rabéjac Uranium deposit in Lodève, France (Ref. 91). Metazeunerite can be found in the United Kingdom in Cornwall and the Dumfries and Galloway region of Scotland (Ref. 31). Important Cornish localities include Wheal Edward (Ref. 52), Ting Tang Mine (Ref. 92) and South Terras Mine (Ref. 52).

Uranium Silicates

Uranyl silicates are some of the most abundant uranium minerals in oxidised parts, in other words the supergene zone, due to the widespread distribution of Si^{4+} in the earth's crust together with of the relatively low solubility of uranyl silicates in most groundwaters and the relative ubiquity of dissolved silicates in these groundwaters. It is due to these three facts that the uranyl silicates formed are very stable and rarely alter into other species. For example, unlike minerals such as torbernite and autunite that readily partially dehydrate to form metatorbernite and meta-autunite respectively, hydrated uranyl silicates do not dehydrate. Uranophane, for example, does not partially dehydrate into 'meta-uranophane'.

Uranyl silicates do not show wide variations in their crystal structures and this leads to them being classed in one of three groups; the uranophane group, the weeksite group and the sklodowskite group, the latter of which is related to the uranophane group. The members of the uranophane group are hydrated uranyl silicates with the following generic formula: $A[(UO_2)(SiO_4)]{\cdot}nH_2O$, where A = Pb^{2+}, Ca^{2+}, K, Na, Cu^{2+}, Mg^{2+}, Co^{2+} and U^{6+}. In this case the U:Si ratio is 1:1. Minerals in the uranophane group include uranophane, kasolite, sklodowskite, cuprosklodowskite, boltwoodite, oursinite, swamboite-(Nd) and parauranophane. The sklodowskite group has the general formula $A(UO_2)_2(SiO_3OH)_2{\cdot}6H_2O$ where A = Mg^{2+} or Cu^{2+}. In terms of stability, the sklodowskite group minerals are resistant Similar to the uranophane group. However, there is also a group of minerals known as the weeksite group in which the U:Si ratio is 1:2.5. Members of the weeksite group have the general formula $M(UO_2)2(Si_6O_{13}){\cdot}nH_2O$ where M = Ca^{2+}, Mg^{2+}, K^+ or, Na^+ and n = 4 – 5, The weeksite group minerals are rarer than those of the uranophane group and possibly form from silica-rich

waters of relatively high pH in which dissolved polymeric silicate species could potentially reach fairly high concentrations. The most uranium-rich uranyl silicate mineral is soddyite with a U:Si ratio of 2:1 whilst the most silica rich example is uranosilite which has a U:Si ratio of 1:1.7.

Coffinite, $U(SiO_4)\cdot nH_2O$

Coffinite (Ref. 93) is the simplest of all of the uranium silicate minerals and is named after Reuben Clare Coffin (1886 – 1972) for his outstanding contributions to the geology of southwestern Colorado. It is not a uranyl silicate but is instead a uranium silicate because it is not formed from any oxidative process. The chemical formula may look simple and infra-red spectroscopy has shown that coffinite contains molecular water, leading to the currently accepted formula of $U(SiO_4)\cdot nH_2O$. In reality though, the presence of water makes coffinite much more complex than if the water was not present. The variable water content in coffinite is due to the alteration of lower hydrates. It is this variation in water content that has led to the currently accepted chemical formula for coffinite being defined by the 'nH_2O' notation. This variability makes structural investigations on coffinite more challenging (Ref. 94) and this has led to the suggestion that the composition of coffinite may contain hydroxide groups leading to the slightly more complex formula $(U^{4+},Th)(SiO_4)_{1-x}(OH)_{4x}$ in which there are no bonded water molecules. The identification of hydroxide groups has been determined by infra-red spectroscopy. The anhydrous, pure uranium end-member of the coffinite-thorite solid solution series is the uranium analogue of zircon and, as such, it is isostructural with both thorite and zircon and crystallises in the tetragonal system. Coffinite often contains ZrO_2 in concentrations of up to 13.8% and yttrium oxide, Y_2O_3, in concentrations of up to 3.4% (Ref. 95). Coffinite occurs most commonly in aggregates of extremely fine crystallites, but can also occur as very small, granular crystals that rarely exceed 200 μm in size, as aggregates of granular crystals (Figure 38), as colloform to botryoidal encrustations, or in the massive state. The crystalline forms of coffinite can be metamict. Although never aesthetic, very rich specimens can be acquired with relative ease. The colour is black, the hardness is 5 – 6 on the Mohs scale and the mineral shows a dull to adamantine lustre. It shows an irregular to sub-conchoidal fracture and the tenacity is brittle.

Figure 38. An abundance of very small black grains and two well-formed black microcrystals (upper left and lower right) of coffinite on a quartz matrix from Homestake Mine, Lisbon Valley Mining District, San Juan County, Utah, USA. FoV 2.7.mm. Alan Barnes collection and photo.

Minerals that are commonly associated with coffinite are uraninite, thorite, pyrite, marcasite, roscoelite, quartz and clay minerals. Amorphous organic matter can also be associated with coffinite.

Coffinite is found in 52 countries, but the most popular localities for collectors are several of the mines in Wyoming, Colorado and Utah in the USA, although Morbihan in France has produced aggregates of coffinite that are as aesthetic as coffinite gets. In the UK, coffinite occurs at Geevor Mine, South Terras Mine and South Crofty Mine in Cornwall, UK (Ref. 96).

Coffinite is the exception to the rule by not forming well-formed crystals because all of the other uranium silicates form very attractive, well-formed, brightly coloured minerals that are more appealing to collectors. Some of the better-known uranium silicates are all uranyl silicates and include minerals such as uranophane, parauranophane, boltwoodite, kasolite, sklodowskite, cuprosklodowskite, soddyite, oursinite and swamboite-(Nd).

Soddyite, $(UO_2)_2(SiO_4)\cdot 2H_2O$

Soddyite (Ref. 97) is named in honour of the British physicist and radiochemist Frederick Soddy (1877 – 1956). Soddy received the Nobel Peace Prize in 1921 for his work on radioactive decay and isotopes. Soddyite is one of only two known uranyl silicates that does not contain other metal cations, the other one being uranosilite.

Figure 39. Groups of blocky brownish yellow crystals of soddyite with platy green crystals of metatorbernite and minor orange curite from Shinkolobwe Mine, Shinkolobwe, Kambove Territory, Haut-Katanga, Democratic Republic of Congo. Filed of view 4.1 mm.
Elmar Lackner photo used with permission.

Soddyite crystallises in the orthorhombic system and typically forms blocky pyramidal crystals (Figure 39) or elongated prismatic crystals to 3 mm, both of which occur in sub-parallel groups or divergent clusters. It also occurs more rarely in platy or fibrous crystals and in the massive state. Crystals show one perfect cleavage on the {001} plane and a second, good cleavage on {111}. The measured density ranges form 4.36 – 4.70 and the hardness is 3.5. Crystals can be amber to yellow in colour, although greenish yellow crystals are also known and the lustre ranges from transparent to translucent with a vitreous to adamantine lustre. Regardless of the crystal colour, the streak is always pale yellow. Massive soddyite shows an earthy lustre.

Minerals that are commonly associated with soddyite include kasolite, sklodowskite, cuprosklodowskite, uranophane, torbernite, curite, heterogenite, swamboite-(Nd), rutherfordine, billietite and digenite.

Soddyite occurs at over fifty localities in 19 countries with the classic localities for it all being in the Democratic Republic of Congo and these are; Swambo Hill, Shinkolobwe Mine, Musonoi Mine and the KOV Open Pit (Ref. 98). Some of the other localities that produce nicely crystallised specimens include Arcu su Linnarbu in Italy and the South Alligator River in Australia.

Uranophane, $Ca(UO_2)_2(SiO_3OH)_2\cdot 5H_2O$ and Parauranophane, $Ca(UO_2)_2(SiO_3OH)_2\cdot 5H_2O$

The name uranophane reflects its chemical composition of uranium and the Greek word *φαίνεσθαι* '*phainesthai*' which means 'to appear'. It used to be called uranotile and some old specimens may still show this name. Uranophane and parauranophane have the same chemical formula and are dimorphous, both crystallising in the monoclinic system (Refs 99, 100). Parauranophane was formerly known as uranophane-β, although other variations of the name such as β-uranophane and uranophane-beta have also been used, but the IMA decided to eliminate the use of multiple names for this species by changing the name to parauranophane in 2022, although older labels will still show the former nomenclature. Similarly, uranophane has also been known as uranophane-alpha and some older labels may still use this name, although it is now more common to refer to it simply as uranophane.

Uranophane occurs in both crystals and very commonly in the massive state as a common secondary mineral in uranium deposits and pegmatites. It is usually formed by alteration of uraninite but is also formed from the alteration of cuprosklodowskite such as at the Musonoi Mine in the Democratic Republic of Congo. Crystals are composite needles that are elongated on [010] and which can reach 1 cm or more in length, but can be either poorly developed, warped or bent. Stellate or spherical aggregates of crystals are not uncommon, especially when they occur as fibrous crystals, but crusts of felt-like crystals are also known (Figure 40). Crystals show a perfect cleavage on [100] and are commonly lemon-yellow to pale straw-yellow, or honey-brown in colour, but can also be greenish yellow, yellowish green or yellow-orange and are transparent to translucent. Crystals show a good

lustre which can be vitreous or pearly on the good cleavage, but otherwise greasy or silky. Massive uranophane shows a dull to occasionally waxy lustre. Uranophane crystals show a weak, green fluorescence under UV, but the massive mineral is generally not fluorescent. Minerals commonly found associated with uranophane include uranophane-beta, kasolite, phosphuranylite, meta-autunite and uraninite.

Figure 40. Spherical aggregates of pale yellow uranophane from Johannesschacht Mine, Wölsendorf, Schwarzach bei Nabburg, Schwandorf District, Upper Palatinate, Bavaria, Germany. FoV 1.5 mm. *Elmar Lackner photo used with permission.*

Uranophane is one of the most common secondary uranium minerals and is widely distributed with classic localities for it being the Madawaska Mine and the Faraday Mine, both of which are in Bancroft, Canada, and the Musonoi Mine, Kolwezi, Mutshatsha, Lualaba, Democratic Republic of Congo. At the Musonoi Mine in the Democratic Republic of Congo, cuprosklodowskite is quite commonly associated with uranophane where the latter is formed from the alteration of the former. In the UK, West Wheal Owles and Wheal Edward in Botallack, Cornwall are well-known localities for it. Merrivale Quarry in Whitchurch and Foggintor Quarry in Princetown are the only two known localities in Devon where it occurs, whilst in Scotland, the best-known locality is the Needle's Eye Mine in Dalbeattie, Dumfries and Galloway.

Parauranophane crystals are prismatic by extension on [100] and can reach up to 5mm in length with square cross sections, or flattened on [010], terminated by large {001}. Sub-radial to fan-like aggregates are not uncommon and velvety or bristly coatings are also known. Twinning is common on {001} with both contact and penetration twinning being known. Crystals show one perfect cleavage, the fracture is conchoidal and the tenacity is brittle. The density is 3.90 and crystals are quite soft with a Mohs harness of 2.5. Parauranophane fluoresces pale green under UV illumination. Crystals are transparent to translucent and are yellowish green to yellow in colour with a vitreous lustre, although aggregates tend to show either a silky, greasy or waxy lustre (Figure 41). Crushing of parauranophane crystals can result in its conversion to uranophane.

Figure 41. Parauranophane crystals to 3 mm from Rossing Uranium Mine, Arandis Constituency, Erongo Region, Namibia. FoV 1.4 cm. Alan Barnes Collection and photo.

Minerals commonly found associated with parauranophane are uraninite, uranophane, umohoite, calcurmolite, quartz, haiweeite, baryte, calcite and fluorite. Liebigite is another mineral that can be found associated with parauranophane.

Although parauranophane is not as abundant as uranophane, it is still fairly widespread occurring at 169 localities in 30 countries. The most important localities for it are: Teófilo Otoni, Minas Gerais, Brazil; Rossing Uranium Mine, Arandis Constituency, Erongo Region, Namibia (Figure 41); Madawaska Mine, Faraday Township, Hastings County, Ontario, Canada and the Krunkelbach Uranium Deposit, Menzenschwand, St. Blasien, Waldshut, Freiburg Region, Baden-Württembrug, Germany and the Johannesschacht Mine, Wölsendorf, Schwarzach bei Nabburg, Schwandorf District, Upper Palatinate, Bavaria, Germany (Figure 40). Whilst uranophane does occur in the UK, parauranophane does not.

Boltwoodite, $(K,Na)(UO_2)(SiO_3OH)\cdot 1½H_2O$

Boltwoodite (Refs 101, 102) is named in honour of Bertram Borden Boltwood (1870 – 1927) who was a professor of radiochemistry at Yale University, USA. Boltwood undertook a series of experiments to prove that uranium and radium exist in a constant ratio in unaltered minerals, the results of which supported those of Rutherford and Soddy who proposed a disintegration theory on the radioactive decay of uranium. Boltwood became friendly with Rutherford and this led to Boltwood spending a year at the University of Manchester, UK working with Rutherford between 1909 and 1910. On his return from Manchester, Boltwood was made professor of radiochemistry of Yale College, a position he held until his death in 1927. Probably Boltwood's most important contribution to radiochemistry was the discovery that geological time could be dated from the U-Pb isotope ratio; this is only possible because the rate of radioactive decay for any given isotope of an element is constant.

Boltwoodite forms in the outer silicate zone of alteration surrounding hydrated uranyl oxides from the oxidation and alteration of primary uranium ore minerals in silica-rich waters where it forms crusts, crystals or, much more commonly, aggregates of crystals on primary uraninite and also filling fractures in sandstones that may be some distance from primary uraninite. It is a sought-after mineral amongst collectors of radioactive species because of the beautiful aggregates of crystals it forms, especially at the Goanikontes Claim in Namibia where the orange crystals form a stunning contrast with the dark matrix.

Figure 42. Spherical aggregate of orange, bladed crystals of boltwoodite measuring 6 mm on brown to black calcite crystals from the Goanikontes Claim, Goanikontes, Arandis Constituency, Erongo Region, Namibia. Alan Barnes *collection and photo.*

Boltwoodite is isostructural with, and is a member of, the uranophane group of minerals. It crystallises in the monoclinic system as radiating acicular to thin, bladed crystals that are elongated along the [100] face plane. Crystals are commonly yellow but can also be orange-yellow to orange in colour with a lustre that ranges from sub-vitreous to waxy, pearly or silky, but in microcrystalline pseudomorphs the lustre tends to be dull or earthy. There are two cleavages, one of which is perfect and the other of which is imperfect. The hardness is 3½ – 4, the density is approximately 4.7 g cm^{-3} crystals fluoresce a dull green colour under both SW-UV (254 nm) and LW-UV (365 nm) illumination. The streak is white, the tenacity is brittle and the fracture is irregular to uneven.

Minerals commonly found associated with boltwoodite include gypsum, becquerelite, brochantite, uraninite, fourmarierite, phosphuranylite and fluorite.

Boltwoodite is a locally common mineral but is still relatively rare occurring in 82 localities in 27 countries. The type locality for the species is the Delta Mine in Emery County, Utah, USA where it occurs as wart-like aggregates of yellow fibres coating fractures in a sandstone matrix, but the Rossing Uranium Mine, Arandis Constituency, Erongo Region, Namibia is the best known locality amongst collectors for its high quality specimens (Figure 42).

Sklodowskite Group.

The sklodowskite group consists of sklodowskite, cuprosklodowskite and oursinite. Both sklodowskite and cuprosklodowskite share a similar uranyl silicate framework and, not surprisingly, form similarly shaped crystals. However, the Cu^{2+} ion in cuprosklodowskite undergoes a Jahn-Teller[8] distortion (Ref. 103) resulting in a lowering of crystal symmetry and coordination compared to sklodowskite in

8 For an explanation see: https://en.wikipedia.org/wiki/Jahn%E2%80%93Teller_effect or the glossary.

which the Mg^{2+} ion cannot undergo such distortion (Ref. 104). Both species give very well-formed crystals making them popular amongst collectors.

Sklodowskite, $Mg(UO_2)_2(SiO_3OH)_2 \cdot 6H_2O$

In Part 1 of this series of papers on uranium minerals, the pioneering work of Marie Curie and her husband Pierre was described. It was for this work that sklodowskite was named after Marie Curie, whose maiden name was Sklodowska (Ref. 105). Sklodowskite is a rare secondary mineral that forms by the chemical reaction of uraninite with silica rich waters, or by the reaction of these same waters with previously formed secondary uranium minerals in the surface zone of uranium deposits. It crystallises in the monoclinic system as acicular crystals showing prismatic terminations; crystals can reach up to 4 mm in size and which commonly form reticulated, divergent (Figure 43), or stellate aggregates, but it can also occur as granular crystals or massive. Crystals are usually transparent, but can be translucent, It is pale to lemon yellow or occasionally greenish yellow in colour. It fluoresces a bright green colour under SW-UV (254 nm). There is one perfect cleavage on the {100} crystal plane, the density is 3.54 g cm^{-3}, the Mohs hardness is 2 – 3 and the lustre is usually vitreous but can be adamantine or silky, but the massive mineral always shows an earthy lustre.

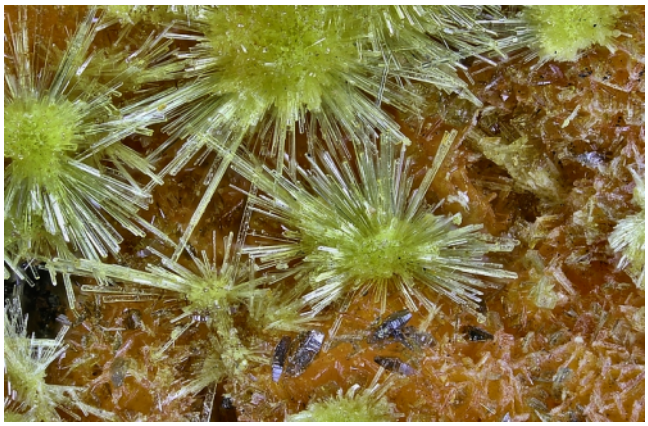


Figure 43. Sprays of yellow sklodowskite crystals with brownish crystals of soddyite on orange gauthierite. Shinkolobwe Mine. Kambove Territory, Haut-Katanga, Democratic Republic of Congo. FoV 3.6 mm.
Carsten Slotta photo used with permission.

Minerals commonly found associated with sklodowskite include kasolite, soddyite, torbernite, uranophane, parauranophane, nováčekite, metazeunerite and curite.

The most famous localities for sklodowskite are the Musonoi Mine, the Shinkolobwe Mine, the Kamoto East Open Cut and at Swambo Hill, all of which are in the Democratic Republic of Congo, but other well-known localities for it include the Clara Mine in Oberwolfach, Germany; the Jomac Mine in San Juan County, Utah, USA; the Paleokamariza Mine Number 18 in Plaka, East Attica, Greece and the Animas Mine, Chihuahua, Mexico.

Cuprosklodowskite, $Cu(UO_2)_2(SiO_3OH)_2 \cdot 6H_2O$

Cuprosklodowskite (Ref. 106) was named as the copper analogue of sklodowskite and was formerly called jáchymovite; significantly older specimens may still be labelled as such. It, like sklodowskite, forms in the superficial oxidation zones or uranium deposits, but in the case of cuprosklodowskite, copper-bearing primary ores are also present which become oxidised releasing soluble Cu^{2+} cations which then combine with previously formed secondary uranium minerals to generate cuprosklodowskite.

Figure 44. Spherical aggregates of pale green, acicular crystals. Musonoi Mine, Kolwezi, Mutshatsha, Lualaba, Democratic Republic of Congo. FoV 4.5 mm.
Alan Barnes collection and photo.

Cuprosklodowskite is often thought of as being the copper analogue of sklodowskite but whilst sklodowskite crystallises in the monoclinic system, cuprosklodowskite crystallises in the triclinic system forming pale to grass-green, acicular crystals that can reach up to 3 cm in length that are frequently somewhat flattened and elongated along the c-axis (Figure 44). It is, therefore, incorrect to state that cuprosklodowskite is the copper analogue of sklodowskite. Radiating groups of cuprosklodowskite

crystals are common and groups of matted fibres are known along with crusts of the massive mineral. Fibrous crystals can be almost white in colour. Thin, narrow bladed crystals are known and occur most commonly at the Musonoi Mine. Bladed crystals show a darker green colour than their acicular counterparts and both crystal habits are transparent to translucent with a lustre that is dull to silky in aggregates. Crystals show one cleavage. The Mohs hardness is 4 and the density is 3.85 g cm^{-3}. It is not fluorescent.

Minerals commonly found associated with cuprosklodowskite are uranophane, parauranophane, becquerelite, sklodowskite, torbernite and kasolite, whilst other minerals that occur less frequently with it are brochantite, rutherfordine, schoepite, vandenbrandeite, liebigite, billietite and compreignacite.

By far the most common locality for cuprosklodowskite specimens is the Musonoi Mine in the Democratic Republic of Congo from where spectacular specimens can be obtained. It also occurs more rarely at the Shinkolobwe Mine, Shinkolobwe, Kambove Territory, Democratic Republic of Congo, at the Posey Mine, Red Canyon Mining District, Utah, USA, at Rabejac Est in Occitanie, France, at the Zalesi Deposit in Czechia, at Val Daone Mine in Trento Province, Italy and at the La Virgen Mine in Andalusia, Spain. For collectors of British minerals, cuprosklodowskite occurs solely in Cornwall at Geevor Mine, West Wheal Owles (Ref. 52) and at Botallack Mine where it can be occasionally found in the small dump below the footpath leading to the Crowns Shaft engine houses.

Weeksite Group

The weeksite group of minerals have the generic formula $M(UO_2)_2(Si_6O_{15})\cdot nH_2O$ where M = K^+, Na^+, Ca^{2+} or Mg^{2+} and where n = 4 – 6. The two best-known members of this group amongst collectors are weeksite and haiweeite. These relatively rare minerals occur in arid environments that possibly result from the evaporation of silica-rich waters having a relatively high pH. In this case, dissolved polymeric silicate-containing species can reach quite high concentrations. As a good general rule, silicate minerals have very low solubilities in water and so once a silicate species like weeksite is formed, it is almost incapable of re-dissolving in fresh water. If, however, the water is free from carbonates, the weeksite group minerals may preferentially lose, for example, some calcium and some silicate ions leading to alteration to more uranium-rich species such as uranophane or soddyite. In more alkaline, carbonate-rich waters, however, these minerals can preferentially lose uranium and in so doing alter to either cryptocrystalline or amorphous silicas such as opal (Ref. 94). Minerals included in the weeksite group include haiweeite, meta-haiweeite and, of course, weeksite.

Weeksite, $K_2(UO_2)_2(Si_5O_{13})\cdot 4H_2O$

Figure 45. Radiating spray of bladed weeksite crystals to about 1.3 mm with two thin crystals of boltwoodite from Goanikontes Claim, Goanikontes, Arandis Constituency, Erongo Region, Namibia. *Elmar Lackner collection and photo used with permission.*

Weeksite (Ref. 107) is named after Alice Mary Dowse Weeks (1909 – 1988) who was a mineralogist for the USGS and who later became a professor of mineralogy at Temple University in Philadelphia, USA. In some respects, it is similar to zeolites in that under the right conditions the potassium ion can become labile and can therefore be substituted by other cations such as caesium, for example. The water content can vary depending on the relative humidity even at room temperature. It is a moderately rare mineral and occurs in opal veinlets in rhyolite, sandstones and limestones and agglomerates.

Weeksite crystallises in the monoclinic system as transparent to translucent, yellow, bladed (Figure 45) or acicular crystals that are elongated along [001] but it can also occur as flat, platy crystals or, more commonly, as spherical aggregates or radiating aggregates of fibrous crystals. Twinning in weeksite crystals is not uncommon and there are two good

cleavages. The crystal terminations on bladed crystals are prismatic. The Mohs hardness is 1-2, the density is 4.1 g cm^{-3} and the lustre is waxy to silky.

Minerals frequently associated with weeksite include opal, calcite, fluorite, gypsum, uraninite, thorogummite, uranophane, boltwoodite, carnotite and margaritasite.

There are currently fifty known localities for weeksite specimens with the Autunite No. 8 Claim, Topaz Mountain, Thomas Range, Juab County, Utah, USA being the type locality for the species. Other notable localities for it include the Goanikontes Claim in Namibia, the Margaritas Mines in Mexico and Mount Painter No. 2 workings in Australia with nicely crystallised specimens being obtainable from all three of these localities.

Haiweeite, $Ca(UO_2)_2[Si_5O_{12}(OH)]\cdot 6H_2O$

Haiweeite (Ref. 108) is quite a rare mineral that occurs on fracture surfaces in granite and in voids in nearby sediments. Some good quality specimens are found at Perus which is north of São Paulo, Brazil where the matrix is a tourmaline-containing granite. Gneiss is another rock on which haiweeite can occasionally be found such as at Bad Gastein in Austria and in the Hingyotoge deposit, Tottori Prefecture, Japan. It is named after the Haiwee Reservoir in California which is close to the type locality for the species.

Figure 46. A group of spherical aggregates of haiweeite crystals from Nopal Mine, Sierra Peña Blanca, Peña Blanca District, Aldama Municipality, Chihuahua, Mexico. FoV 4.5 mm. Elmar Lackner photo used with permission.

It crystallises in the orthorhombic system and occurs most commonly as very small, spherical aggregates of yellow to more rarely greenish yellow, bladed crystals (Figure 46) or as single granular crystals that appear as flakes that are flattened on {100}. Crystals show one good cleavage, have a hardness of 3.5, a density of 3.35 g cm^{-3}, are weakly fluorescent under UV illumination, the fluorescence colour being green and are translucent with a pearly lustre. The streak is white.

Minerals associated with haiweeite include autunite, meta-autunite, uranophane, parauranophane, phosphuranylite, torbernite, metatorbernite, chernikovite and a uranium-containing opal.

The type locality for the species is an unnamed uranium occurrence in Inyo County, California, USA, but other notable occurrences include the Rossing Uranium Mine in Namibia, the Nopal Mine in Mexico and Teófilo Otoni in Brazil.

Figure 47. Matted aggregate of yellow uranosilite crystals measuring 3 mm from the Krunkelbach Uranium Deposit, Menzenschwand, St. Blasien, Waldshut, Freiburg Region, Baden-Württemburg, Germany.
Thomas Prögler photo used with permission.

Uranosilite, $(UO_2)Si_7O_{15}$

Uranosilite (Ref. 109) is the most silica rich member of the uranophane group with a U:Si ratio of 1:1.7. It is an extremely rare mineral occurring at just two localities worldwide with the Krunkelbach Valley Uranium Deposit being the type locality for the species.

It crystallises in the orthorhombic system as small to very small, yellowish-white, acicular crystals that are only visible when viewed under magnification (Figure 47). Due to the extremely small crystal size, it has not been possible to physically determine a hardness or a

density, although calculations from the unit cell give a density of 3.25 g cm^{-3}. Crystals are semi-transparent and show a vitreous lustre.

Minerals associated with uranosilite include quartz, hematite, studtite and uranophane.

Other than the type locality, the only other confirmed locality for uranosilite specimens is Crucea in Romania, although it is possible that it also occurs at the Madison Lead Mine, in Madison, New Hampshire, USA.

Swamboite-(Nd), $Nd_{0.333}[(UO_2)(SiO_3OH)](H_2O)_{\approx 2.5}$

Although not part of the weeksite group, Swamboite-(Nd) (Refs 110, 111) is an interesting mineral on account of its somewhat unusual chemistry. It is the only rare earth uranyl silicate in which one rare earth cation (neodymium) is shared between three crystallographic unit cells. It was formerly known simply as swamboite after the locality from where it was discovered (Swambo Hill), but the IMA re-defined the name in 2017 to reflect the dominant rare earth cation (Nd). The crystal structure was also re-defined at about this time and was published in 2018. Specimens in collections obtained before these dates will almost certainly still show the previous name.

Figure 48. Swamboite-(Nd) with typically blocky crystals of orangey-yellow soddyite from Swambo Hill, Democratic Republic of Congo. FoV 12 mm. Paul DeBondt specimen and photo used with permission.

It crystallises in the monoclinic system forming deep to pale yellow acicular crystals that reach up to 1mm in length and which occur both as single crystals and as nodular fibrous aggregates (Figure 48). The Mohs hardness is 2.5 and the density is 4.0 g cm^{-3}.

Minerals frequently found associated with swamboite-(Nd) are gypsum, soddyite and curite.

Swamboite-(Nd) is a very rare mineral that occurs at only three localities worldwide. The locality from where specimens are most frequently collected at the type locality at Swambo Hill, Kambove Territory, Haut-Katanga, Democratic Republic of Congo. The two other localities at which it occurs are the Jomac Mine in San Juan County, Utah, USA and the Lagoa Real Uranium Province in Bahia, Brazil.

Conclusions

In this paper, an insight into just a few of the minerals of thorium and uranium has been given with the main focus being on secondary uranium minerals such as hydrated oxides, carbonates, phosphates and arsenates, and finally silicates with the aim of giving the reader at least a brief introduction to the extensive chemistry or uranium and thorium.

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A glossary of some of the more technical and descriptive terms used in this article is given below.

Glossary

Acicular:	shaped like needles.
Adamantine:	diamond-like lustre.
Alpha-radiolysis:	the breakdown of water by highly ionising alpha radiation into highly reactive chemical intermediates that form, amongst other species, hydrogen peroxide.
Amorphous:	without any clearly defined shape or form.
Anhedral:	minerals that show no crystal faces.
Anion:	a negatively charged anion. Chloride and sulphate are both anions.
Anthropogenic:	formed by the influence of human beings on nature.
Back Scattered Electron (BSE):	Once of the techniques used in scanning electron microscopy (SEM).
Botryoidal:	a habit similar to that of a bunch of grapes.
Carbonatite:	types of intrusive or extrusive igneous rocks having a carbonate content of greater than 50%.
Cleavage:	refers to the tendency of a crystalline substance to split into fragments along specific planes of weakness in its structure.
Cleavage plane:	a flat surface along which a mineral naturally splits.
Colloform:	a mineral that resembles a colloid and, more specifically, one that has a botryoidal (grape-like), mammillary (rounded) or internally concentrically banded structure.
Conchoidal:	a conchoidal fracture is one where a mineral breaks without following any natural planes of separation, unlike cleavage which occurs along specific crystal planes. A conchoidal fracture gives a surface that is smooth, curved and frequently concave that resemble the inside of s seashell.
Contact twin:	two or more crystals that share a common twin plane.
Crystal lattice:	the geometric arrangement of constituent atoms, ions or molecules in a crystalline solid. The lattice can be viewed as being an infinite array of points in three-dimensional space in which each point represents a lattice site occupied by an atom, ion or molecule. The entire crystal structure is formed by repeating this lattice pattern in all directions and over a long range.
Crystallite:	a very small crystal.
Dendritic:	having a branch-like appearance similar to that of a tree.
Detrital:	formed from pre-existing rock through weathering and erosion.
Dike:	a sheet of rock that is formed in a fracture of a pre-existing rock. A dike can be either magmatic or sedimentary.
Dimorph:	a property of a mineral that allows it exist in two distinct forms or crystal structures. Calcite and aragonite are dimorphs of one another, for example.
Divergent:	crystals that grow out of a central point in sprays are called divergent sprays.
Encrustation:	a crust or hard coating of a mineral on, for example, a matrix.
Equant crystal:	a crystal in which all of the sides are the same length, i.e. a cubic crystal.
Fracture:	the breaking of a mineral other than along cleavage planes. A mineral can be described in part by its characteristic fracture; examples are conchoidal and hackly.
Granular:	minerals that are comprised of particles or grains that are closely packed together into aggregates resulting in a grainy texture. Granular minerals often break into small, irregular fragments on breakage.

Gummite:	a mixture of uraninite and secondary uranium minerals of variable composition including uraninite, uranophane, soddyite, kasolite, curite, clarkeite and boltwoodite. It is not an approved mineral due to its variable composition.
Habit:	is the tendency of a mineral to repeatedly grow into characteristic shapes, the shape formed is largely influenced by the atomic structure of the mineral, but it can also be influenced by the environment in which the crystal grows.
Halide:	an anion of a halogen (F, Cl, Br, I, As). An example is a chloride anion (Cl^-).
Hydrothermal:	hot water (containing dissolved minerals).
International Mineralogical Association IMA:	is the largest organisation promoting mineralogy, coordinating mineral nomenclature and facilitating global collaboration among mineralogists. It makes the final decision as to decides whether a potentially new mineral is significantly different enough from any other known species in order for it to be declared a new mineral.
Interpenetrant twin:	a twinned crystal in which parts of the twin seem to intertwine to give an irregular or undefinable contact surface. Fluorite forms nice interpenetrant twins, but amongst radioactive minerals uranophane can form such twins.
Ionisation:	the dissociation of a mineral species into water-soluble ions.
Isomorphous:	two minerals that have the same crystalline form.
Isostructural:	minerals that have the same crystal structure but which may differ in chemical composition or cell dimensions.
Jahn-Teller distortion:	geometric distortion of non-linear molecules or complexes that removes electronic degeneracy, lowering the system's energy and symmetry. It involves atoms or molecules bonded to a transition metal ion such as Cu^{2+} on the z-axis plane with the bonds between the central metal ion and the atoms or molecules being either lengthened or shortened. If the bonds on the z-axis are lengthened, those on the x- and y-axes are shortened, and vice versa. It is this bond lengthening or shortening that results in the removal of electronic degeneracy and hence a lowering of the system's energy.
Kaolinised:	converted into kaolin claystone rich in kaolinite.
Labile:	chemical entities in a molecule that undergo rapid change, particularly in the ease of breaking and forming bonds are said to be labile. Water is an example of a labile molecule.
Lamellae:	small plates or flakes oriented into a structure that looks like gills.
Lamellar:	a sheet like structure.
Levinson rules:	a systematic nomenclature system for minerals with essential rare earth elements that names the mineral with a suffix showing the most abundant rare earth element in that mineral. Common suffixes are –(La) and (Ce). The suffix –(Y) is usually added to minerals in which yttrium is an essential element and although it's chemistry is very similar to that of most of the rare earth elements, it is not itself a rare earth element.
Lustre:	describes the light-reflecting characteristics of the surface of a mineral.
LW-UV:	long wave ultraviolet light, typically has a wavelength of 365 nm.
Massive:	a mineral that shows no crystalline form.
Microcrystalline:	crystals that are small that they can only be seen under the microscope.

Metamict:	a mineral that looks like a well-formed crystal but in which the crystal structure has been disrupted by radiation from contained or nearby radioactive atoms.
Molecular structure:	the three-dimensional arrangement of atoms within a molecule and the chemical bonds that hold them together
Monoclinic:	in a monoclinic crystal there are three axes of unequal lengths. Two of the angles between these axes, α and γ, are 90° whilst the third, β, is not 90°.
Monohydrate:	a mineral with just one molecule of water of crystallisation per molecule of mineral.
Opaline:	resembling the mineraloid opal.
Orthorhombic:	a crystal having a rectangular prism with a rectangular base.
Oxidation:	a process in which a substance reacts with oxygen and in so doing loses one or more electrons (LEO = **L**oss of **E**lectrons is **O**xidation).
Pegmatite:	An igneous rock with a very coarse texture.
Penetration twinning:	two crystals that grow through each other.
Polymetallic:	ores or deposits containing multiple commercially desirable metals. As an example, a polymetallic ore may include lead in the form of galena, zinc in the form of sphalerite, copper in the form of chalcopyrite, gold, or silver.
Precipitation:	a process in which a dissolved mineral solidifies to give crystals or masses of that mineral. Precipitation occurs either when the solution becomes over-saturated with the mineral. This usually happens when the solution cools.
Prismatic crystal:	a crystal with one dimension markedly longer than the other two. Beryl forms good prismatic crystals.
Pseudohexagonal:	minerals that show a hexagonal habit without having hexagonal symmetry.
Pseudomorph:	A mineral with the external crystal form of one mineral but the internal chemistry of another mineral.
Pyramidal:	a crystal habit dominated either by pyramids or bipyramids.
Reniform:	kidney-shaped.
Resinous:	resembling resin, like amber.
Reticulated:	aggregates of crystals intersecting in several directions giving a net-like appearance. Cerussite sometimes forms exquisite reticulated aggregates.
Scanning Electron Microscopy (SEM):	a powerful technique for examining exceptionally small crystals that uses a focussed beam of electrons to produce high-resolution images showing the composition, structure and surface topography of a material.
Sectile:	a property of a mineral that allows it to be cut with a knife (argentite) or shaved giving a curled off-cut (gypsum).
Serpentinite:	metamorphic rocks composed predominantly of serpentine group minerals formed by the serpentinisation of mafic or ultramafic rocks. Serpentines tend to look like snake skin and the name may be derived from the word serpent meaning snake.
Solid solution:	a mixture of two or more minerals that form a single crystal structure.
Sorption:	explains how minerals interact with a the minerals in a host rock leading to the formation of mineral deposits on the rock. Factors that affect sorption include pH, ionic concentration, the nature of the sorbing chemicals and the presence of organic matter in the solution.

Specific gravity (SG):	a dimensionless ratio that compares the density of a substance to the density of a reference material (usually water for liquids and solids).
Stellate:	star-like.
Streak:	the colour of the powder left behind when a mineral is abraded on a ceramic plate.
Striated:	lines on a crystal face caused by the juxtaposition of two crystal faces. This occurs when one face gets truncated or overtaken by another one leaving a line in the crystal face. This is repeated as the crystal grows giving rise to a series of lines on a crystal face. Pyrite sometimes shows striated faces.
Sub-adamantine:	lustre that is almost as good as diamond, but not quite as intense.
Sub-conchoidal:	a sub-conchoidal fracture is similar to conchoidal fracture, except that it has less-pronounced curvature.
Subhedral:	a crystal that shows some characteristics of the ideal crystal shape but is not fully developed due to spatial/environmental constraints during crystal growth.
Sub-parallel aggregate:	a group of mineral grains or crystals that are aligned in roughly the same direction, but which are not perfectly parallel.
SW-UV:	short wave ultraviolet light, typically has a wavelength of 254 nm.
Tenacity:	the resistance of a mineral to breaking, bending or deformation.
Termination:	the endpoints or geometric shapes formed at the top of a crystal structure, influencing its overall appearance and properties. The terminations can vary significantly and are dependent on several factors such as the chemical composition of the crystal, its growth environment, and external conditions during formation.
Tetragonal:	tetragonal crystals have three mutually perpendicular axes, two of which are of equal length forming a square base with the third axis being of different length giving rise to a rectangular prism. Zircon forms nice tetragonal crystals
Tetravalent:	a cation having a charge of 4^+.
Translucent:	semi-transparent.
Trigonal:	often considered to be a member of the hexagonal crystal system trigonal crystals are characterised by a principal three-fold axis of rotation, in other words the crystal can be rotated by 120° around this axis to produce an indistinguishable crystal face
Trivalent:	a cation having a charge of 3^+.
Twinning:	an intergrowth of two separate crystals that are tightly bonded to each other. The surface along which the lattice points are shared in twinned crystals is known as a composition surface or a twin plane.
Unit cell:	the smallest unit possessing all of the defining characteristics of a mineral species.
Unit cell parameters:	these define the geometry of the unit cell in a crystal lattice, including the edge lengths (a, b, c) and angles (α, β, γ).
Uraniferous:	containing uranium.
USGS:	United States Geological Survey.
Vitreous:	glass-like.
Water of crystallisation:	water molecules that are chemically integrated into the crystal structure of a compound, usually in a fixed ratio , or sometimes a narrow range stoichiometric ratios.

Zeolites: a group of several microporous, crystalline aluminosilicate minerals consisting mainly of silicon, aluminium, and oxygen. Gyrolite ($NaCa_{16}Si_{23}AlO_{60}(OH)_8{\cdot}14H_2O$) is an example of a zeolite.

Zoned/zoning: A systematic variation in the composition and/or other properties of a single crystal that occurs due to a separation of the chemical components of the crystal during its growth.

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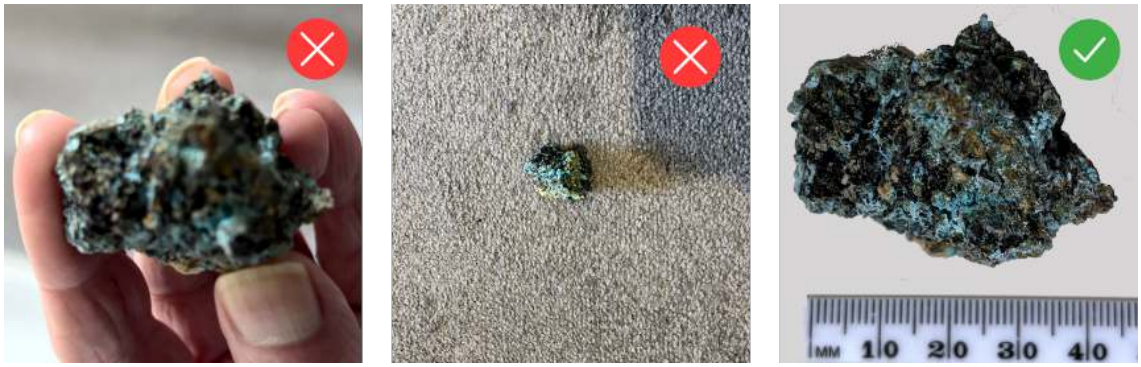

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