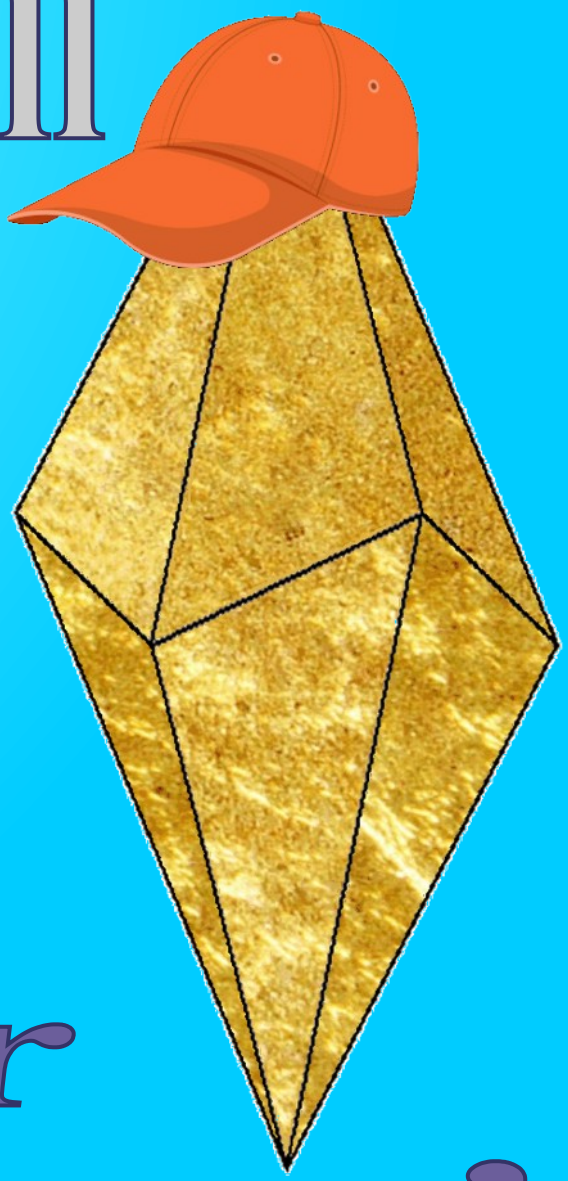
The Russell Society



Junior Members' Magazine

Issue No. 3 March 2026

CONTENTS

The Page numbers here link to bookmarks within the magazine, just click to go to the page. You can return to this page using the link (*Contents*) located in the footer of each page.

FROM THE EDITOR

Welcome to the third edition of the JMM

This Juniors Members' Magazine (JMM) was originally produced specifically for the younger members of The Russell Society who are mostly just beginning their journey into the hobby of mineral collecting and learning more about the wonderful minerals that nature creates. Junior Members are disadvantaged by the fact that insurance and health and safety restrictions mean that they are not able to join in many of the Society organised field trips for mineral collecting, thus we felt that they deserved something else to engage them and help them grow their interest in preparation for the time that they are able to fully participate in Society activities. Originally the JMM was only made available to Society members via the secure page of our website and thus not widely available to any other interested young persons or anybody just starting out on their mineral collecting hobby.

A member of The Russell Society and of the Geologists' Association pointed out to me that there were young people who were members of "Rockwatch", the UK's nationwide geology club for children run by the GA, who have an interest in minerals and would possibly benefit from having this publication made available to them. These young people are potentially the future of the Russell Society and we felt that we should encourage all those who collect and study minerals. To this end all editions of the JMM are now free to download from the Society website at https://russellsoc.org/junior-magazines. Please tell you friends who might be interested and pass on the knowledge. Rockwatch have publicised the JMM on their website and in their magazine so we hope to reach out to and engage with a much greater audience.

The Society and many of its individual members spend their time at shows and events publicising the Society and promoting the interest in mineralogy and minerals. We have all found that there has been a resurgence of interest in the hobby with many people now with a genuine interest in the subject. This is very pleasing and, if we can encourage this, it will be of benefit to all the organisations who cater for the hobby and further our knowledge and the preservation of our mineralogical heritage. Thus I welcome you all to the third edition of the Junior Members' Magazine.

In this issue we are looking at some of the different aspects of mineral collecting and study. Roy Starkey has shared his considerable experience in the, very popular, subject of "Micromounting" and the study of small, but perfect, mineral specimens.

Michael Dunmore has produced an article on the ways of viewing and photographing these tiny specimens using the now widely available digital microscopes and I have compiled an article on optical stereo microscopes that can enable you to take the hobby to new dimensions and open up a whole new world of amazing minerals. Some of these are illustrated in some wonderful images produced by Dr David Green.

Phil Taylor continues his fascinating series on *Rocks and Minerals through Time and Space* which now brings us closer to Earth with the formation of our Moon from a cataclysmic collision of two planets some 4.53 billion years ago.

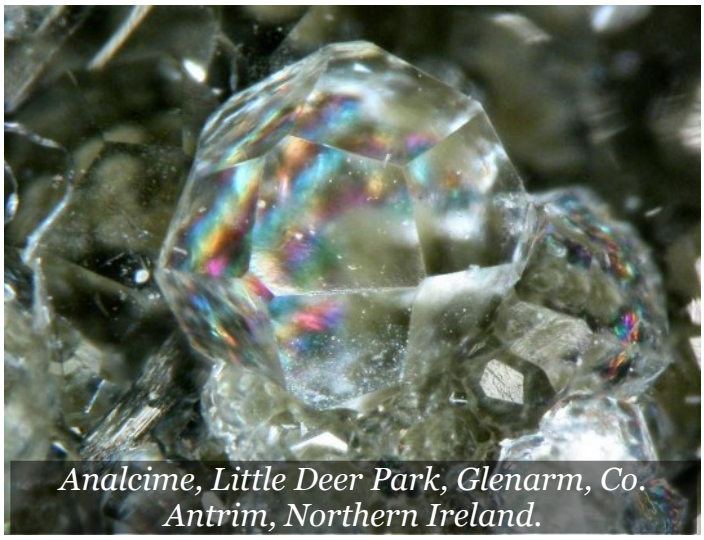
Alan Barnes has put together a superb, and very detailed, article on radioactivity and radioactive minerals with both their chemistry and occurrence. Don't worry if you find it too technical for you, learning must begin somewhere and radioactive mineral collecting is an unusual aspect of the hobby that some take a great interest in.

I welcome feedback on articles in the JMM. 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.

Gary Morse, Editor.

Amazing Minerals

In the last issue of the JMM we looked at the spectacular, huge crystals of minerals that nature forms when given the time and right conditions. These are exceptionally rare and the chances of finding one are even rarer. What nature also does is produce small, but perfect examples. In this edition of the JMM we will be looking at micro-minerals and the ways we can enjoy these wonderful creations. Within The Russell Society and the wider mineral collecting community there are some very skilled people who have the equipment to find, identify and photograph these miniature wonders, some even rendered in 3D. Here are some micro-minerals photographed by Dr David Green.



Analcime, Little Deer Park, Glenarm, Co. Antrim, Northern Ireland.

Anatase, Tan-y-grisiau, Gwynedd, Wales.

Azurite, New Cliffe Hill Quarry, Stanton under Bardon, Leicestershire.

Calcite, Whitesmith Mine, Strontian, Loch Sunart, Highland, Scotland.

Eulytine, Buckbarrow Beck, Waberthwaite, Copeland, Cumbria.

Aspects of Mineral Collecting

In Issue 1 of this magazine we gave a list of the various types of mineral collecting with ten different more specialist aspects of the hobby that are practised by many mineral collectors worldwide. In this issue we have taken some of these categories of mineral collecting and, with the help of people who engage in them, give you an insight into these options for specialisation in your mineral collecting hobby.

Micromounting

Micromounting is a term used by mineral collectors to describe the practice of acquiring, identifying, preparing, mounting for examination and studying, small but perfect, mineral specimens. The finished specimen is called a micromount. These micromount specimens can only be appreciated using magnification, as a minimum a 10x hand-lens or usually a stereo-microscope that can magnify up to around 40x with a zoom. Microscopes are discussed later. Micromount specimen collecting has a number of advantages over collecting larger specimens. One benefit of a micromount collection is that you can amass a large collection of specimens that will fit into a relatively small space and cost a lot less than larger display specimens. Some minerals are only found as microscopic examples and these need magnification for identification. It is a fact that usually small crystals can be more perfectly formed and some exhibit properties not seen in larger examples of the same mineral. Finally there is that thrill of discovering a small, aesthetically pleasing specimen and the satisfaction of preparing and preserving it for future enjoyment by yourself and others.

Mimetite from Dry Gill Mine, Caldbeck, Cumbria, England.
Specimen and photograph © David Green.

Hope's Nose, Torquay, Devon dendritic native gold specimen ≈ 7 mm long.
G. Morse specimen GM1135.

Below is a summary of micromounting together with links for you to discover more about this extremely interesting aspect of mineral collecting and study. There are no hard and fast rules to micromounting but good practice will give the best results and a more satisfying and scientifically important collection. The information published here has been kindly supplied by Russell Society member and founder of the British Micromount Society, Roy Starkey.

Making a Micromount Collection

Given the small size of the specimens (and sometimes fragility) involved, they are typically securely mounted inside small, transparent plastic boxes to protect them from damage and dust. There is a huge array of styles and sizes of boxes available. The one most commonly referred to is the hinged "Perky box" which was invented in 1960 by Willard Joseph "Perky" Perkin, a collector of small mineral specimens and dealer born in California in 1907. Typically boxes are around 2.5 cm square and of variable height to accommodate specimens. They are usually clear polystyrene with white or black bases. Boxes are widely available from online geological stores. When you have decided on a style of box for your specimens try and stay with it as it makes storage and labelling easier.

Some examples of plastic boxes that can be used for micromount specimens. The top left box is sometimes termed a "Perky box". The bottom left box has a lid with a built in magnifier.

Once you have started a micromount collection you will need suitable storage for the plastic boxes. As your collection will inevitably grow over time, a good system of storage will be

essential to be able to find specimens easily when needed. Many people use the A4, metal, multi-drawer, office stationery cabinets which will hold many hundreds of specimens. These can be picked up second-hand quite commonly from office clearance sales but are expensive new. Alternatively there are available stackable, clear plastic drawer units that work well and are relatively inexpensive.

Stackable, plastic drawer units.

There are two different methods for the preparation of micromounts. These are permanent mounts where the specimen is glued, sometimes on a small stand or pedestal, into its box and is never intended to be removed. The other is semi-permanent where the specimen is attached to the base of the box using suitable adhesive putty that will not degrade or damage the specimen. The following are instructions for the "traditional" permanent micromount.

One drawer of multi-drawer metal cabinet filled with micromount specimens.

Preparing Permanent Micromounts

The tools and materials required to prepare a micromount are neither expensive nor difficult to obtain. Many of the more useful items may already be available in your home. In the initial stages of forming a micromount collection it is possible to manage with a good 10x hand-lens. However, a suitable microscope is an essential possession for the full enjoyment of your specimens and should be acquired as soon as finances permit. We shall discuss the various microscope options later.

Another important consideration is a suitable workspace with a work bench, good lighting, power available and with space and drawers to leave and store equipment safely for ready use. The dining room table is not the best place to go trimming rocks on.

In terms of equipment, the following list may be considered to cover the bare essentials for traditional permanent micromounting of small specimens. You are free to adapt techniques or find tools that suit your adopted methods.

1. A good light source.
2. A good magnifier (10x hand-lens, digital microscope or stereo-microscope).
3. Forceps (tweezers) with both straight and curved tips.
4. Modelling knife or scalpel.
5. Micromount boxes.
6. Suitable material for pedestals (such as blackened balsa wood sticks or plastic rod).
7. Suitable clear organic solvent based adhesive (not "super glue").
8. Adhesive labels to suit the box size.

We do not intend to discuss in detail the various methods employed in the preparation of micromounts and there are many. Much information is available online about the various techniques that can be used.

The general procedure for preparing a permanent micromount is described below:

1. Examine your specimens of interest under magnification with a hand lens or low power microscope to identify any areas with suitable specimens present.
2. Once identified carefully trim away any waste material around it using different tools and techniques depending on the size, fragility or hardness of the matrix. **Wear eye protection**.

Roy Starkey examining a specimen after trimming and prior to mounting.

3. After trimming and re-examination, proceed with a suitable cleaning method if necessary. Gentle air dusters work well to remove fibres and debris. It may be safer to leave very fragile or water soluble specimens uncleaned and seek advice from other micromounters to avoid losing a good specimen.
4. Traditional micromounts are mounted on a small stand or pedestal to raise them up from the box base. These can be fabricated from soft wood, cork, plastic rod or any other suitable material and coloured black to minimise light interference when examining under a microscope. A black permanent marker pen works well. Use a craft knife to cut the pedestal to the right length so that when the specimen is mounted it will be below the top of the closed box. The cut end to hold the specimen should be blackened.
5. The cleaned and dry specimen is carefully glued onto the cut length of pedestal material and the adhesive allowed to harden. Use a clear, solvent drying adhesive that will allow for some re-positioning of the specimen before it fully hardens. Use the minimum amount of adhesive and prevent runs and strings.
6. The micromount box to be used is carefully dusted and the bottom centre of the box is roughened to provide a key for the adhesive. The prepared specimen, fixed to its pedestal, is checked for height, and if necessary the pedestal trimmed. It is then glued into position in the box. Leave the box open to allow the solvent to fully evaporate and the adhesive harden.
7. Finally the box is labelled with a catalogue number, the name of the mineral, locality and other desired information. The finished mount is now ready for viewing or storage. Enter the specimen details in your catalogue.

The above method describes the preparation of a traditional permanent micromount that will be well preserved for future examination and study. Because it is glued into the box it would be difficult to remove the specimen without possible damage and probably require solvent cleaning to remove the hardened glue. Instead of mounting on a pedestal or gluing some people use a specially formulated adhesive putty sometimes referred to as "mineral tack" that will hold specimens in place in the box and can be easily removed without damaging the specimen. We will look at this below.

Below are illustrated some of the tools and techniques that will allow you to achieve good permanent micromounts.

Breaking down a large specimen with a "rock splitter" to extract the area of interest.

A selection of tools for trimming specimens to size. From left to right: carpenters pincers, ceramic tile nibblers, nut splitter (clamp the body in a vice to use) and a commercial "C-clamp splitter".

Rock splitters are expensive engineered pieces of equipment and work well but they are not essential. Some mineral collecting clubs and societies may have splitters that members can use. Careful use of hammers and cold chisels on a hard surface support followed by delicate trimming with hardened jaw cutting tools will, in most cases, give very satisfactory results. Please wear suitable, impact protective eye-shields or goggles and protective gloves when splitting or trimming rocks. Working inside a large plastic or cardboard box will help catch pieces that go flying off and stop them being lost. Examine all the waste products from trimming as you might have revealed something special in a hidden cavity.

The steps involved in preparing a micromount of a micro-specimen (with thanks to Roy Starkey).

1. Cut the required length of pedestal material.
2. Gently sand the cut ends flat and square using an emery board. The sanded ends can be blackened after if required.
3. Apply a small drop of adhesive to the end of the pedestal.
4. Carefully position the specimen onto the glued end ensuring that the area of interest is aligned correctly to allow for optimal viewing under magnification when complete.
5. Set the whole aside to allow the glue to dry. Support the mount to prevent the specimen from moving during drying using a suitable support like a pin in a cork or similar.
6. To allow the adhesive to stick to the base of the box it is advisable to abrade or scratch the area for attachment with a sharp point, file or blade to give a good key.
7. Apply a small drop of adhesive to the pedestal base.
8. Carefully position the pedestal and specimen in the centre of the box aligning the specimen in the desired direction for viewing.
9. Print or write a suitable label and glue or adhere it to the box. Then enter the specimen details into your micromount collection catalogue.

Preparing Non-permanent Micromounts

The operations to prepare a specimen for non-permanent mounting are the same as above although typically the specimens can be larger to fill the box as they will not be glued on a pedestal and there is no need to abrade the base of the box. Some "traditional micromounters" frown upon this technique but it is still a valid method for preserving small, perfect specimens and not just a work of art.

The mounting material used is a synthetic putty commercially commonly sold as "Mineral Tack". "MinTack" or "Geo-Tac". An online search for these terms will give numerous supply sources. Please do not use the poster hanging pressure adhesives such as "Blu Tack" used to stick things to walls. These are not suitable for mineral specimens as they harden with age, contain oils which can be absorbed into specimens and can be very difficult to remove after a long period of time. Specialist specimen mounting putty is a different formulation that resists drying and hardening and is claimed to be easily removable without leaving any residues thus making it reusable. The amount of putty illustrated left will last a very long time as only small amounts are required to hold a small specimen in place in a micromount box. Keep a small portion for routine use available in an empty mounting box and store the bulk in a grip seal bag.

Strips of white specimen mounting putty.

One disadvantage with mounting putty is that it does not adhere well to specimens with a powdery or friable, sandy matrix. This can be overcome by applying a thin coat of a water based PVA (polyvinyl acetate or "white glue") adhesive to the intended mounting area and allowing it to dry thoroughly to stabilise the surface. When using the putty pull off a piece of the required size and roll it between your fingers to soften it up and make it pliable, this will allow it to mould the shape of the specimen more readily. Apply the softened ball of putty carefully to the area of the specimen with as little pressure as possible. Apply the pressure slowly to allow the putty to conform to the specimen matrix. Once applied the whole can be attached to centre of the mounting box the correct position again using slow, gentle pressure. The position of specimen can be carefully tweaked to give the optimal orientation for subsequent examination of the micromount specimen. Another minor disadvantage of soft putty is that top heavy, specimens may fall over if kept in a warm place. The trick is to mould the putty such that it supports the specimen higher up its length. Most importantly always record the full details of your specimens in your catalogue.

Small, lustrous cassiterite crystal from Wheal Roots, Trenear, Cornwall mounted on Mineral Tack.
Ex the late Frank Sharp specimen.

Here are some more of David Green's excellent photomicrographs of micro-specimens to whet your appetite for the wonder of micro-minerals, proof that good things do come in small packages.

From left to right: Apatite, Chywoon Quarry, Mabe, Cornwall. Allanite-(Ce), Ardragh Quarry, Maam Cross, Connemara, Connacht, Ireland. Chalcopyrite, Smallcleugh Mine, Nenthead, Alston Moor, Cumbria. Calcite, Glenwherry Quarry (was Robinson Quarry, formerly Craigs Quarry), Ballymena, Co. Antrim, Northern Ireland.

Where Next?

Micromounting is not a new idea. It dates from the 1870s, when collections were being assembled by the Rev. George Gilbert Rakestraw (1827 – 1904) and George Washington Fiss (1835 – 1925), both working in the USA. However, the hobby only really emerged in the UK in the 1970s. In North America there are hundreds of micromount enthusiasts, and in Europe the story is the same. Micromount collectors can be found in almost every country in the world, and they are commonly eager to exchange specimens and are very generous with making material freely available for others to examine and discover new specimens. This can be a good way of adding specimens to your collection at very little cost. Remember to always acknowledge the source of your material in your catalogue for full traceability of specimens.

The British Micromount Society (BMS) was founded in 1981 to promote interest in micromounting throughout the UK. The society publishes a newsletter three times a year on micromount topics. This includes reviews of equipment together with hints and tips from members etc. Back issues are freely available online. Every year they hold a symposium where members congregate to talk about, look at and discover new specimens. They also maintain a national micromount reference collection that has been built up over the years and contains over 1500 specimens. Specimens are available for loan to members.

Further reading

Two English language publications which are devoted entirely to micromounting are:

Speckels, M. L. (1965) *The Complete Guide to Micromounts*. Gembooks, Mentone, California.

This valuable little book is designed for the American micromounter, and must surely represent the best value for money of any mineral related publication. 97 pages including the inside covers are packed with information, hints and tips. There are chapters covering the history of micromounting, sources of specimens, tools and materials. Practical instruction is given on specimen preparation, choice of materials, trimming, cleaning and mounting specimens. Basic principles of mineral identification are also covered together with sources of information regarding cataloguing and curation An extensive bibliography guides the newcomer into many hours of enjoyable reading – the oldest reference is to Elmer Benge writing in The Mineral Collector in 1904!

White, Q. (1993) *The Complete Book of Micromounting*. Mineralogical Record. Tucson, Arizona.

This book brings together the many diverse facets of micro mineral collecting. Chapters cover the history of micro mineral studies, trading and field collecting methods, specimen preparation, identification, mounting and conservation techniques, microscopes, photography and micromount symposia worldwide. Also included is a colour album of 165 beautiful micro-mineral photographs taken by some of the world's most talented photographers. The publication draws on contributions from Neil Yedlin and Paul Desautels and sometimes reads as three books in one. Although clearly aimed at an American audience, it is a book many British micromounters will wish to own. Unfortunately both of these books are out of publication but second hand copies do turn up for sale online occasionally.

Some useful internet links:

The British Micromount Society

https://bms.31pendleton.com/ - lots of useful information, details of how to join, the annual British Micromount Symposium and more.

The Baltimore Mineral Society (which hosts the Micromounters Hall of Fame)

https://www.baltimoremineralsociety.org/what-is-micromounting.html

A series of informative videos can be found here:

https://www.youtube.com/playlist?list=PLuqbdWpfWWaHEbZ8ydmJlCaYoaVElMKbD

A simple online search for "Micromounting" will turn up many other sites with advice, photographs, equipment and instructions.

Ways of Magnifying and Photographing Minerals

by Michael Dunmore

Looking closely at a mineral specimen can reveal many beautiful surprises that cannot be seen with the naked eye. For example, richly-coloured sprays of small crystals, or tiny cavities that are packed with multiple shapes and colours.

Yellow fluorite and white baryte crystals, Melbeck Moor, North Yorkshire. Field of view 18 mm.

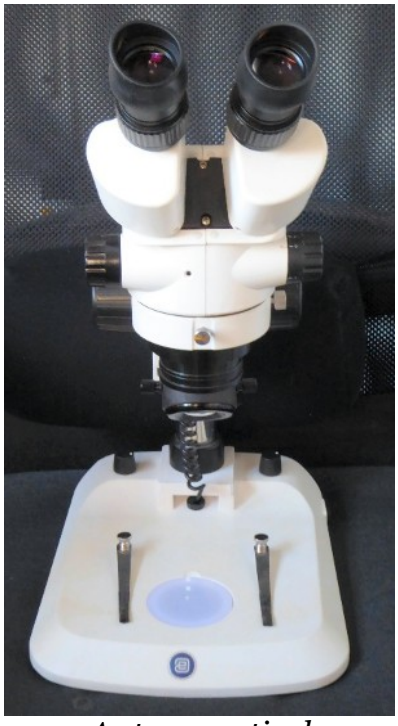
Green pyromorphite crystals, Melbeck Moor, North Yorkshire. Field of view 9 mm.

A selection of hand lenses. The silver one at the top of the picture includes a light for illuminating an object and an ultra-violet (UV) light source for testing whether a specimen responds to UV light by glowing (fluorescing).

A magnifying glass, hand lens or loupe, with a magnification of x10 or more is an inexpensive aid for viewing mineral specimens and seeing greater detail than is possible with the naked eye. [Hand lenses were discussed in the JMM issue 1, March 2025, page 16 – Ed.]

An optical stereo-microscope (a microscope containing several lenses) gives greater flexibility and quality of viewing than a loupe, but good microscopes are far more expensive than a loupe.

Local auction houses and online auction sites might be a source of a reasonably-priced used microscope. And don't forget that you will need a built-in or separate lighting to illuminate a specimen so that it is clear and sharp when viewing it through the microscope.



A stereo optical microscope with built-in lighting. Turning the zoom knob on the side of this microscope increases the magnification up to 40x.

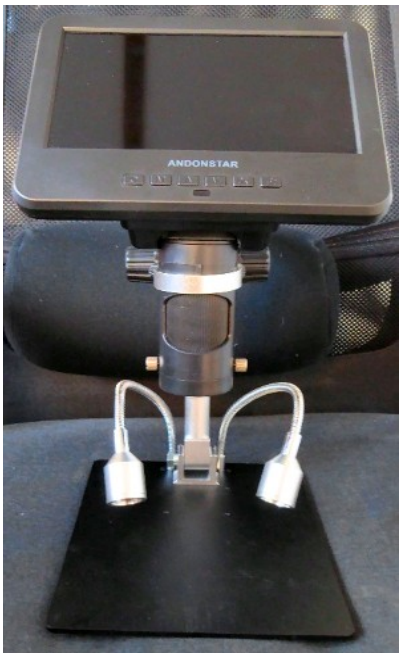
Developments in digital technologies have created new ways to view and photograph mineral specimens. Many mobile telephones have good quality cameras with a macro function for taking photographs of small items. Also, macro lenses can be added to mobile telephones as an inexpensive way to magnify areas of a specimen for photography. Macro lenses are available with different levels of magnification. A flexible stand, remote control and LED lighting system can be added with little

expense to make the system more versatile and allow good, clear, in focus images to be produced. These can later be enhanced and edited in the photo-editing software.

Macro-lenses can be clipped over the camera lens on a mobile telephone to magnify areas of a mineral specimen.

The market for digital microscopes has ballooned in recent years, with microscopes that include many different features and at many different price points. Websites such as Amazon and Ebay promote hundreds of different digital microscopes. Typically, digital microscopes do not give an image that is as clear as that of an optical microscope, but they can include a camera for taking photographs or videos, which can be very difficult through an optical microscope.

If you are thinking of purchasing a digital microscope it is very helpful to consider what is most important for you to help with your decision-making and choice. For example, does it have a camera, and what is the quality of the photographs and videos it produces? Check the megapixel (MP) rating for photographs and progressive scanning (P) rating for video. The higher for both the better, but more expensive, as an absolute minimum go for 12 MP and 1080P. Beware of claims for magnification. Digital magnification is just the size of the screen image and not true optical magnification.



A digital microscope that includes in-built lighting and a screen for viewing the magnified image of a mineral specimen.

Does the microscope give you flexibility with the size of specimen you can view? Ones mounted on a pillar stand are better as the overall height can be adjusted. Some digital microscopes have several easy-to-change lenses (typically three) to enable specimens of different sizes to be viewed, and to give a wide range for magnification. Others have a variable zoom facility allowing a much greater flexibility in use.

Can you see what you are viewing on a high-definition (HD) built-in screen, and how large is the screen? Does the microscope have built-in lighting so that you don't need to obtain a separate lighting source? For the best colour rendition the illumination should be "daylight" with a colour temperature of 6500 K. The best lighting is those on flexible arms and not vertically down from the microscope body. With flexible lighting you can adjust it to eliminate reflections from crystal faces, illuminate the inside of cavities and place diffusion media over the light source to reduce shadows.

A digital microscope with flexible LED lighting and remote control for operating the camera.

Can you connect the microscope to a computer to see what you are looking at on a computer screen? Can images be saved to a card that is inserted within the microscope, or can they be transferred immediately to a computer? Does the microscope come with a Micro SD card? Does it come with a lead for connecting the microscope to a computer? Is the microscope compatible with all makes of computer and their core operating systems? Some now connect by Wi-Fi or Bluetooth to mobile phones via an app.

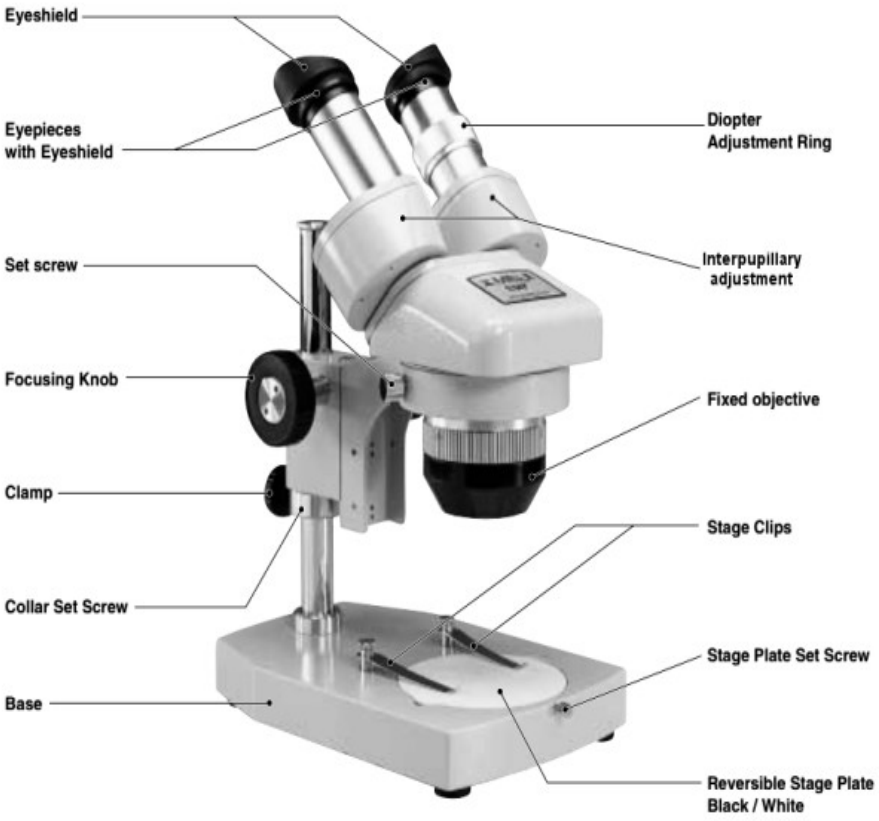
Taking pictures by pressing a button on the microscope will almost certainly lead to the microscope moving and poor-quality images. Microscopes with remote controls for taking photographs help overcome this. Some may have software that allows you to operate the camera from a computer, tablet or a mobile phone.

The Optical Stereo Microscope

by Gary Morse

A stereo microscope is a precision optical instrument designed for low magnification, typically 5x – 40x, examination of a sample using light that is reflected from the surface rather than transmitted through it like a conventional compound microscope. A true stereo microscope uses two separate optical paths with two objectives and eyepieces to provide slightly different viewing angles to the left and right eyes. This arrangement produces a three-dimensional visualisation for detailed examination of samples and is ideal for mineral specimens. A stereo microscope also has a much greater working distance between the objective lenses and the object to be examined. This allows for the specimen to be manually moved around with ease during examination and minimises potential damage to objective lenses and specimens.

Be aware that some microscopes advertised as "stereo" are not. They may have two eyepieces but they only have one objective and will not give a three dimensional rendition of the specimen. These microscopes are really "binocular" having two oculars (eyepieces) for comfort of use. The other important thing is that conventional compound microscopes produce an inverted image at the eyepiece. A stereo microscope has an image orientation identical to that of the specimen being examined. This makes moving specimens under the microscope much more intuitive when examining them.



The anatomy of an optical stereo microscope from the Meiji EM Series microscope manual.

Microscope Terms

Understanding the anatomy of a stereo microscope is essential if you wish to get the most from it. Following are some of the terms that are used to describe the various components of a basic stereo microscope. There are also many sites online that explain the optics and how the microscope works.

Eyepieces – these are the lenses through which you view the specimen. There are two identical eyepieces both having the same diameter and magnification. They slide into an eyepiece tube that is of a standard internal diameter to allow for interchangeability of different eyepieces with different magnifications and properties.

On a good quality microscope one eyepiece tube will have a dioptre adjustment that allows the user to compensate for differences between their eyes. This is achieved by closing the eye that looks through the eyepiece with the adjustment and focussing the microscope on a suitable flat subject then, without changing anything, view the same image with the other eye open and the original eye closed. If the image is not in sharp focus adjust the dioptre ring until it is. The stereo image, when viewed with both eyes, will now be in focus for both eyes. Note the + or – dioptre setting on the dioptre ring so that it can be set again in the future if required. Both eyepiece tubes are movable so that you can adjust

Eyepiece dioptre setting ring.

the interpupillary distance, that is the distance between each eye so that a clear view through both lenses is achieved. This should be adjusted prior to adjusting the dioptre setting. Eyepieces may be fitted with detachable, soft rubber cups or eye shields to make viewing more comfortable. These must be kept clean to prevent potential transmission of contagious eye infections when microscopes are shared.

Some eyepieces are termed as wide-field (WF) which indicates that the eyepiece provides a larger diameter field of view. Wide-field eyepieces are beneficial for scanning larger areas of the specimen, making it easier to locate and observe specific details. Other inscriptions often found on these eyepieces include: UWF for ultra-wide-field, SW or SWF for super wide-field.

Some microscopes may be supplied with what are called "high eyepoint" eyepieces that are indicated by an eyeglasses symbol on them. These allow you to position your eyes further away from the eyepiece to get a good field of view. The purpose is to allow you to continue to wear prescription glasses (hence the symbol) when viewing. The disadvantage is that if you put your eyes up to the lens then you will not be able to view the image. The only way is to move your head back and forth until you see the full image. For most standard eyepieces the recommendation is to remove prescription glasses when using the microscope. This also helps prevent inadvertent damage to your glasses.

High eyepoint, wide-field (WF), 10x, 24 mm eyepiece.

Objectives – At the other end of the microscope are the objective lenses. These are a pair of lenses that are identical and joined together at a fixed angle so that they converge on a common focal point at a set distance from the subject. This distance is known as the "working distance" (WD) and for large samples this is very important so that the specimen will fit under the microscope and be able to be manipulated and focussed on. It also helps to prevent possible damage to lenses by contact whilst moving specimens around. A WD of 100 mm should be considered the minimum for acceptable use but up to 200 mm is better. Some stereo microscopes with interchangeable objectives may affect the WD as the magnification increases.

Slide in objective lenses with 4x magnification.

The range of objective lens options for stereo microscopes is very large and the more versatile, the more expensive. The basic system utilises separate objectives that are swapped over manually to give different magnifications. Some microscopes have different objectives incorporated into the microscope body and these are switched in and out with a knob on the side of the microscope.

The most versatile objective system is the continuously variable zoom lens that was first developed by Bausch & Lomb in 1959. This allows the user to increase the magnification in a smooth way between the lowest and highest available magnification without affecting either the focus or working distance. Typically the zoom range is from <1x to 3-4x and it is controlled by a graduated knob or ring on the microscope body.


The zoom control knob on a Bausch & Lomb Stereozoom microscope.

Obviously, the more sophisticated and versatile a stereo microscope is the more expensive it becomes. The one caveat is to buy a reputable brand as the quality of the optics will be assured. Very cheap models may not give the image quality required and thus will be a waste of money and a great disappointment. Looking at online shopping sites there are some reasonable instruments available at prices between £100 and £200. Take advice from experienced people and, if possible, try out a microscope before purchase. The other thing to remember is that you will need a good, versatile lighting system to illuminate the specimens you are viewing (see above).


The objective selection knob on the side of a microscope showing the magnifications.

Microscope Stands

Stereo microscope body mounted on a single arm, variable boom stand.

Most stereo microscopes are usually self-contained "pods" that hold all the controls and optics. This allows them to be used in a variety of ways to suit different applications. The usual configuration is a simple stand that holds the microscope and possibly the illumination system. These are somewhat limiting for specimen examination as the space in the working distance is fixed and the size of specimen that can be examined is limited.

A variation on the fixed stand is the "column base" as shown on the Meiji EM Series microscope image above. This system allows the microscope body to be raised or lowered on a metal column and clamped into place, with a locking ring and screw, for use. For smaller specimen examination these are ideal as the height can be adjusted to accommodate different sizes of specimen.

The ultimate microscope support system is a variable boom arm stand that allows the microscope to be moved in two or even three different axes, up and down, left and right and in and out. The bases on these systems are very heavy so that the microscope will not fall over at the maximum extension. The boom arm stands can also accommodate illumination systems usually fibre optic light pipes. Again the more sophisticated the support system the more expensive. The minimum set up should be an adjustable column base that will accommodate the majority of specimens to be examined.

Microscope Magnification

Determining the magnification of your microscope is essential if you wish to convey the size information of a specimen or photograph taken with a microscope.

A WF 10x/22 mm diameter FoV eyepiece.

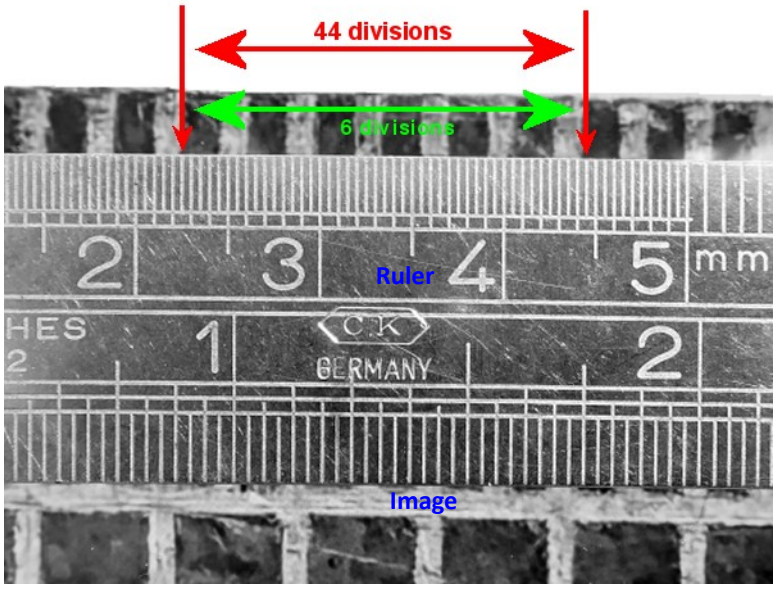
For conventional optical microscopes the magnification is the product of the eyepiece (or ocular) magnification and the objective lens magnification. The eyepiece magnification should be engraved on the eyepiece itself and should be the same on both, obviously. The objective magnification will be marked on the objective lenses themselves or obtained from the graduations on the objective setting control knob or the zoom control.

Example: Your stereo microscope has 10x magnification eyepieces fitted and the objectives are set at 4x. Thus the magnification of the microscope is 10×4 = 40x. A very simple calculation. If you replace the 10x eyepieces for 20x ones the magnification will become 20×4 = 80x. So for an optical stereo microscope it is very easy to find out the magnification that you are viewing your specimens at but for a digital microscope with a viewing screen and no eyepiece lenses or marked graduations on any zoom control discovering the magnification requires a bit more work.

To calculate the magnification of a digital microscope screen you will need a scale. The easiest way is to use a small (150 mm) engineers stainless steel rule with accurate, finely engraved graduations to ideally 0.5 mm although 1.0 mm will give results at lower magnifications. The process to discover the magnification at which you are viewing or photographing a specimen is as follows:

A 150 mm engineers stainless steel rule with graduations to 0.5 mm at the first 5 cm.

1. Store the photograph of the specimen at the required magnification.
2. Without changing any settings on the microscope remove the specimen and place the steel rule flat on the base.
3. Focus the smallest rule graduations on the screen without changing the overall magnification and store the screen image.



Aligning the rule 0.5 mm graduations with the image of the same graduations and determining the number of graduations between coincident points.

4. Remove the rule or use a second identical rule and place it on the stored image of the graduations aligning the same scale with that on the image, as shown in the example left.
5. Because the magnified image makes the graduations appear a lot wider look for points of coincidence at the edges of the magnified scale. This is shown by the left hand red arrow where the right edge of the image mark is aligned with the mark on the rule.
6. Without moving the rule look for the next similar point of coincidence as far as possible to the right of the first. As shown by the right hand red arrow.
7. Count the number of graduations between the coincident points on the image. In the example this is six divisions (green dimension).
8. Calculate the number of 0.5 mm graduations between the two coincident points. In the example this is 44.5 mm minus 22.5 mm (red dimension) times 2 to obtain the number of 0.5 mm graduations thus: (44.5−22.5)×2 = 22×2 = 44 divisions.
9. To obtain the magnification divide the number of ruler divisions by the number of divisions on the image thus: 44÷6 = 7.33x. This would be better rounded to 7.3x as only one decimal place is adequate. The more coincident divisions you can count the better the accuracy.

This is a bit more complicated but it does give a reasonably accurate value for the magnification of an image taken with a digital microscope.

Depth of Field

Every lens system in a stereo microscope has one perfect focal point which is the distance from the objective lens where everything is in focus. Further up or down from that focal point results in the image becoming progressively blurrier as it moves away from the perfect focal point of the lenses. Depth of field (DoF) is a measure of how far the specimen being observed can be away from the true focal point whilst still remaining acceptably in focus. It denotes the range of distance where objects are still sharp and detailed. It can be given a numerical value but it is very complicated. A shallow depth of field will provide only a narrow band in which objects can be in-focus, while a deeper depth of field will allow you to see the details on objects much farther away from the focal point.

Photomicrograph showing blue azurite on green tyrolite from Dolyhir Quarry, Powys showing the effects of depth of field where the background and foreground are progressively out of focus.

The mineralogist, physicist and mathematician Max Berek (1886 – 1949), published, in 1927, the results of his extensive experiments on the subject of visibly experienced depth of field. Berek's formula gives practical values for visual depth of field and is still used today. In its simplified form, it is as follows [still rather complicated – Ed.]:

$$T_{VIS} = n\,[\lambda/(2 \times NA^2) + 340\ \mu m/(NA \times M_{TOT\,VIS})]$$

where:

- T_{VIS} is the visually experienced depth of field (what is acceptably in focus);
- n is the refractive index of the medium in which the object is situated (if the object is moved, the refractive index of the medium that forms the changing working distance is entered in the equation). This is very near to 1.00 for air at normal room temperature and pressure;
- λ is the wavelength of the light used, for white light it is 0.55 µm;
- NA is the numerical aperture (the range of angles over which the system can accept light) in the region of the sample; and
- $M_{TOT\,VIS}$ is the total magnification of the microscope.

What is obvious from Berek's formula is that DoF is influenced by the magnification in use and the wavelength of the illuminating light. This highlights that for the best depth of field a light source that emits the full visible spectrum evenly is essential.

More in-depth information is available, if you are interested, at: https://www.leica-microsystems.com/science-lab/microscopy-basics/depth-of-field-in-microscopy and also a PDF https://www.qualitymag.com/ext/resources/files/white_papers/WhitePaper-SelectingaMicroscope__GT5K4NLSSH__-1.pdf [both accessed January 2026].

Now, macrophotographs can be created using what is known as "focus stacking" where many single photographs are taken of the specimen at different focal points and some very clever software (many are free) is used to combine all the in focus parts of these images together to render an image that has the full depth of the specimen in focus. You can even render these to appear as 3D images now. For more information on focus stacking go to the University of Otago blog: https://blogs.otago.ac.nz/si-geology/focus-stacking-images

There is a good article on using focus stacking and creating 3D images on Mindat at: https://www.mindat.org/article.php/2182/On+generating+stereo+images+with+focus+stacking+software [both accessed January 2026].

Finally

An optical stereo microscope is a precision piece of mechanical and optical engineering and with care will give many years of pleasurable service. They do need taking care of though. Follow the manufacturers guidelines for maintaining your microscope.

- Carefully carry the microscope by both the body and stand whilst supporting the base.
- Keep it covered and stored safely to exclude dust and harmful fumes when not in use.
- Avoid storing it in places with large fluctuations of temperature or humidity to prevent corrosion or condensation forming on lenses that could ruin them if fungal growth forms.
- Clean and lubricate mechanical parts as recommended by the manufacturer.
- Clean eyepiece lenses with a microfibre lens cleaning cloth after every use to remove any contamination.
- Wash rubber eye cups to prevent any potential eye infections being transmitted.
- Remove any specimen dust that may be present on the base or viewing stage. If this contains degradable sulphides it could set up corrosion and the dust could get deposited on lenses.
- Love your microscope and your microscope will reward you with many happy hours of discovery of the wonderful mineral world that they reveal.

If you would like to discover more about microscopes then the excellent microscopy UK web site is a tremendous resource with articles, guidance and much more: http://www.microscopy-uk.org.uk

The Nikon Microscopes web site has a very good Introduction to Stereomicroscopy with interactive animations that illustrate the various properties and construction of stereo microscopes. https://www.microscopyu.com/techniques/stereomicroscopy/introduction-to-stereomicroscopy

[all links accessed January 2026].

Rocks and Minerals through Time and Space

Part 3: Origin of the Moon

Phil Taylor

Introduction

In Part 1 we examined how all known 92 natural elements were formed and then seeded throughout the nebula which eventually collapsed to form our Solar System. Next, in Part 2, we looked in some detail at the formation of the early Solar System and how planetary differentiation altered the distribution of elements within the Earth, especially in its outer crust, the only part of the Earth we can access to collect minerals. In Part 3 we'll examine what was probably the main key event in Earth history, the formation of the Moon.

So, why is this crucial you may ask, it's Earth and its minerals in which we are interested? The reasons are many, but listing just three will make the importance of the Moon's formation all too apparent:

1. The process which formed the Moon delivered a vast amount of iron to Earth, so greatly increasing its mass and the size of its metallic core. Prior to the Earth's final phase of planetary differentiation, the increased iron content attracted even more iron-loving elements, the siderophiles (see Part 2), therefore markedly changing the element distribution in the Earth's crust.
2. It is likely this same process delivered much of the Earth's inventory of hydrogen and oxygen. As the Earth then cooled, these would go on to form the oceans and atmosphere as the planet slowly degassed.
3. The formation of oceans and the atmosphere were the initial drivers in the formation of organic molecules which would eventually lead to the origin of life; that point in time where geochemical processes imperceptibly transformed into biochemical processes. The Moon, now long established, imposed strong tidal forces on the Earth and its oceans, causing them to rise and fall as they do today. The repeated daily cyclic filling and evaporation of rock pools is now considered an important driver in the origin of life. As we'll discover in a future article within this series, living organisms go on to create the oxygen-rich atmosphere that has such an influence on mineral chemistry and that many mineral species are created by microbial activity.

Fifty four years have passed since NASA's Apollo programme last successfully landed men on the Moon and returned them, together with precious geological samples, safely back to Earth. Around this same time, the Soviet Union (USSR) ran their Luna programme of unmanned spacecraft, three of which returned soil and rock samples to Earth, albeit in much smaller quantity. Through the subsequent mineralogical analysis of samples over the last half century, our understanding of the Moon has increased immeasurably, one important aspect being its origin. Things have certainly come a long way since I first read my Ladybird book of *The Night Sky* (Figure 1) back in the 1960s!

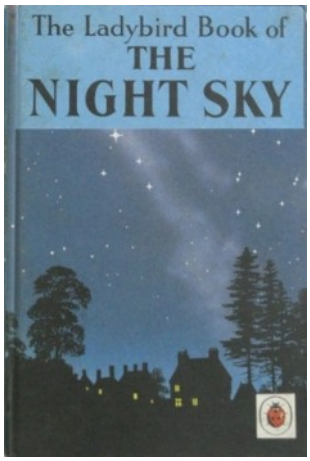


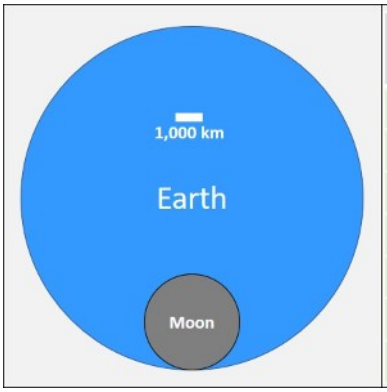
Figure 1. The Ladybird Book of The Night Sky.

To describe the current and most widely accepted theory of the Moon's formation requires as much mention of basic astrophysics as it does mineralogy, however, during the evolution of the early Solar System, mineralogy and astrophysics were completely entangled.

A problematic Moon: As early as the nineteenth century, astronomers and astrophysicists were aware of the Moon's different characteristics to those of the moons of other planets in our Solar System, primarily its size. Figure 2 compares planet Earth to its only natural satellite, the Moon. We are not used to seeing the two bodies side by side and at first glance, the Moon probably

appears small compared to Earth. However, the Earth and Moon have the largest size ratio by far of any moon and planet in the Solar System, so much so that the Earth-Moon system can be classed as a binary planet. The diameter of the Moon is a little over a quarter that of the Earth and is about 1/81 its mass. This is exceptional within the Solar System and the Moon remains classified as the fifth largest satellite of the 431 currently known.

Small moons such as those of Mars, Phobos and Deimos, are most likely to be captured asteroids. The much bigger moons of the outer gas giant planets are thought to be formed from debris left over from planet formation. Jupiter's moon Ganymede is the largest moon in the Solar System and is even 8% larger than the planet Mercury. Despite this, its fractional mass to that of Jupiter is only 0.000078 compared to 0.0123 of the Moon to Earth.



	Earth	Moon	fraction of Earth
Mean radius, km	6,371.0	1,737.4	0.2727
Surface area, km^2	51.0072×10^7	3.7930×10^7	0.074
Volume, km^3	1.083×10^{12}	2.1958×10^{10}	0.020
Mass, kg	5.97237×10^{24}	7.342×10^{22}	0.0123
Mean Density, gcm^{-3}	5.514	3.344	0.6064
Surface gravity, ms^{-2}	9.806	1.62	0.1654 g
Escape velocity, kms^{-1}	11.186	2.38	0.2127

Figure 2. Comparison of the Earth and Moon.

To account for our anomalous massive moon, three theories were postulated between about 1899 and the 1960s: *Fission theory*; *Capture theory* and the *Co-accretion theory*. All three had merit but nothing could be done to prove or disprove them until scientists could examine Lunar samples. To date, almost 400 Lunar meteorites have been discovered on Earth, but until we had rock samples known to be from the Moon, there was no standard to identify that such meteorites were of Lunar origin.

Lunar missions: Of all the various international space missions, only nine have ever returned geological samples from the Moon's surface. Six of these were the NASA Apollo manned missions between July 1969 and December 1972 (Apollo's 11, 12, 14, 15, 16 and 17), the remaining three being the USSR's Luna programme, of which Luna 16, 20 and 24 were sample return missions. In all, 382 kg of soil (regolith) and rock samples have been returned to Earth, the vast majority from the Apollo flights. See Table 1 for Moon landing details.

Mission & Type	Mission Date	Lunar Landing and Sampling Site	kg of samples	Extravehicular Activity (EVA) sampling area
Apollo 11 (H)	July 1969	Mare Tranquillitatis	21.55	Local to LM – 1 moonwalk
Apollo 12 (H)	November 1969	Oceanus Procellarum	34.35	Local to LM – 2 moonwalks
Luna 16	September 1970	Mare Fecundities	0.10	Fixed location – robotic
Apollo 14 (H)	January 1971	Fra Mauro Highlands	42.80	Local to LM - 2 moonwalks
Apollo 15 (J)	July-August 1971	Hadley – Apennine	76.70	LRV covering 27.90 km
Luna 20	February 1972	Terra Apollonius	0.03	Fixed location – robotic
Apollo 16 (J)	April 1972	Descartes Highlands	95.71	LRV covering 26.70 km
Apollo 17 (J)	December 1972	Taurus – Littrow valley	110.52	LRV covering 35.74 km
Luna 24	August 1976	Mare Crisium	0.17	Fixed location – robotic
Total (kg) of rock and soil samples returned:			**381.93**	

Key

Mission type **H**	Precision manned lunar landing demonstration and systematic lunar exploration
Mission type **J**	Extensive scientific investigation of Moon on lunar surface and from lunar orbit

LM	Lunar Module
LRV	Lunar Roving Vehicle

	USA (NASA) – manned missions
	USSR (various Soviet agencies) robotic missions

Table 1. Apollo and Luna mission lunar soil/rock sample weights and their locations.

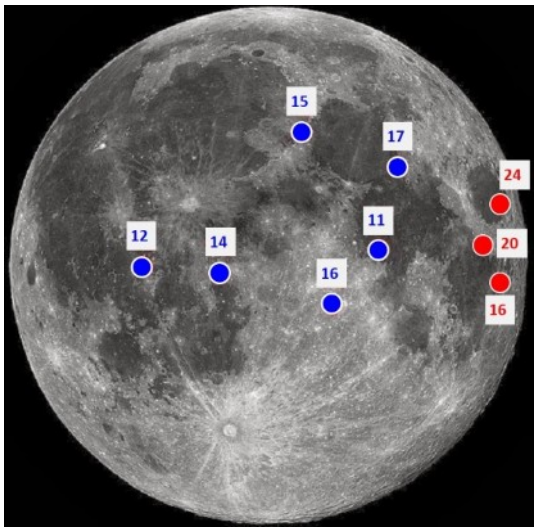


Figure 3. Landing sites of the Apollo (blue) and Luna (red) missions.

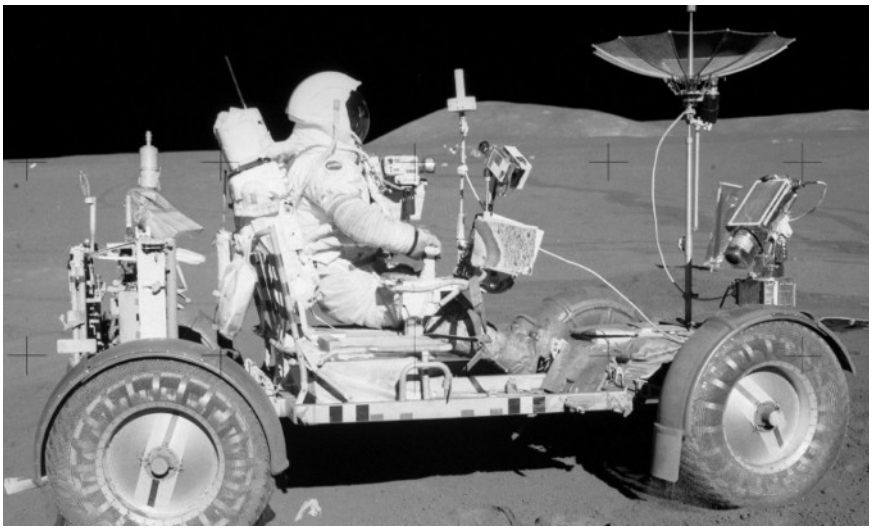


Figure 4. The Lunar Roving Vehicle (LRV) used in the Apollo 15, 16 and 17 missions.

Figure 3 indicates the locations of the nine Moon landing sites from which geological samples have been returned. Although we tend to think of the returned samples as Moon rock, a significant fraction was soil, also known as regolith, an extremely fine-grained material similar in texture and particle size to talcum powder. The last three Apollo missions were equipped with the Lunar Roving Vehicle (LRV), Figure 4, enabling a total of 90.34 km to be covered, so greatly extending the sampling areas. The final NASA mission, Apollo 17, took the first and only professional geologist (and Lunar Module pilot) Harrison Schmitt.

Analysis and Discoveries: Analysis by single crystal and powder x-ray diffraction, optical absorption and electron microprobe, revealed that while the Moon's minerals have a very similar distribution of elements to those on Earth, the Moon contains much less iron, more titanium and different isotopes of chromium. These, amongst many other characteristics, proved that none of the three existing origin theories were correct, or at best, not entirely correct. By the mid 1970's planetary geologists and astrophysicists were formulating an entirely new theory based on a massive impact of Earth from a small planet and in the process, giving birth to the Moon. This is now known as the *Giant-impact hypothesis*.

Theia and the Giant-impact hypothesis: When we concluded Part 2, the Proto-Earth was now born, the third planet from the Sun, but it remained alone, with no natural satellite. The name *Theia* has been given to a hypothetical planet which impacted the Earth, so creating the Moon. In Greek mythology, Theia was the mother of Selene, the goddess of the Moon. Based on Lunar mineralogy, geophysics, celestial mechanics and computer modelling, Theia is believed to have been about 6,100 km in diameter (close to the size of Mars) and likely to have coalesced in the outer Solar System, but was gravitationally perturbed, so moving into near-Earth orbit. Simulations show it eventually established a stable orbit around the Sun at one of the Lagrangian points. There are five Lagrangian points in the Sun-Earth system; gravitational points at which a smaller object will remain in solar orbit without being taken out of orbit and captured by the gravitational pull of either. Figure 5 illustrates these stable positions within the gravitational fields of the Earth and Sun; numerical modelling indicates Theia occupied either the L4 or L5 point.

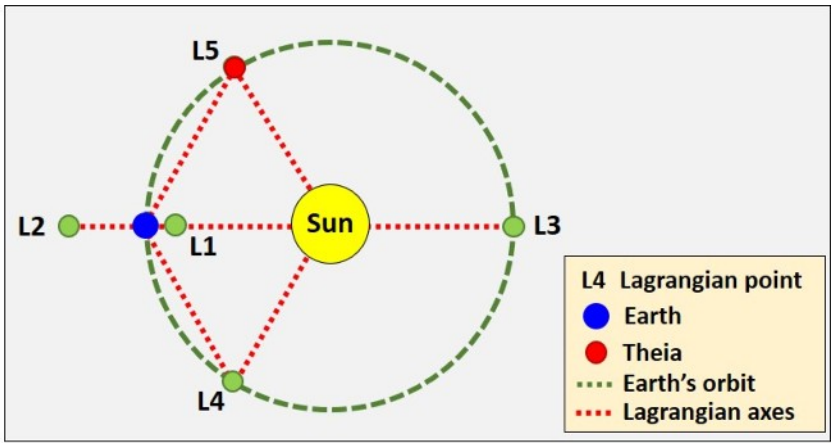


Figure 5. The five Lagrangian points of the Sun-Earth system with Theia shown at L5 (not to scale).

Such an object sitting at L4 (leading) or L5 (trailing) is termed an Earth Trojan. In 2010 a 150 to 500 m diameter asteroid (2010 TK_7) was discovered at L4; no objects are currently known to occupy L5. As a matter of interest, since late January 2021, the James Webb Space Telescope (JWST) has been in orbit around the L2 point at about 1.5 million km from Earth.

Outside the Lagrangian points, no two bodies can occupy the same orbit (a law of astrophysics), with the larger object always capturing the smaller. Models indicate Theia was likely gravitationally perturbed by Venus, through either gravitational resonance or a giant impact on Venus, so causing Venus to adopt its current retrograde (clockwise) spin. Once removed from its L4 or L5 position, Theia was doomed to collide with Earth.

Initially, Theia was thought to have dealt a glancing blow to Earth, but evidence now strongly indicates the impact was full on, blasting molten mantle material from both Earth and Theia into a near-Earth orbit. The entire impact and mantel ejection process is computed to have taken only about 30 minutes.

Coalition and birth of the Moon: The majority of Theia's dense iron core remained within the Proto-Earth and the Earth-Theia mantel ejecta formed a broad orbital ring at around 24,140 km, or 3.79 Earth radii, from Earth's centre. The stability of any natural satellite around its primary is dependent on the Roche limit of the planet-satellite system. Figure 6 shows the Roche limits and position on the newly formed Moon, some 4.53 billion years ago; distances are measured from the centre of the Earth.

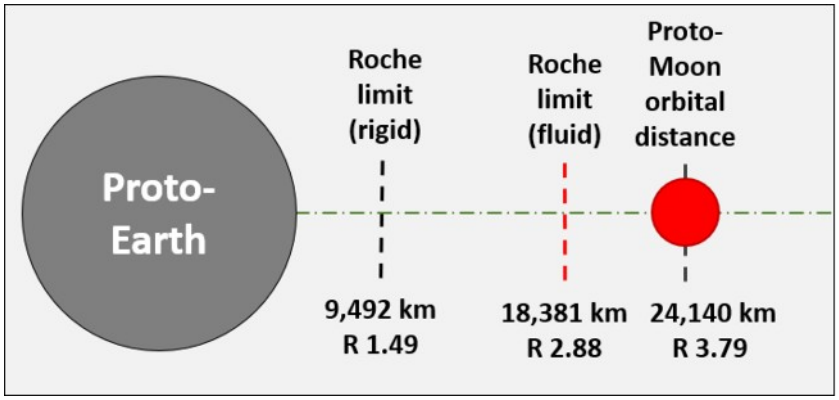


Figure 6. Roche limits of rigid and fluid satellites orbiting the Proto-Earth.

The Roche limit (or radius) around any celestial body is the point in its gravitational field where tidal forces exceed the gravitational self-attraction and material strength of its satellite. Within the Roche limit, the satellite will disintegrate forming rings around its primary (such as those around Saturn); conversely, outside the limit, material tends to coalesce. Figure 6 also shows the Roche limits for a rigid satellite (solid rock) and a fluid body (molten magma from the mantel). Over a period of just about a month, the debris coalesced forming the early Moon. Material ejected into lower orbits would lie within the fluid Roche limit, hence forming rings which eventually rained material back to Earth.

Figure 7, drawn roughly to scale, shows the relative sizes of the Earth and Moon and the initial and present-day positions of the Moon. Through gravitational tidal drag, angular momentum is constantly transferred from the Earth to the Moon, causing the Earth's rotation (day length) to gradually slow and the Moon's distance to increase. The length of an Earth day is increasing by about 2 milliseconds per century (termed tidal deceleration) with the Moon's distance from Earth increasing at a rate of 3.8 cm per year.

Figure 7. Scale diagram of increasing orbital distance of the Moon: Hadean to present day.

Observations and Evidence: The *giant-impact hypothesis* satisfies data and observations from fifty years of regolith and rock analysis, surface and remote Earth and Lunar geophysics, complex computer modelling and telescope (optical and radio) observations of exoplanetary systems. Some evidence for the Giant impact hypothesis is set out here:

Earth Observations:

1. Most of Theia's iron content ended-up in the Earth, leaving the Earth's core containing more than would be expected for a planet of its size.
2. Evidence gathered in 2019 suggests Theia originated in the outer Solar System and delivered most of Earth's water inventory; Earth's original volatiles would have been blasted away by highly energetic solar winds during the Sun's initial T-Tauri phase.
3. Theia's impact shifted the tilt of Earth's rotational axis to its high value of 23.4°.
4. Most of the Earth-Moon system's angular momentum resides in the Moon.
5. The Earth's sidereal year (fixed star to fixed star) has remained almost unaltered (i.e. 365.25 present Earth days) since the Earth was formed. This is not the case for the sidereal rotation period or day. An Earth day currently lasts 23 hours 56 minutes 4.1 seconds but began at around 5 hours, with about 1,753 days per year. Tidal coupling with the Moon causes the Earth's rotation period to decrease, with the result of an increase in day length of about 19 hours since the Moon's formation. The length of the sidereal day can be found in the fossil record; one example being daily growth marks in fossil corals. Devonian coral reefs (about 400 million years old) indicate a day length of 22 hours (398.4 days/year) when the Moon was about 15,200 km closer to Earth.

Moon Observations:

1. The Moon does not have a large iron core; the Earth's core is about 33% of its total mass whereas the Moon's is < 3%. Impact melting and higher metal densities resulted in most of the iron remaining in, or falling back, to the Proto-Earth.
2. The Moon's average density is about 2/3 that of the Earth, again, due to its lack of iron and other heavy elements.
3. There are almost no traces of the most volatile elements in the Moon's regolith and rocks, for example hydrogen, nitrogen, carbon and sulphur. No water-bearing minerals of any type have been found in the Moon rocks, suggesting most volatiles were baked-off. This agrees with the original material being molten blast ejecta.
4. The ratios of oxygen (O16) and its rare isotopes O17 and O18 are identical in both terrestrial and Lunar rocks, strongly indicating that the Moon was derived from the Earth. Despite the brevity of the Theia-Earth impact event, the two molten bodies would have co-mingled giving rise to near indistinguishable rock chemistry.
5. The Moon orbits the Earth in the same direction and in a common ecliptic plane.
6. The Moon has a large equatorial bulge, about 20 times greater than expected for its rotation period. The bulge has been determined to have formed during the Hadean eon, the earliest subdivision of the Pre-Cambrian. It formed due to land tide uplift on the Lunar molten interior, exerted by the near-Earth's strong gravitational field. This proves the two bodies were in close proximity and that the Moon was still in a molten-plastic state. As the Moon receded from Earth and cooled, the bulge became 'frozen' or fossilised.

Conclusions: At the time of writing, all combined evidence suggests the Giant-impact hypothesis to be the most likely of all those suggested to date, including some more modern theories not discussed here. The earliest of the three original theories, the Fission Theory, may still partly integrate with the current impact model: the oxygen isotope data providing strong support. The Fission Theory was postulated by George Darwin, fifth son of Charles Darwin, while holding the chair of Astronomy and Experimental Philosophy at the University of Cambridge. Fission Theory suggests the Moon was

expelled from a high-speed rotating Earth due to excessive centrifugal force. Work continues and maybe one day the two theories will be unified.

Next time…

In Part 4 we'll look at other key events in Earth history which have determined the variety of over 6,150 mineral species known today.

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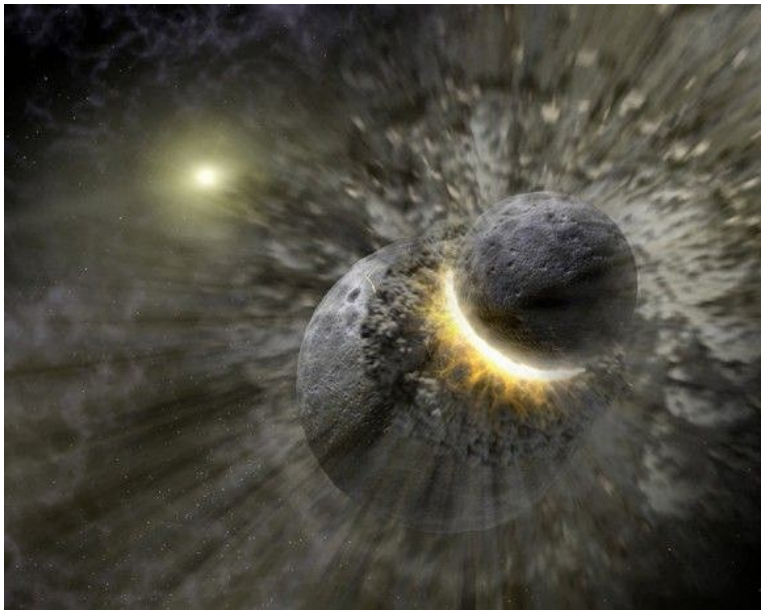
Wikipedia, on-line Encyclopedia: various sites for moon missions and astrophysics.

Further Reading

The NASA website has an excellent page on "How did the Moon form?" with some brilliant animated graphics, images and a super-computer generated simulation of the collision and the Moon's formation.



Theia colliding with the Earth. NASA image

Take a look at the NASA website: https://science.nasa.gov/moon/formation

[Accessed January 2026]

There is a rather interesting BBC television programme "Do We Really Need the Moon?" presented by Dame Dr Maggie Aderin-Pocock (who presented the 2025 Royal Institution Christmas lectures) that explores the formation of the moon and how it affects the Earth. It can be found on the BBC iPlayer at:

https://www.bbc.co.uk/programmes/b00yb5jp

[Accessed January 2026]

An Introduction to Radioactive Minerals – Their Origin, Occurrence, Chemistry and Identification

Alan Barnes

Introduction

Radioactive minerals are those that contain uranium (U) or thorium (Th) and whilst all of the other elements in the periodic table also have radioactive isotopes, the minerals containing them are not classed as being radioactive because the concentration of the respective radioactive isotopes is generally too low for the radiation to be detected by equipment commonly used by mineral collectors and their half-lives are generally short or very short. It was the discovery of uranium, thorium, radium and polonium along with their radioactivity that led to some major advances in science and the application of minerals containing them but also brought them to the attention of collectors as objects of study and excitement. However, it was in the early 20th century with the dawn of the atomic age that led to a significant growth in the demand for uranium for commercial applications. Many mining and prospecting projects were undertaken to find new sources of it. With mining comes mine dumps which were, and still are, searched by collectors for uranium minerals, not just for their beauty and scientific curiosity, but also because there is money to be made from waste. At about the same time, the commercialisation of relatively low cost Geiger counters made it much easier for collectors to find and collect radioactive specimens on the mine dumps. Some of the more common secondary, or supergene, uranium-containing specimens such as autunite, torbernite and carnotite were, and still remain, popular amongst collectors due to their bright yellow, green, red, orange or much more rarely blue colours and, of course, their radioactivity. Some of these minerals such as autunite are fluorescent when exposed to ultra-violet (UV) light and this further adds to the appeal of radioactive minerals to collectors. [There is a glossary of terms used in this article at the end – Ed.]

Thorium was discovered by Jöns Jacob Berzelius (1779 – 1848) in 1828 when he analysed a new mineral found by the priest and amateur mineralogist Morten Thrane Esmark in a pegmatite on the island of Løvøya in Telemark, Norway (Refs 1 – 2). This mineral came to be called thorite ($ThSiO_4$). From this new mineral, Berzelius was able to prepare a somewhat crude specimen of the new element by reducing potassium pentafluorothorate, $K[ThF_5]$, with potassium metal (Refs 3-4). He named the new element thorium after Thor, the Norse god of thunder and war. Marie Curie (1867 – 1934) and Gerhard Carl Schmidt (1865 – 1949) both independently discovered that thorium was radioactive, Schmidt publishing the results of his work just two months before Curie. Although thorium never occurs as the native element, it is the 38th most abundant element in the Earth's crust in which the average concentration is approximately 6 parts per million (ppm), although some estimates state that its concentration is as high as 12 ppm (Ref. 5). It has been estimated that the Earth contains approximately 6.4 million tonnes of thorium. Thorium metal (Fig. 1) is used in a range of applications, but the largest potential use is as a potential nuclear fuel because it is a safer and more abundant alternative to uranium. The isotope ^{232}Th can be changed into the uranium isotope ^{233}U in a molten salt nuclear reactor which has two main advantages over conventional reactors: improved safety and less nuclear waste to dispose of. Thorium also finds use in the strengthening of magnesium alloys, as a coating on tungsten filaments for light bulbs, thorium dioxide (ThO_2) has been used to make camera lenses and scientific instruments because it improves the clarity and performance of the lens, whilst the isotope ^{227}Th has the potential to be used in cancer treatment. The dioxide also finds use in heat resistant ceramics such as laboratory crucibles due to its extremely high melting point of 3,350 C. Thorium metal finds use in welding and alloys where it is used as an alloying material for tungsten electrodes that are used in gas tungsten arc welding, although its use in this application is declining.

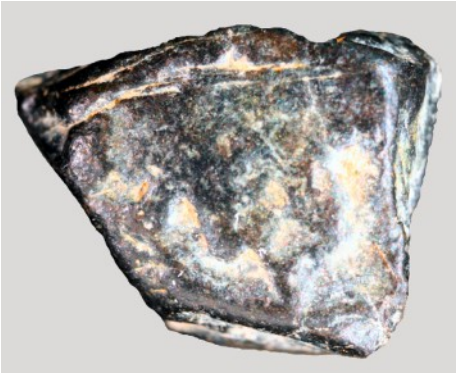


Figure 1. Thorium metal with oxidised surface.

Uranium is the better-known element of uranium and thorium, even though it only has a concentration of about 2.1 ppm in the Earth's crust (Refs 6-9). Uranium was named by the German chemist Martin Heinrich Klaproth (1743 – 1817) in 1789 after analysing a specimen of uraninite from a silver mine in Joachimstahl (now known as Jáchymov) in the Karlovy Vary Region of the Czech Republic. Klaproth named the new element after the planet Uranus, which was discovered by William Herschel on 13th March 1781, about eight years before the discovery of uranium. Although Klaproth identified that a new element was present in the uraninite specimen, he was unsuccessful in isolating uranium metal from it. It was not until 1841 that the French chemist Eugène-Melchior Péligot (1811 – 1890) successfully isolated uranium metal (Fig. 2) by reacting uranium tetrachloride (UCl_4) with potassium metal (Ref. 10). In 1895, Wilhelm Conrad Röntgen (1845 – 1923) discovered x-rays but at that time, he did not understand how the x-rays were generated (Ref. 11). Only a year after Röntgen's discovery, Antoine Henri Becquerel (1852 – 1908) exposed a photographic plate to compounds of uranium and found that strange, foggy areas appeared on the plate that could only be due to rays that were similar in their penetrating power to x-rays and that were emitted by uranium compounds. He also demonstrated that this radiation was independent of an external source of energy and so must arise spontaneously from uranium itself. This groundbreaking discovery disproved the accepted theories of atomic structure at the time that atoms could not be broken down. It was based on these two important discoveries that Marie and Pierre Curie decided to continue Becquerel's work, and it was during their research that they discovered that the air around uranium compounds was ionised and conducted electricity. During the course of Marie Curie's work, she discovered that uraninite (known as "pitchblende" at the time) and torbernite were both more radioactive than uranium metal. This led Curie to state that "*The fact is very remarkable and leads to the belief that these minerals may contain an element which is much more active than uranium.*" (Refs 5, 10). After extracting tonnes of uranium ore, in July 1898 the Curies successfully isolated an element that they would call polonium after Curie's native Poland (Ref. 14). Almost five months later, on 1st December 1898, the Curies announced the discovery of a second radioactive element which they named radium after the Latin word for 'ray' (Refs 12, 13, 15-17). From one tonne of pitchblende, in 1902, Curie managed to isolate just 0.1 grams of radium chloride, $RaCl_2$, but it was another eight years before she successfully managed to isolate pure radium metal (Refs 12, 18). She never succeeded in isolating polonium metal due to its relatively short half-life of just 138 days. Subsequent research by Ernest Rutherford (1871 – 1937), Bertram Boltwood (1870 – 1927) and Frederick Soddy (1877 – 1956) on radioactive decay developed the technique of isotopic dating. One of the outcomes of their research was that they argued that Lord Kelvin's calculations, which showed that the Earth was no more than 20-30 million years old, could not be correct.

Figure 2. Uranium metal.

Compounds of uranium have been used for over 2,000 years where they have found applications in ceramics, glass, steel making and catalysis. Uraninite, for example, was ground into fine powders to create yellow and green glazes for pottery and glass in ancient Rome and Persia. The discovery of uranium in the 18th century led to compounds containing it to be used as colouring agents in glass and ceramics (samples of coloured glass made in 79AD have been found to contain uranium oxide), but because of its radioactivity its uses in modern times are more restricted because of health concerns arising from long term exposure to radiation. Uranium that is highly enriched in the ^{235}U isotope is used as a nuclear fuel and this is its major use in modern times, whilst depleted uranium (^{238}U) is still used in armour-piercing weapons where it's very high density (19 g cm^{-3}), which is approximately one and a half times that of lead, means that it can penetrate the thick steel shells of tanks. However, due to concerns with using radioactive materials, the use of uranium in ballistic applications is declining, with tungsten being used instead of uranium. Like thorium, uranium also finds use in cancer treatment where the isotope ^{230}U is usually used.

Both uranium and thorium are much more abundant on Earth than the better-known elements such as silver, arsenic, lead, and tin.

The Cosmic Origins of Thorium and Uranium

Isotopes of elements that have remained unchanged since their formation are called primordial nuclides and ^{232}Th is a good example of a primordial nuclide because it constitutes almost all of the thorium on Earth due to its very long half-life of 14 billion years (which is about the same age as the universe). The Earth is much younger at about 4.54 billion years old. Consequently, all of the thorium on Earth must have been formed before the Earth was formed. All of the thirty one other isotopes have half-lives ranging from 141 ns (^{217m1}Th[1]) to 75,400 years (^{230}Th).

It is because of this that it is easy to conclude that thorium was most certainly not formed on Earth. Research has shown that these heavy, radioactive elements were instead formed by a very high energy process called nucleosynthesis in which lighter elements such as hydrogen and helium underwent nuclear fusion reactions due to the extreme conditions in sufficiently massive stars. This nuclear fusion occurred in a series of stages by a process called sequential hydrostatic burning such as helium burning, carbon burning, oxygen burning, etc. In this process, after compressional heating, the products of one nuclear fuel become the fuel for the next burning stage in the sequence. The products of these hydrostatic burning reactions are overwhelmingly alpha nuclides where $A = 2Z$, where A is the nuclei of the product and Z is the fuel. For example, two ^{4}He fuse together to generate a single ^{8}Be. The addition of another ^{4}He nucleus to the beryllium nucleus generates ^{12}C (carbon-12), which then undergoes further fusion with a ^{4}He nucleus to generate ^{16}O. This series of fusion reactions continues generating, in order, ^{20}Ne and then ^{24}Mg, and so on, with two protons and two neutrons being added to each fuel. All of this fusion releases an incredible amount of energy and a rapid final explosive burning is generated by a sudden, rapid temperature spike that arises due to a radially moving shock wave generated by the gravitational collapse of the core of the star. The final shock burning process synthesised the non-alpha-nucleus isotopes much more effectively than hydrostatic burning could have done. This strongly suggests that shock-wave nucleosynthesis is an essential component of nucleosynthesis in supernovae. The combination of shock-wave nucleosynthesis and hydrostatic burning processes produce most of the isotopes of ^{6}C, ^{8}O and the elements ^{10}Ne to ^{28}Ni. Due to the formation and subsequent ejection of these newly synthesised isotopes by supernova explosions, their abundances steadily increased within the interstellar gas clouds from which astronomers discovered that the initial abundances of these isotopes in newly born stars exceeded those in older stars. If you read Phil Taylor's excellent articles entitled "Rocks and Minerals through Time and Space: Part 1 The Early Solar System and Earth", in Issue 1 of the Junior Members' Magazine published in March 2025, you will have seen that there are six processes by which elements can be formed whilst in Phil's article "Rocks and Minerals through Time and Space: Part 2 The Early Solar System and Earth" (published in September 2025), a graph was given showing that there is a general decline in the concentration of the various elements as the atomic number increases. So far in this article, we have succeeded in generating nickel (atomic number 28), but uranium has an atomic number of 92. So how do we get from nickel to uranium? At atomic numbers greater than 28, the elements become less abundant as the atomic number increases because of their nuclear binding energies per nucleon (in other words, it becomes harder to fuse larger atoms than it is to fuse small ones). However, the elements with atomic numbers greater than that of nickel are still generated by supernovae, although it is a much more energetically challenging process.

The isotope ^{56}Ni has one of the largest binding energies per nucleon of all the elements. It is, therefore, the last one to form during core silicon burning. This process releases energy by nuclear fusion and is an exothermic process, i.e. it releases heat. The binding energy per nucleon for atomic weights in excess of 56 decreases. The major impact of this is that it puts an end to fusion's ability to supply energy to the star. When the mantle of a supernova hits the semi-solid core of the star, the energy released is immense at approximately one hundred times the energy released by the supernova as the kinetic energy of its ejected mass.

Nuclear fusion reactions that produce elements heavier than iron absorb energy rather than release it. Such reactions are called endothermic reactions, meaning that for such a reaction to happen, the fuel

1 ^{217m1}Th = A nuclear isomer. A metastable (m) state of an atomic nucleus in which one or more protons or neutrons occupy higher energy levels. [https://en.wikipedia.org/wiki/Nuclear_isomer]

has to absorb energy from its surroundings. However, if endothermic processes dominate in the nucleosynthesis of elements heavier than iron, the initial temperature that supports the outer layer of the star decreases. The result is that the "outer envelope" of the star is no longer supported by the radiation pressure and so the star's own gravity pulls its mantle inwards…rapidly! (Fig. 3.). This causes the star to collapse and the mantle then violently collides with the increasingly growing incompressible core. The core has a density which is almost as high as that of an atomic nucleus and this produces a shock-wave that travels outwards of the core through the unfused elements in the outer shell of the star. That shock-wave holds an immense amount of energy which is enough to start fusion in those as-yet unfused elements. This is a process known as explosive nucleosynthesis. The energy dissipated by the shock-wave leads to the star's explosion resulting in the now-fusing elements in the mantle above the core being dispersed into space.

In the process of supernova nucleosynthesis there is a process known as the r-process (rapid neutron capture process) that occurs in core-collapse supernovae and which also occurs in neutron star mergers (Refs 18, 19). The r-process is responsible for producing approximately half of the elements of higher atomic number than iron, the other half being produced by a process known as the s-process (slow neutron capture process) which is a much lower energy process (although still very high energy) than the r-process. In the r-process, heavy nuclei are hit with a very high neutron flux. This generates very unstable, neutron-rich nuclei that decay by emitting beta-particles. The result of this is that whilst the number of neutrons in the nucleus of the atom does not change, the number of protons increases by one each time (see the beta-decay reactions Figures 2 and 3 in the Types of Radiation section below). This presents a viable mechanism by which more stable atoms with an atomic number greater than that of iron can be formed. The neutron density is exceptionally large at about $10^{22\text{-}24}$ neutrons per cubic centimetre (Refs 22-24). Some examples of some of the elements produced by the r-process include gold, platinum and, of course, thorium and uranium, whilst some examples of elements produced by the s-process include barium, zirconium, yttrium, strontium, lanthanum, ytterbium, lithium, bismuth and lead that are generally not considered to be radioactive even though they do contain small amounts of radioactive isotopes. The very high amounts of energy involved in the r-process led to enormous explosions that formed and then violently dispersed thorium (and all of the other elements) throughout the galaxy, some of which ended up in the Earth when the Earth was formed some 4.54 billion years ago. In core-collapse supernovae, so-called heavy seed nuclei (such as ^{56}Fe) capture neutrons at such an elevated rate that the rate of neutron capture is much faster than the nuclides that are formed can decay by beta-emission to form more stable isotopes. As a result of this, this process is the only way that elements such as thorium and uranium can be formed because nuclear fusion in elements after iron in the periodic table is endothermic (Ref. 20). Between ^{56}Fe and the isotope of bismuth ^{209}Bi, the elements are stable (although they all do have minor radioactive isotopes), but because of the abrupt loss of stability past the primordial bismuth isotope ^{209}Bi, all elements after bismuth in the periodic table are radioactive meaning that they require a lot of energy to produce them. However, in 2003 it was discovered that even ^{209}Bi is very slightly radioactive and undergoes alpha decay to ^{207}Tl with a half-life that is estimated to be approximately one billion times longer than the age of the Earth (Refs 21, 22). Whilst there are other mechanisms by which these elements could potentially be formed, they are all too slow and the isotopes formed decay before they can capture enough neutrons to generate

Figure 3. NASA's Hubble Telescope image of Eta Carinae, one of the closest stars to Earth likely to explode in a supernova in the relatively near future (in astronomical timescales the "near future" could be a million years away).

Image Credit: ESA/NASA
https://science.nasa.gov/missions/hubble/preview-of-a-forthcoming-supernova-2

thorium and uranium (Refs 21, 23-25). All of the currently known elements up to atomic number 103 are shown in Figure 4.

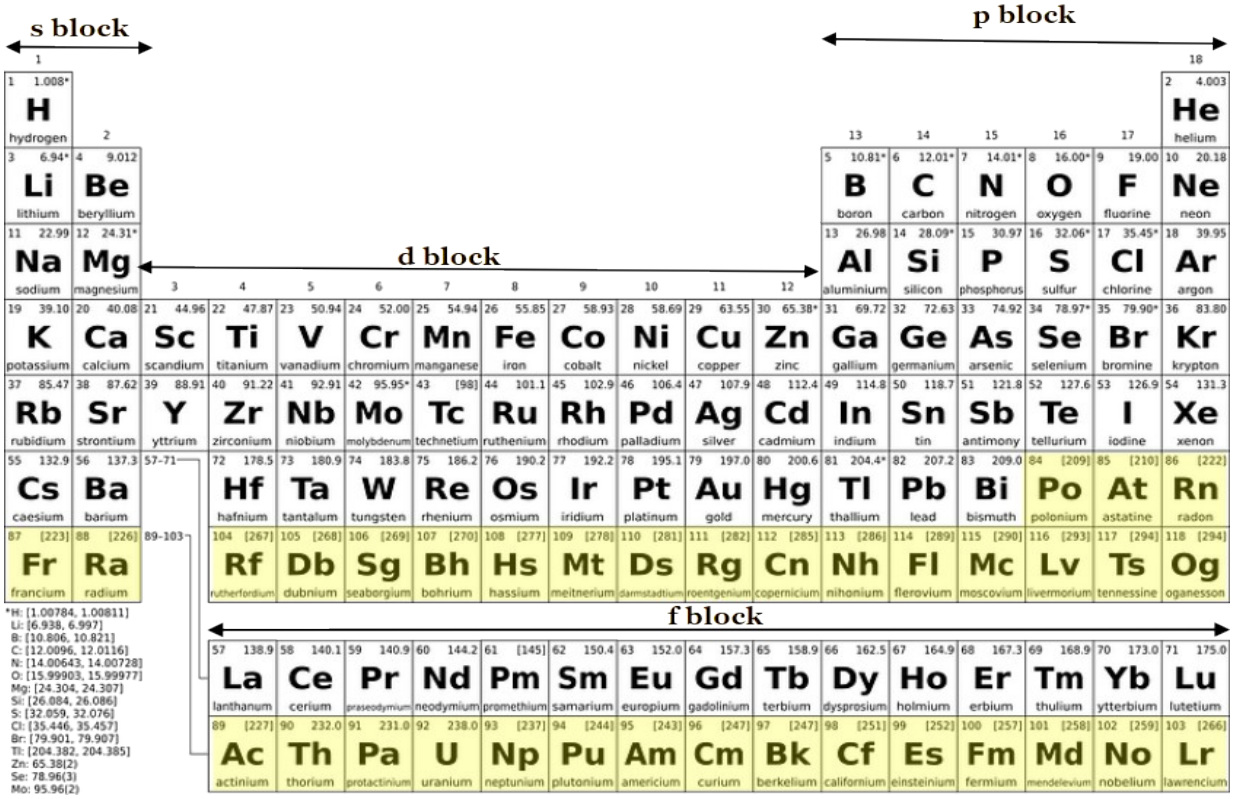


Figure 4. Periodic table with the yellow colour indicating radioactive elements and the identification of the four blocks denoting the type of atomic orbitals in which the valence electrons are situated.

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Types of Ionising Radiation

There are three types of ionising radiation that are relevant to the radioactive decay of uranium and thorium; alpha particles, beta particles and gamma rays.

Alpha

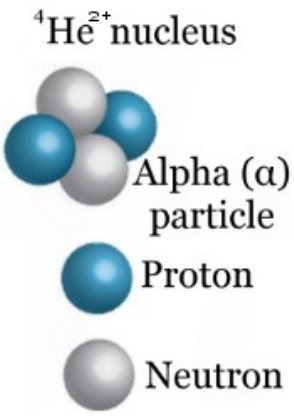

Figure 5. A helium-4 nucleus alpha particle of two protons and two neutrons.

Alpha particles, which are sometimes called alpha rays or alpha radiation, consist of two protons and two neutrons that are bound together into a particle that is identical to a helium-4 (^{4}He) nucleus (Fig. 5) (Ref. 26). Helium gas has two protons and two neutrons in the nucleus of its atoms and two electrons that orbit the nucleus. However, in an alpha particle, the two electrons are missing and so an alpha particle can also be represented by the annotation $^4He^{2+}$, although this is not commonly done. Instead, alpha particles get their name from the first letter in the Greek alphabet, alpha, α, and it is almost always the α symbol that is used to denote an alpha particle. They are usually produced in the process of alpha decay but can also be produced in other ways, such as in nuclear fission, for example. Because α particles are missing two electrons, they are highly ionising and seek to find two electrons from wherever they can. Air provides a rich source of these electrons from the molecules it contains. Once the $^4He^{2+}$ ions gain the two required electrons, the alpha particle becomes a normal (electrically neutral) helium atom ^{4}He that we know as helium gas. Much of the helium occurring on Earth results from the radioactive decay of uranium and can become concentrated in gas wells where its concentration can be as high as 7% by volume. Due to their relatively large

size and strong interaction with other matter, α particles are the most strongly ionising of all the three types of radiation and so travel only very short distances (typically 1 – 3 cm in air) from the source from which they emanated. They are easily absorbed by a sheet of paper or the outer layer of skin (which is dead). An example of α decay is the conversion of $^{238}_{92}U$ to $^{234}_{90}Th$.

Beta

Beta particles are sometimes called beta rays, or beta radiation and they are named from the second letter in the Greek alphabet beta, β. They are high-energy, high-speed electrons (e^-) or positrons (e^+) emitted in the radioactive decay of a nucleus in a process called beta decay. There are two forms of beta decay, β^- decay and β^+ decay, that produce electrons and positrons respectively. β^- decay occurs in nuclei that have an excess of neutrons. When these nuclei undergo β^- decay, a neutron is converted into a proton, an electron, and an antineutrino (the antiparticle of the neutrino). By undergoing β^- decay, ^{232}Th is converted to ^{234}Pa which then undergoes a second β^- decay to form ^{234}U. β^+ decay occurs when an unstable nucleus has an excess of protons. In this process, which is also sometimes called positron decay, a proton is converted into a neutron, a positron and an electron neutrino. Both uranium and thorium can undergo β^- decay and even though ^{238}U decays mostly by emitting α particles, it can also decay by emitting a β^- particle to form ^{238}Np. ^{234}Th decays by emitting an α particle to form ^{226}Ra, but three extremely rare isotopes of thorium, ^{231}Th, ^{233}Th and ^{234}Th decay by β^- emission resulting in the formation of the isotopes ^{231}Pa, ^{233}Pa and ^{234}Pa. Beta particles are less ionising than alpha particles, but more so than gamma rays. Depending on their energy they can travel between 1 m and 6.3 m in air. They can penetrate paper or skin but are absorbed by a sheet of aluminium a few millimetres thick, a thick sheet of cardboard, or an acrylic or polyethylene sheet. However, the effectiveness of these materials at absorbing beta particles can vary depending on the energy of the emitted radiation; plastics are good at absorbing higher energy beta particles whereas aluminium is better at absorbing lower energy beta particles.

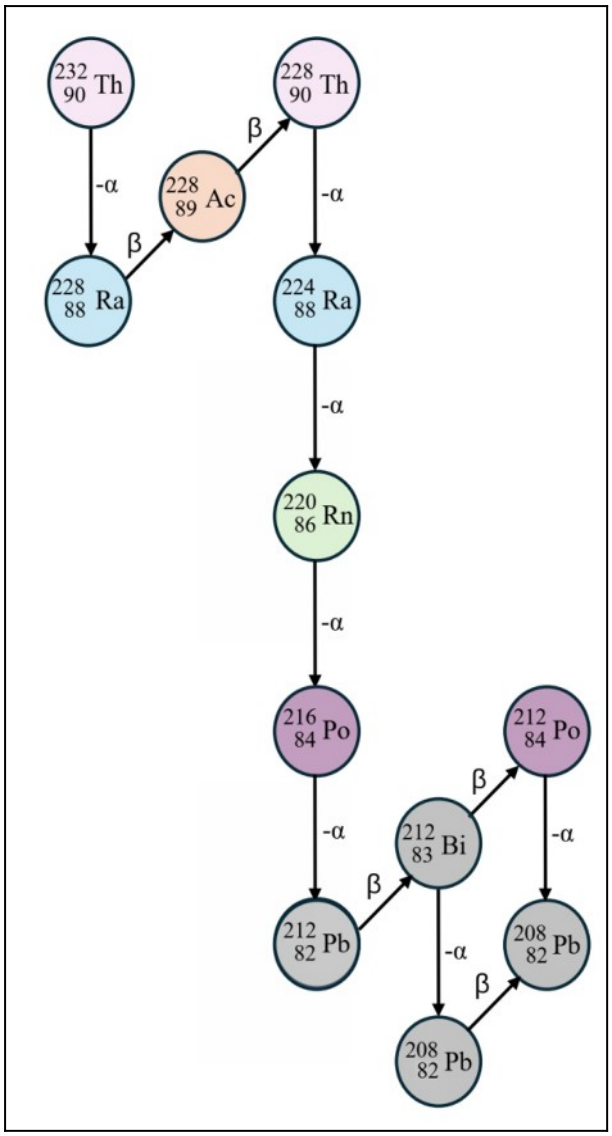

Figure 6. Radioactive decay of ^{232}Th showing the various other isotopes formed before finally finishing up with the stable lead isotope ^{208}Pb.

Gamma

Gamma rays, denoted by the Greek letter gamma, γ, are the lowest energy of the three types of radiation discussed here, although they are still classed as high-energy ionising radiation. When an unstable nucleus decays by either α or β decay, the resulting nucleus is left in a high energy state. To lose the excess energy, the nucleus emits γ radiation. Unlike α and β, γ radiation does not lead to the formation of other elements. Gamma rays have no electric charge and no mass and so the release of this energy merely results in a more stable nucleus. Due to their high energy, γ rays can penetrate many materials which makes them dangerous to biological organisms. They can travel between 130 m and 350 m in air, depending on their energy; high energy γ rays can travel longer distances than their lower energy counterparts. Gamma rays can be absorbed by lead sheets that are a few centimetres thick, or lead bricks. Concrete, water, boron and steel also absorb them but are not as effective as lead. Examples of nuclei that emit γ radiation include the potassium isotope ^{40}K which is found in bananas and the human body. Other examples include the caesium isotope ^{137}Cs,

the synthetic cobalt isotope ^{60}Co, the metastable isotope ^{99m}Tc and the americium isotope ^{241}Am which used to be used in smoke detectors and which turns into the neptunium isotope ^{237}Np by α decay with some γ radiation also emitted. A summary of the radioactive decay patterns by which thorium and uranium decay is shown in Figures 6 and 7.

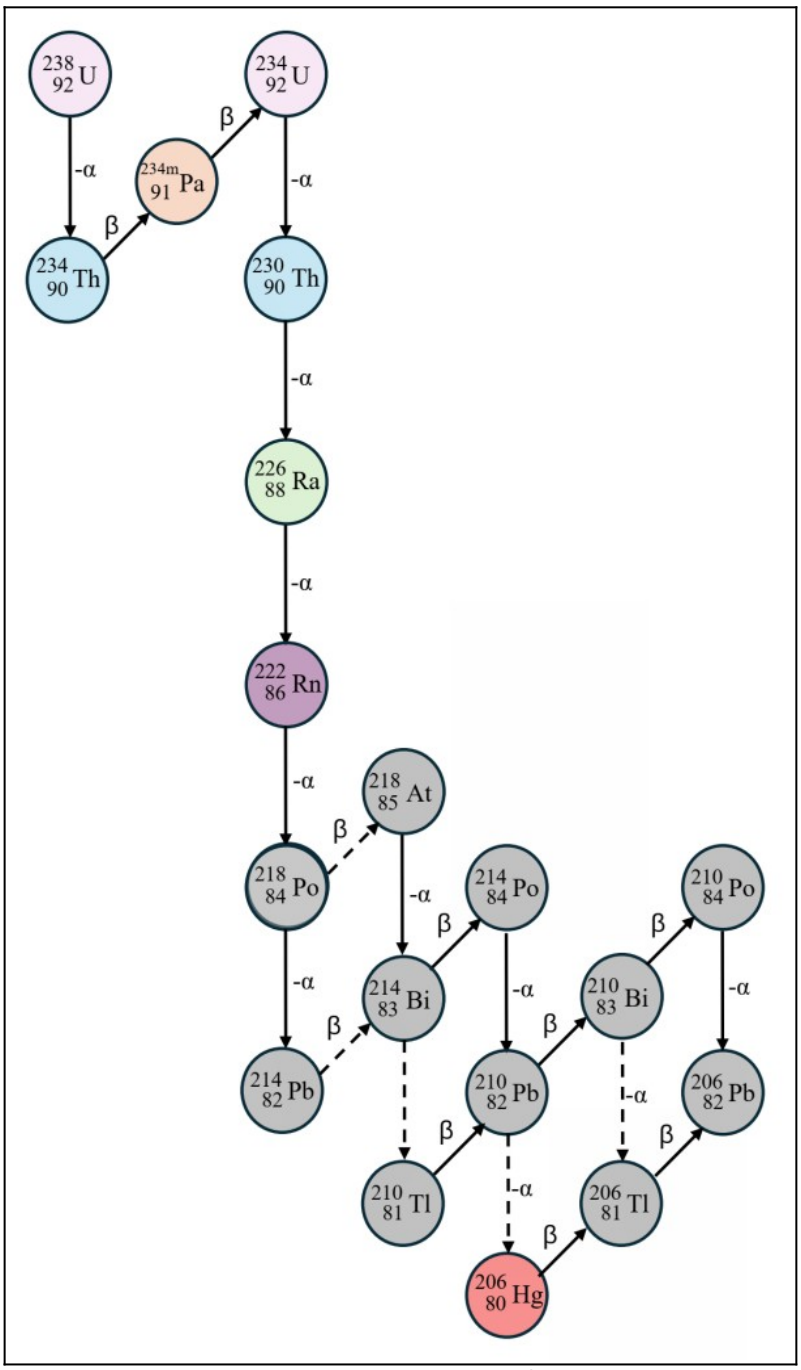

Figure 7. Radioactive decay of ^{238}U showing the various other isotopes formed before finally finishing up with the stable lead isotope ^{206}Pb.

The Geology of Uranium and Thorium Deposits

It has previously been assumed that biological processes played little or no part in the formation of uranium ores, but more recently, following analysis of a sediment core from uranium deposits in Wyoming (Ref. 27), a number of articles have been published that have indicated that some uranium ore-bodies may have been influenced by micro-organisms such as the proteobacteria *Geobacter metallireducens*, *Geobacter uraniireducens* and *Shewanella oneidensis* (Refs 27, 28). All of these micro-organisms have the ability to use uranium containing species as a terminal electron acceptor (Ref. 29).

The formation of uranium and thorium minerals depends not only on the mineralogy of the host rocks and the chemistry of hydrothermal fluids, but also on geological factors. For the mineral collector, a detailed knowledge of the geology of the deposits in which uranium and thorium are found is not usually necessary, but a basic understanding of the type of matrix that these minerals are found in can give an informative guide as to where they may be found.

Geological factors that have an influence on the formation of secondary uranium minerals include the porosity of the host rocks and features such as faults and folds in the rocks. All of these can give rise to higher permeability pathways through which the solubilised uranium cations can travel. They can also create localised zones in which the uranium can concentrate; this then leads to the formation of secondary uranium minerals. There are two aspects to the porosity of rocks that are important. Firstly, the extent of cementation during the lithification of sedimentary rocks affects the primary porosity (i.e. the initial pore sizes in rocks and sediments). Secondary porosity refers to the porosity that develops after the initial formation of the rocks and occurs due to geological processes such as dissolution, fracturing and dolomitisation. These processes can significantly change the water storage in, and flow capacity of, the rock. Sandstones are important in the formation of secondary uranium minerals because they are much more porous than granites which enables the solubilised UO_2^{2+} cations to flow through them with much greater ease than they could through a rock with a much lower porosity such as a granite. Heinrich published a notable

account of the deposit types that radioactive minerals are found (Ref. 30); he showed that there were eleven types of deposit yielding radioactive minerals. These are described below.

1. Unconformity-Related Deposits

Unconformities are often indicative of older rocks being eroded before younger layers are deposited. In regions where the soluble uranium concentration is high, unconformities can be areas in which secondary uranium minerals are formed (Figure 8).

Figure 8. An angular unconformity, Navajo Sandstone, Page, Arizona, USA.
John Nakata photo used with permission under an Adobe.stock image subscription standard copyright licence.

2. Syngenetic Deposits in Igneous Rocks

Syngenetic deposits are those that form at the same time as the rocks that they occur in. Magmatic deposits, such as granites, are considered to be syngenetic because the ore minerals contained in them crystallise from the same molten rock that produces the silicate minerals of the intrusive rock. Radioactive minerals that occur in granites include zircon, fluorapatite, allanite and the rare-earth minerals xenotime and monazite, although the concentration of uranium and thorium in these minerals is quite low. Radioactive minerals tend to be accessory minerals that are minor constituents of this type of deposit. Examples of such minerals include uranothorite, thorianite, thorite and davidite.

3. Pegmatite Deposits

Pegmatites are igneous rocks that have a very coarse texture and contain large, usually interlocking crystals that can range between about 1 cm and 1 m in size (Figure 9). They are the last fraction of magma to crystallise. Most pegmatites are comprised of quartz, feldspar (very notably potassium feldspar and plagioclase feldspar) and mica (very commonly muscovite and biotite). They have similar quartz contents to granites which can reach up to 63% quartz. Uranium and thorium are relatively common minor constituents of pegmatites but, like syngenetic deposits in igneous rocks (see above), they do not contain enough uranium and thorium to make them economically worth mining on a commercial scale for these elements. Despite this, pegmatites are an excellent source of many primary uranium and thorium minerals that collectors of radioactive minerals enjoy.

Figure 9. White feldspar crystals growing in a pegmatite rock.
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Some are primary minerals that have formed directly from magmatic or hydrothermal processes whilst others are supergene minerals formed by the action of rainwater or ground water on primary minerals in the presence of oxygen. Uraninite is an excellent example of a primary radioactive mineral found in pegmatites that can form very nice crystals. It is much more abundant in them than thorianite. They are also the main sources of mixed oxide minerals such as members of the pyrochlore group, the samarskite group, the aeschynite group, davidite and chevkinite. Phosphate minerals such as monazite and, to a lesser extent, xenotime are quite commonly found minerals in pegmatites along with silicates such as thorite, allanite, gadolinite and zircon (which can contain up to 2% hafnon, $HfSiO_4$).

Supergene uranium minerals that occur in pegmatites are formed due to weathering of the pegmatite. Weathering occurs close to the surface of the Earth where primary minerals such as sulphides are exposed to the effects of water and oxygen. Other processes that occur during weathering are hydration, dissolution and precipitation. Uranophane is a good example of a supergene uranium mineral that forms from the weathering of uraninite. Other examples of such minerals include; phosphates such as autunite, torbernite and the very rare mineral althupite; hydrous uranyl oxides such as schoepite; carbonates such as rutherfordine, phosphates such as torbernite, arsenates such as autunite and vanadates such as carnotite. 'Gummite' also occurs in pegmatites and is a mixture of different oxidation products of uranium; consequently, it does not have a fixed chemical formula and so it is not an approved mineral.

Some important pegmatite localities for primary radioactive minerals are the Bancroft area of Canada, the Ruggles Mine in New Hampshire, USA and the area near Colorado Springs in Idaho, USA.

4. Carbonatites

Nearly all carbonatites are intrusive carbonate-silicate rocks of magmatic origin that consist of more than 50% carbonate minerals with smaller amounts of silicates, oxides and phosphates (Fig. 10.). They frequently form the lower part of the necks of some explosive volcanoes, but can also occur in other geological features such as dikes or breccia zones and are frequently associated with nepheline syenite ring deposits. The carbonate minerals found in carbonatites are mostly calcite or dolomite, although other carbonate minerals such as ankerite or siderite can also occur in them. Thorium tends to be more abundant than uranium in carbonatites with thorite and thorianite being the only two notable thorium minerals present. Some examples of uranium minerals that are found in these rocks include uraninite and uranium-containing rutile, bastnäsite, parisite and brannerite, but carbonatites always contain more thorium minerals than uranium minerals.

Figure 10. Carbonatite from Jacupiranga Estado de São Paulo, Brazil. Specimen size is 20 x 14 cm and comprises black magnetite, white calcite and green olivine.

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5. Pyrometasomatic Deposits

Pyrometasomatic deposits are also known as skarn deposits. These are formed when high temperature fluids alter rocks which leads to substantial changes in their mineralogy and chemistry. They tend to occur in limestones or marbles that are either at, or are close to, igneous contacts where hot mineral-rich solutions pass through reactive rocks. Gold, copper and tungsten are valuable metals that are obtained from this type of deposit that often also contain garnets and pyroxenes. Wheal Edward in Botallack, Cornwall is famous amongst collectors for its uranium minerals such as uraninite, torbernite, saléeite, zippeite and autunite; it is a good example of this type of deposit.

6. Hypothermal Deposits

Hypothermal deposits are a type of hydrothermal deposit that form at high temperatures and pressures at depths in the Earth ranging between a few hundred meters and about 5 kilometres. These rocks either crystallise from hot water, or alter because of the hot water passing through them. Davidite veins and brannerite deposits are both good examples of hypothermal deposits. In this type of deposit, uranium and thorium tend to be closely associated with davidite and brannerite. Thorian uraninite is the only radioactive mineral of any significance in this type of deposit in which it is commonly associated with minerals such as ilmenite, hematite, pyrite, magnetite and molybdenite.

Occasionally though, other minerals such as hubnerite, cobaltite and cassiterite can be associated with thorian uraninite.

Davidite vein deposits occur at Radium Hill in Australia and in the Mavuzi district of Mozambique where davidite crystals more than 30 cm in diameter have been found.

Brannerite deposits occur at the California Mine in Colorado and at the molybdenite deposit at Chateau-Lambert in Bourgogne-Franche-Comté, France (brannerite and uraninite are the only uranium minerals that occur here).

7. Mesothermal Deposits

Mesothermal deposits are formed at depths of 1-10 km and at temperatures ranging from about 250 C to about 400 C. They are usually formed by hydrothermal fluids that travel through cracks in the host rock. As the fluids cool and the pressure decreases, the minerals dissolved in them crystallise. This leads to the formation of quartz veins in the host rock that contain gold and other valuable minerals. Gangue minerals found in this type of deposit are either carbonates or poorly crystallised quartz. Sulphide minerals such as galena, sphalerite, pyrite, chalcopyrite and arsenopyrite are very common in this type of deposit, although arsenopyrite is less common than all of the other minerals shown here.

There are three types of radioactive mesothermal deposit; the nickel-cobalt-silver (Ni-Co-Ag) type, the pitchblende-pyrite type and the monazite/thorite veins. The best example of a Ni-Co-Ag type deposit is the famous Shinkolobwe Mine in Haut-Katanga, Democratic Republic of Congo. This mine is famous for producing a large number of very well-crystallised uranium minerals, some of which are extremely rare. An example of a pitchblende-pyrite type deposit are the Margnac Mines in France whilst an example of a monazite deposit is at Steenkampskraal, South Africa where the monazite is associated with quartz, pyrite, hematite, and fluorapatite.

Radioactive minerals found in this type of deposit are mostly uranium minerals such as uraninite, or secondary minerals such as carnotite, autunite and torbernite. However, the Shinkolobwe Mine in the Democratic Republic of Congo produces some very rare minerals including phosphates, silicates, oxides, hydroxyl oxides and those that contain either yttrium [bijvoetite-(Y)], or gadolinium [lepersonnite-(Gd)] as the dominant rare-earth element.

8. Epithermal Deposits

Epithermal deposits are those that form at depths less than 1,500 metres and temperatures between 100 C and 200 C. They are created when hot fluids that are rich in minerals circulate through fissures and fractures in the host rocks and are not rich in sulphide minerals, but pyrite and marcasite are often present with minor amounts of galena, sphalerite and chalcopyrite. They are frequently associated with volcanic activity and sometimes contain valuable metals such as gold and silver, for example. They form high grade ores albeit in relatively small quantities. Associated minerals in such deposits include fluorite and/or quartz, iron and/or manganese oxides, pyrite, marcasite, galena, sphalerite and chalcopyrite.

Epithermal thorite veins contain the minerals thorite and thorogummite, but also usually contain significantly smaller amounts of uranium minerals. Associated minerals in this case include feldspar, smoky quartz, hematite, fluorite and barite.

Silica-rich epithermal deposits produce quartz and pitchblende that has replaced pyrite. The host rocks are either granitic or monzonitic[2]. Oxidation of the pitchblende in these deposits gives rise to a number of secondary uranium minerals including meta-autunite, metatorbernite, metazeunerite, phosphuranylite, uranophane and uranophane-β.

Fluorite-Sulphide veins contain localised concentrations of uraninite and uranothorite in breccia pipes hosting fluorite. Minerals associated with the uraninite include pyrite and ilsemannite as well as secondary uranium minerals including uranophane, tyuyamunite, carnotite and walpurgite.

2 Monzonite is an igneous intrusive rock, formed by slow cooling of underground magma that has a moderate silica content and is enriched in alkali metal oxides. It is composed mostly of plagioclase and alkali feldspar.

Fluorite-Quartz-Sulphide Veins, such as the fluorite vein deposits in Wölsendorff, Germany contain an array of secondary uranium minerals including schrökingerite, johannite uranophane, uranophane-β, tyuyamunite, metatorbernite and phosphuranylite.

Collapsed breccia pipes are another type of epithermal deposit and these comprise a circular, vertical collapse that is between 30 m and 200 m in diameter and up to 1km deep. The pipes are filled with coarse fragments and a fine matrix comprising of the penetrated sediments. Most of the uranium in these structures lies mostly within the sandstone breccia within the pipe. Uraninite is the most commonly found uranium mineral in these structures which are very rare, with most currently known examples being located near the Grand Canyon in Arizona, and more so in the Arizona Strip in northern Arizona, USA although a breccia pipe cutting Eday sandstone occurs at Orphir Bay, on mainland Orkney, Scotland (Fig. 11).

Figure 11. Breccia pipe (tuffisite dyke) cutting Eday Sandstone at Orphir Bay, Mainland Orkney.
Image: Mike Norton, CC BY-SA 3.0.

Thorite veins and breccia pipes, an example of which is the Thorium Mountain Claims in Custer County, Colorado, USA, contain quartz, barite, fluorite, galena, hematite, siderite and minor amounts of microcline feldspar. Thorite and thorogummite are usually found as fine veinlets or pods that are disseminated throughout the veins in which the rare-earth mineral xenotime can be quite abundant in places.

9. Deposits in Sedimentary Rocks

Sandstone ore deposits are important sources of uranium for commercial mining because they are often very large, easy to mine and have good economic potential. Uranium in sandstone deposits occurs in medium or coarse-grained sandstones and is precipitated under reducing conditions caused by a variety of natural reducing agents within the sandstone such as carbonaceous material from decaying plants, humates[3] or marine algae, or in sulphur rich environments containing sulphides or the extremely toxic gas hydrogen sulphide (H_2S).

In more modern times, sandstone is also seen as being more environmentally friendly than other types of deposit and constitute about 28% of guaranteed resources with the potential to constitute perhaps up to 40% of possible resources. It is only because of the size of these deposits that they are worth mining because the typical concentration of uranium in low to medium grade sandstones can be anywhere between 0.05% and 0.35%; individual orebodies are not typically more than of medium size but which nonetheless contain up to 50,000 tonnes of uranium. The main minerals found in sandstones are uraninite and coffinite. The countries having the most economically most important reserves of uranium are the USA, Niger, Kazakhstan and Uzbekistan.

Sandstone deposits can be sub-divided into five different sub-types, although they are often not one single type:

- Basal channel deposits. These are wide channels that are filled with permeable sediments.
- Tabular deposits. These are flat, layered bodies that can be either horizontal or at an angle.
- Roll-front deposits. These are uranium deposits that are crescent (bow-shaped) deposits that typically occur in sandstones.
- Tectonic/lithologic deposits. These occur in sandstones adjacent to a permeable fault zone and have tongue-shaped ore zones along sandstone layers that lie adjacent to a fault. The Lodève

3 Here humate refers to geological materials, such as weathered coal beds (leonardite), mudrock, or pore material in sandstones, that are rich in humic acids.

district in France is a good example of this type of deposit and is famous among collectors for its autunite specimens.

- Mafic dykes or sills in Proterozoic sandstones. These deposits give important insights into both the magmatic activity and the tectonic formation of the Earth's crust. They are primarily comprised of mafic minerals that are rich in iron such as pyroxene, olivine, hornblende and biotite mica.

The main minerals found in all of these deposits are uraninite and coffinite.

10. Placer Deposits

Placer deposits are commonly found in marine or alluvial sediments and are mostly comprised of coarse, quartz-rich minerals. They are formed by gravity separation from a host rock during sedimentary processes (Ref. 31). They typically contain "black sand" which is a lustrous, black mixture of iron oxides comprised mostly of magnetite with lesser amounts of hematite and ilmenite (Ref. 32). The valuable minerals contained in the black sands include monazite, rutile, zircon, chromite, wolframite and cassiterite (Ref. 32). Such deposits were easily accessible for early, easy mining and quite large in size. Uraninite is the most commonly found uranium mineral in placer deposits, but other uranium-containing species can also be present including samarskite, gadolinite, davidite and brannerite. Both thorite and thorianite are found in placer deposits and the sands found on beaches. The sands in Madagascar and Sri Lanka are well-known to be quite rich sources of these two thorium minerals. Thorium minerals are well-known to be stable towards oxidation because the chemistry of it dictates that it loses all four of its electrons from its outermost electronic shells meaning that once those four electrons have been lost and the Th^{4+} oxidation state is achieved, it does not have any further electrons that it can lose (see the Chemistry of Thorium and Uranium section below). Although thorium minerals are electronically stable towards oxidation, they are frequently metamict due to highly ionising α-radiation and lack the long range order that a crystalline solid requires (Fig. 12).

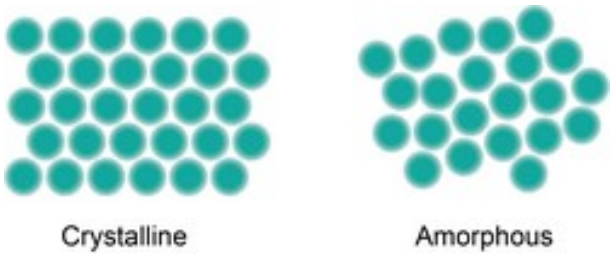

Figure 12. Comparison of the long-range order evident in crystalline solids with the lack of such order in amorphous solids.
Image used with permission under CC BY-SA 4.0. Image author reference number Qs6160.

This has a tendency to reduce their ability to somewhat resist weathering and alteration. Consequently, at least from a commercial point of view, the most radioactive placer deposits contain mixtures of the minerals found in all types of pegmatite including monazite, zircon, thorite, euxenite, samarskite and xenotime. The only placer deposits of any interest to collectors are in alluvial gem gravels containing sapphire, chrysoberyl, aquamarine and ruby from Balangoda, Sri Lanka where thorianite occurs as small, water-worn, black, cubic crystals that reach up to 1.5 cm in size. The Ambosoary Sud district of Madagascar produces thorianite crystals that reach up to an impressive size of 6 cm.

11. Deposits Formed by Weathering and Groundwater

To collectors, this type of deposit is perhaps the most interesting because it is here that the interesting geochemistry of uranium becomes apparent. Brightly coloured uranium secondary minerals can be green, greenish yellow, yellow, orange or red. Such minerals are generated either on or near to the primary deposit and form coatings, replacements or pseudomorphs of other minerals. Mineral veins that are oxidised *in situ* originate as veins of the primary mineral uraninite that also contain sulphide minerals such as pyrite, galena, sphalerite, chalcopyrite, and others. When hydrothermal fluids pass over uraninite, a process called alpha-radiolysis occurs in which the powerfully ionising alpha-radiation generates hydrogen peroxide in the water. Hydrogen peroxide is a strong oxidising agent. This can then oxidise uraninite to the very water soluble uranyl cation, UO_2^{2+}. The now-solubilised uranium can be carried by water, sometimes over considerable distances, before precipitating out from solution when the chemistry of the water changes. Hydrogen peroxide also oxidises sulphide minerals to sulphates; whilst lead sulphate (anglesite) is insoluble in water and hence remains *in situ*,

other sulphides such as those of copper, cobalt and zinc that may also be present in the vein can also be oxidised by hydrogen peroxide releasing the corresponding solubilised metal cations and sulphate anions. These cations can then get mixed in with uranyl cations and sulphate anions in the water from which insoluble uranium minerals are precipitated if the chemistry of the water changes or the fluid cools to the point where secondary minerals crystallise out of solution.

The most common uranium secondary minerals that form tend to be uranyl phosphates, sulphates and silicates. If ions such as Ca^{2+}, Cu^{2+}, Zn^{2+} or Co^{2+} are present, minerals such as autunite, torbernite, uranophane, uranocircite, parsonsite, saleeite, zippeite, uranopilite, schröckingerite and uranopilite form, all of which are relatively common (although some are far more common than others). If the primary ores contain vanadium, uranyl vanadate minerals such as carnotite can form whilst primary ores containing arsenic can lead to the formation of uranyl arsenate minerals such as zeunerite and uranospinite to name but two.

Secondary uranyl oxides such as becquerelite, schoepite and masuyite tend to form either as pseudomorphs or as alteration layers on uraninite. However, these minerals can be simply washed away when there is a high flow rate of groundwater.

The depth of an oxidation zone can vary between 50 m and 300 m and can be defined by the depth of the water table. That does not mean, however, that oxidation cannot occur below the water table. It can occur, for example, in cases when the depth of the water table fluctuates with changing seasons. Other examples of when oxidation occurs at greater depths than the water table include large variations in permeability generated by local fractures in the surrounding rocks, or when the water table was previously lower.

Some deposits of this type are formed by the redistribution of groundwater when the mobile, water soluble $(UO_2)^{2+}$ cations become absorbed onto coal. Some coal deposits in Europe and the USA are radioactive due to the presence of secondary uranium minerals such as 'gummite', autunite, torbernite and saleeite, although the quantity of uranium minerals in the coal is exceedingly small so as to not be of any concern at least until the coal is burnt, after which only the non-combustible components of the coal, which are normally minerals, remain. This increases the concentration of uranium in the ash.

Chemistry of Thorium and Uranium

The nucleus of all of the elements comprises a mixture of protons and neutrons. Protons carry a positive electrical charge, whilst neutrons are uncharged. Electrons, which carry a negative electric charge, orbit the nucleus in a series of fixed energy levels known as electron shells. Each shell consists of one or more sub-shells and each corresponds to a principal quantum number, $\boldsymbol{n}$, where $\boldsymbol{n}$ = 1, 2, 3, 4, etc. Each of the periods (lines of elements going across the periodic table) represents an electron shell. Hydrogen (H) has $\boldsymbol{n}$=1 whilst lithium (Li) has $\boldsymbol{n}$=2 and sodium (Na) has $\boldsymbol{n}$=3, and so on. The nearer an electron shell is to the nucleus, the lower its energy. Each of these shells can only contain a certain number of electrons. The maximum number of electrons that a shell can contain is given by the formula $2\boldsymbol{n}^2$. When $\mathbf{n}$=1, that electron shell can hold two electrons, whilst a shell with $\boldsymbol{n}$=2 can contain eight electrons and a shell with $\mathbf{n}$ = 3 can contain eighteen electrons. The factor of two comes about because the number of allowed states doubles with each successive shell because of electron spin. Electrons are not static. Not only do they orbit the nucleus, but they also have a spin, meaning that they can rotate around their own axis. Within each shell, there can be multiple atomic orbitals. There are four different types of atomic orbital known as s, p, d and f orbitals (the s block, p block, d block and f block elements in Fig. 4 are so-named because they represent the filling of, for example, the s, p, d or f atomic orbitals with electrons). Each orbital has two additional quantum numbers to the principal quantum number and these are the angular quantum number, ℓ, (sometimes called the azimuthal quantum number) and the magnetic quantum number, m_ℓ, which correspond to the energy of an electron, its orbital angular momentum and its orbital angular momentum projected along a chosen axis respectively. Each orbital has a unique shape and energy level; the shape of the orbital is defined by the angular momentum quantum number. The s orbitals (which have m_ℓ = 0) are spherical in shape and hence have highest symmetry. However, whilst the p orbitals, which are shaped like a

dumbbell) can hold up to six electrons, each orbital can only contain two electrons, so there must be three p orbitals (which have m_ℓ = -1, 0 and +1) and these are denoted by p_x, p_y and p_z where, for example, the p_x orbital has two lobes of electron density that lie along the x axis. The same is true for the p_y and p_z orbitals in which the lobes lie along the respective axis. All three of the p orbitals are degenerate, meaning that they all have the same energy (Fig. 13).

The d-orbitals (which have m_ℓ = -2, -1, 0, +1 and +2) and f-orbitals (which have m_ℓ = -3, -2, -1, 0, +1, +2 and +3) are more complex, but still have dumbbell shapes. There are five degenerate d-orbitals (d_x, d_y, d_z, $d_{x^2-y^2}$ and d_{z^2}) in the elements, each of which can hold two electrons, one in each lobe meaning that the d-orbitals can contain a maximum of ten electrons (note in the periodic table shown in Figure 4 that the d-block contains ten elements). There are seven degenerate f-orbitals (f_{z^3}, f_{xz^2}, f_{yz^2}, f_{xyz}, $f_{z(x^2-y^2)}$, $f_{x(x^2-3y^2)}$ and $f_{y(3x^2-y^2)}$) in the f-block elements and again, each of the two lobes in an orbital can each contain one electron meaning that the f-orbitals can contain a maximum of fourteen electrons. Figure 4 shows that the f-block contains two periods, the upper one of which is called the lanthanide (or rare-earth) group whilst the lower one is called the actinide group. Both of these periods comprise fourteen elements each.

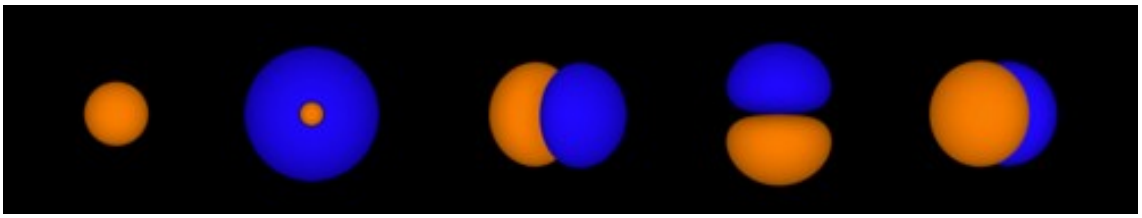

Figure 13. The first five atomic orbitals are 1s, 2s, $2p_x$, $2p_y$, and $2p_z$ have the above shapes. The two colours show the sign of the wave function which describes the behaviour of an electron in each region.
Diagram is used after being released into the public domain.

Electrons occupy these orbitals, although they are not "hard-walled" areas into which electrons are confined but instead they are mathematically calculated regions of space in which there is a high probability of finding an electron.

Each atomic orbital, with the exception of the s orbitals, has two lobes and each lobe contains one electron meaning that each atomic orbital can contain two electrons. In one lobe, the electron has a spin of +½ whilst the other contains an identical electron except that this time, the electron spin is -½. Electronic configurations are built up by filling the lowest energy levels (the ones closest to the nucleus) first. By applying this principle, the electronic configuration of sodium (atomic number 11) can be written as $1s^2\ 2s^2\ 2p^6\ 3s^1$. Nickel (atomic number 28) has the electronic configuration $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^8$. However, by the time the heavy elements are reached, writing the electronic configurations out in this way becomes rather long-winded. The electronic configuration of thorium, for example, is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6\ 6s^2\ 4f^{14}\ 5d^{10}\ 6p^6\ 7s^2\ 6d^2$. Consequently, it is common to condense this using the noble gas core notation $[Rn]7s^2\ 6d^2$ where [Rn] is the electronic configuration of radon. Note that in the long version of the electronic configuration of thorium, the 4f shell lies in between the 6s shell and the 5d shell. This is because the 4f orbitals have a higher "n + l" value, which is the total of the principal quantum number, n, and the azimuthal quantum number, l. The 4f orbital in thorium has an "n+l" value of 7 whilst that of the 5d orbital is 6. The difference in energy levels and "n+1" numbers is due to what is called electron shielding, where the inner electrons in the 5d and 6s orbitals are filled before the 4f orbitals which results in the 4f orbital being the last to be filled with electrons. This is because the effects of shielding mean that the energy levels of the orbitals are not strictly ordered solely by the sum of their principal and azimuthal quantum numbers.

All thorium minerals contain thorium in the +4 oxidation state and are resistant to further oxidation. This is because the unique electron configuration of thorium, $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6\ 6s^2\ 4f^{14}\ 5d^{10}\ 6p^6\ 7s^2\ 6d^2$, means that the loss of both electrons in the 7s sub-shell and both electrons in the 6d sub-shell mean that a highly stable electronic structure is obtained known as a noble gas configuration (in other words, by forming Th^{4+} ions, thorium achieves the same number of electrons

as the noble gas, radon. Noble gases such as helium, neon and argon are extremely unreactive because they have very stable, full outer electronic shells; the only other shells that are stable are those that are either completely empty or half-filled.

In primary rocks and magmas, uranium is always present as the large, highly charged U^{4+} cation which effectively prevent it from being incorporated into the usual rock-forming silicate minerals as they crystallise on cooling from the magma. However, uranium can exist in more than one oxidation state; in minerals, the oxidation states commonly encountered are U^{4+}, U^{5+} and U^{6+}. The electronic configuration of uranium metal is $[Rn]5f^{3}6d^{1}7s^{2}$. Loss of all six of these electrons results in the formation of the U^{6+} cation which is only stable in a few simple compounds such as uranium hexafluoride, UF_6, and in a handful of minerals such as orthobrannerite. However, the vast majority hexavalent uranium minerals, which are formed by oxidation of uraninite in the presence of water, exist as the very stable, readily water-soluble uranyl cation, UO_2^{2+}. The two oxygen atoms attached to the uranium atom in the uranyl cation render this cation stable. Other factors that determine the exact chemistry of the minerals formed in solution are the pH of the solution and the availability of other anions of the water and it must be remembered that there will usually be several ionic species present at different concentrations. The concentration of each species in solution is determined by the equilibrium constant of the particular reactions. In acidic solutions having a pH of <4, the $(UO_2)^{2+}$ cation is the only uranium species present. However, at pH 6, four species are possible: $(UO_2)OH^{+}$, $(UO_2)SiO(OH)_3^{+}$, $(UO_2)(HPO_4)_2^{2-}$ and $(UO_2)CO_3$, depending on the availability of the respective anions. At pH 7, only three species are present in solution: $(UO_2)_3(OH)_5^{+}$, $(UO_2)(HPO_4)_2^{2-}$ and $(UO_2)(CO_3)_2^{2-}$. Due to the high mobility of the $(UO_2)^{2+}$ ion in water, it can travel great distances before it meets a suitable anion with which it will react to form a mineral with a much lower solubility which causes it to precipitate out of solution as the hot water cools. The solubility of the precipitated mineral depends on the chemistry of the anions that react with the UO_2^{2+} cation. The solubility of these uranyl minerals follow a fairly regular sequence, and the order of decreasing solubility is as follows: carbonates > sulphates > phosphates and arsenates > silicates > vanadates. This is why the most commonly encountered uranyl minerals are vanadates such as carnotite and tyuyamunite, followed by the phosphates and arsenates, then silicates (especially uranophane), then sulphates (e.g. zippeite) and finally carbonates (e.g. rutherfordine). There is a large range of possible combinations of the UO_2^{2+} cation with other metal cations and this, in combination with six potential anions (or combinations thereof) creates a broad diversity of brightly coloured secondary minerals.

Although much rarer, uranium can also exist in the U^{5+} oxidation state in minerals such as wyartite, richartite, shinkolobweite and nollmotzite, all of which are examples of mixed oxidation state minerals where uranium exists in two oxidation states in the same crystallographic unit cell. In all of these minerals, the very stable uranyl cation is present alongside the much less stable U^{5+}. For example, the chemical formula for wyartite is $Ca[U^{5+}(U^{6+}O_2)_2(CO_3)O_4(OH)](H_2O)_7$.

Some rare uranium minerals contain two other, different oxidation states; ianthinite and moluranite both contain both U^{4+} ions and $(UO_2)^{2+}$ ions, whilst orthobrannerite contains uranium in both the U^{4+} and U^{6+} oxidation states (note that the hexavalent uranium in orthobrannerite is unusually not present as the more common uranyl cation).

Tetravalent uranium is not common in minerals with the only commonly known species to contain the U^{4+} cation being uraninite, coffinite and brannerite, all of which are dark brown to blackish in colour. Although uraninite is the most abundant uranium mineral, the poor solubility of the U^{4+} cations in water means that, unlike the $(UO_2)^{2+}$ cation, it cannot travel great distances in water. This significantly reduces the chances of it encountering suitable anions with which it can form other minerals. However, there are some very rare minerals that also contain the U^{4+} cation and these are ishikawaite, lermontovite, mourite, sedovite, vysokýite, štěpite, uranopolycrase, vyacheslavite and běhounekite, the latter of which is the only known simple tetravalent uranium sulphate, $U(SO_4)_2.(H_2O)_4$.

Identification of Radioactive Minerals

If you think you have an unknown radioactive specimen, first of all, identifying that it is indeed radioactive is a good starting point. There are apps available for your mobile phone that can be downloaded. Some work by blocking all of the light coming into a phone's camera sensor using a piece of tape or plastic film. High energy radiation causes artifacts on the CMOS camera sensor inside the phone resulting in radiation being captured as tiny flecks of white light on the screen. Whilst these apps tell you that something is radioactive, they only work with gamma radiation and x-rays and they do not always provide a numerical value for the dose rate, however there are some apps available that give graphical information. The main disadvantage of this type of radiation detector is that many mobile phones do not have specialised radiation detection technology. Instead, they tend to rely on internal smartphone sensors, such as the accelerometer or magnetometer. These are not designed for this purpose. As a result, these apps may struggle to detect low levels of radiation or differentiate between natural background radiation and potentially harmful sources which leads to a compromised ability to provide precise readings. However, whilst the Android app called "Radiation Detector" also uses the phone's camera sensor to detect ionising radiation, such as gamma rays and beta particles, it can also display radiation levels in real-time, with a colour-coded scale indicating the level of radiation detected. While these apps have some function as radiation detectors, the best way to detect radiation quantitatively is to use a conventional Geiger counter which uses a Geiger-Müller (GM) tube as the sensor and which can be calibrated (using a Cs-137 source which has a half-life of 30 years and costs in the region of £800). However, there are specialist companies who will calibrate a Geiger counter, but this is not a cheap option, especially for private individuals. One of the most commonly used Geiger counters amongst collectors of radioactive minerals is the Mini I series 900 Mini Monitor, Fig. 14, (although there are other models in the Mini I series). These can be obtained second hand for about £300-400 from eBay, for example. Some Geiger counters can be obtained from Amazon for less than £100 and they are all but essential if you are going to collect radioactive minerals. Geiger counters give an approximate dose rate and many are battery-powered meaning that they are readily portable for use in the field. Of course, they cannot identify a mineral, all they can do is to tell you that it is radioactive and, if so, to what extent. The Geiger-Müller tube on such Geiger counters will not detect all types of radiation; some measure just alpha radiation whilst other measure beta, gamma and x-ray radiation depending on the Geiger-Müller tube. The latter are the most expensive costing up towards £1,000.

Figure 14. Mini-Instruments radiation monitor 900 with a 15 cm² detection area EP15 GM probe that will detect α (> 3 MeV), soft β and γ radiation.

Once you have a good feel for whether your specimen is radioactive or not, you need to identify it.

There are a number of good books that can be bought second-hand that can also be useful in identifying minerals, all costing under £20. One such example is the *Identification Guides Rocks and Minerals* by E. Fejer, S. Frampton and C. Fitzsimmons and published by Flame Tree Publishing in 2007 (ISBN 9781844519217).

In the Junior Members' Magazine of September 2025 (Issue 2) the editor, Gary Morse, gave an excellent and very detailed account of simple tests that can be performed at home with simple, low-cost or no-cost equipment. Not only are these tests fun to do, but by amassing as much data as possible about a mineral from these tests it is possible to get a very good indication as to what the unknown mineral is. Of course, knowing the exact location a specimen comes from substantially reduces the number of possibilities as to what the unknown mineral might be, so this coupled with test data can usually give an identification with a reasonable degree of certainty. The internet can also be an invaluable aid for identifying minerals that have either been self-collected or acquired from other people. Mindat (www.mindat.org) is by far the most commonly used website for mineral collectors and can be a valuable tool for helping with the identification of an unknown mineral. It is an incredibly extensive database of minerals and shows photographs of many of all of the known minerals and a list of the different mineral species found at a particular location. However, even Mindat is not exhaustive and doesn't provide a photograph of every mineral found at every locality, but it can be useful if there is a photograph on the website from the locality that your unknown specimen is from. Comparison of your results with those in the Physical Properties section of a mineral on Mindat and a subsequent comparison of the appearance of your unknown mineral with those in photos of what you think it might be can be used to confirm the identity of a mineral, especially if there is a photo of that species from the same sample locality on Mindat. The relatively new advent and rise of "AI" technology has led to a number of websites that use "AI" to identify unknown minerals. Whilst it is easy to visit these websites and put all of your faith into the results that they give, please bear in mind that these are far from reliable and can give very misleading results, so please do not put your trust in this technology because they are notoriously very poor and inaccurate and are no substitute for the traditional ways of mineral identification, which are also a lot

Figure 15. Some superb specimens of radioactive minerals. Clockwise from top left: Autunite from Daybreak Mine, Mount Kit Carson, Spokane County, Washington, USA. Size: 6.7 x 4.2 x 3.8 cm. *Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.* *Torbernite from Old Gunnislake Mine, Gunnislake, Cornwall. No size given.* *James St. John Flickr stream CC-BY-2.0.* *Cuprosklodowskite from Musonoi Mine, Kolwezi, Democratic Republic of Congo. Size: 3.6 x 2.7 x 2.2 cm.* *Rob Lavinsky, iRocks.com – CC-BY-SA-3.0.* *Uraninite from Trebilcock Pit, Topsham, Maine, USA. Size: 2.7 x 2.4 x 1.4 cm.* *Rob Lavinsky, iRocks.com – CC-BY-SA-3.0. All images from Wikimedia Commons.*

more fun. The best way to identify a mineral is to do your own research and compare your unknown with that of a known specimen from the same locality.

Facebook has a number of mineral collecting groups, including one for radioactive minerals in which there are people with a lot of experience who may be able to assist in the identification of a mineral. However, the chances of receiving a reasonably confident identification often depends on how information about the specimen can be given to the person or people trying to identify the mineral for you. Details such as the matrix, the mine and location from which the specimen came from, along with any known associated minerals can be very helpful in identifying the unknown mineral.

If, however, after performing these simple tests and knowing where the specimen is from, you are still unsure as to the identification of the unknown mineral, the Russell Society has some members who are experts in radioactive minerals or who have considerable collecting experience at a particular mine or in a particular region. Many of these members are "walking textbooks" and are more than willing to share their knowledge and experiences to help younger collectors with the identification of a mineral. Remember, we all started off in the same position as you and many of us were collecting long before the internet was even invented!

Where to Acquire Radioactive Specimens

Some mines have not been active for many years and are now, regrettably, in an unsafe condition for collecting and exploration. Other sites famous for radioactive specimens, such as Wheal Edward in Botallack, Cornwall, are now Sites of Special Scientific Interest (SSSI) which means that to all intents and purposes, mineral collecting is not permitted. Permission may be granted to reputable groups such as the Russell Society, but prior written consent must be obtained from the National Trust and Natural England (or whoever the landowner is) before any specimens can be removed. However, it is not all doom and gloom! The Russell Society's mission is to encourage the study, recording and conservation of mineralogical sites, material and minerals and as part of that, we want to encourage younger collectors like you. However, although the Russell Society groups organise a number of collecting trips every year, the insurance unfortunately does not cover people under 18 years of age and so it is not possible for people under this age to go on Russell Society field trips.

Every year in the UK, there are a number of mineral shows where you can purchase specimens (and sometimes even negotiate a deal with a dealer!). Whilst this can never compete with the thrill of going out on a field trip and collecting your own specimens, they do give you the possibility of acquiring specimens for your collection and many of the dealers are very knowledgeable about the specimens they sell. If you ask, they can also be very good sources of information. Many good, knowledgeable collectors attend these shows which provide an easy avenue for you to build up a good network of like-minded people, some of whom may even have excess specimens in their collection that they may be willing to sell or even just give to you. At one time, some dealers had radioactive specimens on their tables, but more recently show organisers do not permit dealers to exhibit radioactive minerals. That does not mean, however, that dealers haven't got any radioactive minerals either in boxes under the tables, or in the back of their car, or at home. If you ask politely, they will tell you whether they have any or not.

The British Micromount Society (known as the BMS) [see above – Ed.] is another excellent group for those wishing to collect just small specimens that are known in the hobby as thumbnails or micromounts. The Society hosts an annual event in September where many British micromounters meet up for a series of talks, some good social interaction, an opportunity to build your network of knowledgeable people and to buy, sell or trade small to very small specimens. Some of the collectors there may have small examples of radioactive minerals that you could acquire for very little money. If you don't see any, just ask! One point to note here is that you must be a member of the BMS to be able to take part in this event and children under 18 years of age must be accompanied by an adult. A family membership costs just £18 per year as at 2025.

Health and Safety

Many mineral specimens contain toxic elements like lead or arsenic, but radioactive minerals also pose the additional risk of radiation. Some radioactive specimens are very radioactive indeed.

Radioactive minerals are constantly emitting radiation and releasing radon gas into the atmosphere, but to put it into some sort of perspective, having a few radioactive specimens in a room that you do not spend a considerable part of the day in will expose you to less radiation than an x-ray on a broken bone does. But that does not mean that you should be complacent about the storage and handling of radioactive specimens. You still need to be very careful. If you are not sure, put a post on the Radioactive Minerals Facebook page, or ask somebody knowledgeable. If you are unsure which species your specimen is, you should be able to do some of the tests in Gary's Mineral Identification article in Issue 2 of the JMM which was published in September 2025. However, you do need to be extra careful when handling radioactive minerals. If you break a crystal off a specimen to do some simple tests, do not get your face too close to the specimen or crystal because you do not want to breathe in any radon (once radon gets into your lungs, it never gets out because it is a very heavy gas) and neither do you want to breathe in any dust or tiny radioactive particles because they will continue to emit radiation in your lungs. (Radon, is invisible and has no smell and is tasteless, so you are never going to know that it is there). A good idea to prevent inhaling particles is to wear a mask (like the ones we used to wear when Covid was at its peak). You may also get radioactive particles on your hands or under your fingernails, so always wash your hands thoroughly immediately after handling any mineral, and especially radioactive ones. Whilst not usually essential for handling radioactive materials, some thin, latex gloves can be used to prevent contamination of the skin with radioactive material, although these can make handling of very small samples a little more tricky and even if you do wear gloves, you should always wash your hands thoroughly once you have finished handling your specimen. Keep as much of your skin covered as far as is reasonably practicable. The outer layer of the skin can block some of the radiation from penetrating further into your body, but unfortunately your eyes do not have that luxury and exposure of the eyes to radiation can lead to long term damage of them. It is therefore a good idea to wear some protective plastic safety glasses to protect your eyes. These are readily available at low cost from online retailers such as eBay and Amazon. It goes without saying that you should never lick or ingest particles of any mineral. Whilst there is no risk to looking at a radioactive specimen for a few minutes, you must avoid prolonged exposure in the close proximity of the body.

Small crystals may require magnification with a loupe to be seen clearly and whilst this is OK for very short periods of time, care should be taken not to breathe in when examining radioactive specimens at very close range because uranium and thorium are undergoing radioactive decay all the time and release small amounts of radioactive radon gas which should not be breathed in. It is a good idea to work on a disposable surface such as a sheet of paper or a sheet of plastic. Use sticky plastic tape to pick up any small particles of your specimens that have dropped off and dispose the contaminated tape in a sealed plastic bag. Whilst some radioactive minerals are fluorescent, which makes them easy to see under UV light, others are not. Whilst you might be tempted to vacuum the area where you have been working, this can blow radioactive particles up into the air. It is better to go round the area with sticky tape to clear the area of any radioactive debris. It is a good idea, if possible, to store radioactive specimens in a closed container. However, doing so allows radon to build up in the container and so it is good practice to open the container outside and leave it for a few minutes to allow the radon to disperse in the air before examining the specimen.

Radioactive minerals should be stored away from areas in which you spend a lot of time, such as your bedroom. Ideally they should be stored outside in a dry shed, outhouse or garage where there is good ventilation. If, however, you do not have access to any outside space, try to collect just small micromount samples that will fit into a plastic display box and keep your collection as small as possible stored all together and properly identified as being radioactive specimens. Keeping your specimens in acrylic boxes will considerably reduce the amount of radiation entering your airspace.

For more detailed information you should read the excellent "*Here be Dragons: The Care and Feeding of Radioactive Mineral Species*" by Alysson Rowan (PDF here).

The Natural Sciences Collections Association (NatSCA) have published in their *Journal of Natural Science Collections* an excellent article on "Identifying and managing radioactive geological specimens." by Monica Price, Jana Horak, and John Faithfull which can be obtained as a PDF at: https://www.natsca.org/article/84 [Accessed January 2026].

The key to safe storage of any radioactive materials is to remember that the radiation is distributed uniformly with a spherical radius having the source at its centre. Intensity decreases very rapidly as the inverse square of the distance from source. So avoid getting too close to your specimens. Distance is the greatest safety factor.

The last thing to consider is transporting radioactive specimens. Keep them securely packaged and properly identified on the outside of the packaging and keep them in the boot of the car. In the UK, and many other countries, radioactive materials and samples are classified as dangerous goods and are prohibited from being sent through the postal systems. There are also issues with carrying them on aeroplanes and they will be detected and may be confiscated.

Finally

In this article, a brief account of the discovery and chemistry of thorium and uranium has been presented along with the different types of radioactive decay, the geological formations in which radioactive minerals are found, some information of where and how to acquire radioactive specimens and some health and safety information. In Part 2, which will be published on 1st September, a much more detailed description and photographs of some of the more commonly encountered radioactive minerals, some uranium minerals with interesting chemistries and some very rare uranium and thorium minerals will be presented along with their physical properties.

Glossary

Amorphous: amorphous materials are also sometimes called non-crystalline solids. These materials lack the long-range order in a crystal lattice that crystals show.

Alteration: natural processes that alter a minerals chemistry or crystallography. Such processes include oxidation, hydration/dehydration, kaolinisation, uralitisation, pyritisation, opalisation, dolomitisation, radioactive decay, serpentinisation, epidotisation and chloritisation.

Atomic orbital: in quantum mechanics, atomic orbitals describe the location and wave-like behaviour of an electron in an atom. It describes the charge distribution around the nucleus of an atom and can be used to calculate the probability of finding an electron in a region of space surrounding the nucleus of an atom.

Breccia pipes: sometimes called 'chimneys', a breccia pipe is a mass of breccia that frequently occurs in irregular or cylindrical shapes. Breccia is a rock comprising either broken fragments of minerals, or rock that is held together by a fine-grained matrix.

Equilibrium constant: a value that shows the ratio of the concentrations of products to reactants when the reaction is in a state of equilibrium (i.e. the concentration of reactants and products does not change in a reversible chemical reaction).

Fault: a separation or discontinuity in a rock or a series of overlying rocks in which there has been a significant displacement of those rocks due to movements of them.

Fold: a stack of rock, such as sedimentary strata that has become either bent or curved during a permanent deformation event.

Hydration: a chemical process in which water is absorbed by a mineral leading to the formation of different minerals known as hydrates.

*Igneous: v*ery hard rocks that are formed from the cooling and solidification of magma. Igneous rocks make up 90 – 95% of the top 16 km of the Earth's crust by volume.

Metamict: a metamict crystal is one that has the outward appearance of a crystal that has undergone the process of metamictisation which is a natural process resulting in the gradual and ultimately complete destruction of the crystal structure of a mineral by highly ionising radiation. This leaves the mineral in an amorphous state.

Oxidation state: describes the degree of oxidation, i.e. the loss of electrons of an atom in a chemical compound.

Permeability: a measure of the ease with which fluids can flow through the pores of a rock. This depends not only on the pore size, but also on the connectivity between the pores.

Positron: a positively charged electron. It is also sometimes called an antielectron.

Principal quantum number: one of four quantum numbers that are used to describe the quantum state of an electron in an atom. The principal quantum number is given the symbol ***n***. It not only defines the energy level of an electron, but also the most probable distance between that electron and the nucleus of the4 atom. The value of ***n*** is any positive number such as 1, 2, 3, etc. with each number corresponding to a specific electron shell. Those electrons in the shell with ***n***=1 sit closest to the nucleus (and show a stronger interaction with the positively charged protons in the nucleus) whilst electrons in the shell with ***n***=5 sit a long way from the nucleus and so have higher energy than those closer to the nucleus.

Unconformity: a geological feature in which there is a buried erosional or non-depositional surface separating two rock masses or strata of different ages, indicating that there must have been a break in the deposition of sediment. Generally speaking the older layer was exposed to erosion for a period of time before the second, younger layer was deposited. An unconformity can also be used to describe any kind of break in the sedimentary geological record.

Unit cell: the smallest repeating unit in a crystal lattice.

Weathering: two types of weathering exist; physical weathering and chemical weathering. Chemical weathering is the deterioration of minerals or rocks by exposure to water, sunlight, atmospheric gases, or in some cases bacteria. Physical weathering is the mechanical breakdown of rocks into smaller fragments through processes such as expansion and contraction, mainly due to temperature changes such as freeze-thaw cycling or heating to high temperatures and subsequent cooling.

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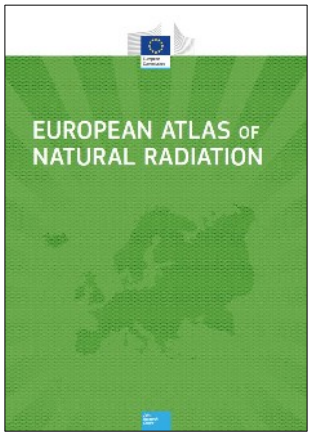
Further reading

European Atlas of Natural Radiation. For anyone with an interest in naturally occurring radioactive materials (NORM) – or those who are curious about the levels of natural radiation in their area – can check out this report from the Publications Office of the European Union. The 195 pages have a huge amount of data but the introductory and explanatory text is very good if you just want to discover more about radioactivity in the environment.



The full PDF document can be accessed at: https://publications.jrc.ec.europa.eu/repository/handle/JRC116795 [Accessed January 2026]

South Terras – Cornwall's Premier Uranium and Radium Mine (Presidential Address by Courtenay V. Smale, November 1992): http://www.dangerouslaboratories.org/rcw3.html [Accessed January 2026]

The Vanadium – Uranium Radioactive Nodules at Littleham Cove, west of Budleigh Salterton, Devon. https://wessexcoastgeology.soton.ac.uk/Budleigh-Salterton.htm#Radioactive-Nodules [Accessed January 2026].

A vanadium – uranium nodule, in situ*, at Littleham Cove. The lighter halos surrounding the nodules is caused by a change in the oxidation state of the iron in the rock due to radiation over a very long period.*
D. Ifold image.

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An occurrence of Vanadiferous nodules in the Permian beds of South Devon, G. E. L. Carter and Radioactive Nodules from Devonshire, Max Perutz. Facsimile reprints are available from the Fairlynch Museum: https://www.fairlynchmuseum.uk/shop.html [Accessed January 2026].

A comprehensive list of radioactive minerals with links to their Mindat page is available here: https://docs.google.com/spreadsheets/d/1suQrACTKJKLzE62Hj65pjF1eHIl5Lv4--9muE7CGemo/edit?gid=0#gid=0 accessed via https://www.mindat.org/mesg-620579.html [Accessed January 2026].

Visit a Museum

The summer holidays will soon be with us and there is no better way to learn about minerals, the associated geology and mining archaeology than to visit a museum or heritage centre with links to geology and mining etc. Below is a list of UK museums and institutions that have geological, mineral, mining collections, and fossils as well, that you could visit during the holidays. Some may be undergoing refurbishment or restructuring so please check the website before planning your visit.

If you discover a UK museum with geological displays during your holidays that is not on this list please let us know so that we can update the list and share it with others.

List of Museums and Institutions in the UK with geological displays

- Big Pit National Coal Museum, Blaenafon, Torfaen, Wales. https://museum.wales/bigpit
- Booth Museum of Natural History, 194, Dyke Road, Brighton. https://brightonmuseums.org.uk/booth-museum-of-natural-history
- Bournemouth Natural Science Society & Museum, Bournemouth, Dorset. https://bnss.org.uk
- Bristol Museum and Art Gallery, Queens Road, Bristol. https://www.bristolmuseums.org.uk/bristol-museum-and-art-gallery
- Buxton Museum, Buxton, Derbyshire. https://buxtonmuseumandartgallery.wordpress.com
- Caerhays Estate, Gorran, St Austell, Cornwall. https://visit.caerhays.co.uk
- Camborne School of Mines Museum, Penryn, Cornwall. https://csm-museum.co.uk
- Charmouth Heritage Coast Centre, Dorset. https://charmouth.org/chcc
- Cliffe Castle Museum, Keighley, West Yorkshire. https://bradfordmuseums.org/venue/cliffe-castle-museum
- Cornwall Museum, 25, River Street, Truro, Cornwall. https://cornwallmuseum.org
- Dinosaur Isle, Culver Parade, Sandown, Isle of Wight. http://www.dinosaurisle.com
- Dolaucothi Gold Mines, Pumsaint, Llanwrda, Carmarthenshire, Wales. https://www.nationaltrust.org.uk/visit/wales/dolaucothi
- Dudley Museum at the Archives, Tipton Road, Dudley. https://www.dudley.gov.uk/things-to-do/museums/dudley-museum-at-the-archives
- Fairlynch Museum, Budleigh Salterton, Devon. https://www.fairlynchmuseum.uk
- Geevor Tin Mine Museum, Pendeen, Penzance, Cornwall. https://geevor.com
- Great North Museum: Hancock, Barras Bridge, Newcastle upon Tyne. https://www.northeastmuseums.org.uk/greatnorthmuseum
- Haslemere Museum, 78, High Street, Haslemere, Surrey. https://www.haslemeremuseum.co.uk
- Horniman Museum & Gardens, 100, London Road, Forest Hill, London. https://www.horniman.ac.uk
- Killhope Lead Mining Museum, Upper Weardale, County Durham. https://killhope.org.uk
- King Edward Mine Museum, Troon, Camborne, Cornwall. https://www.kingedwardmine.co.uk
- Lapworth Museum of Geology, University of Birmingham, Edgbaston, Birmingham. https://www.birmingham.ac.uk/cultural-attractions/lapworth-museum-of-geology
- Liskeard and District Museum, Pike Street, Liskeard, Cornwall. https://liskeardmuseum.com

- Lyme Regis Museum, Bridge Street, Lyme Regis, Dorset. https://www.lymeregismuseum.co.uk
- Manchester Museum, The University of Manchester, Oxford Road, Manchester. https://www.museum.manchester.ac.uk
- Museum of Barnstaple & North Devon, The Square, Barnstaple, North Devon. https://barnstaplemuseum.org.uk
- Museum of Lead Mining, Wanlockhead Village, Dumfries and Galloway, Scotland. https://www.leadminingmuseum.co.uk
- National Coal Mining Museum for England, Caphouse Colliery, New Road, Overton, Wakefield. https://www.ncm.org.uk
- National Mining Museum Scotland, Lady Victoria Colliery, Newtongrange, Midlothian, Scotland. https://nationalminingmuseum.com
- National Museum of Scotland, Chambers Street, Edinburgh, Scotland. https://www.nms.ac.uk/national-museum-of-scotland
- National Museum Wales, Cathays Park, Cardiff, Wales. https://museum.wales/cardiff
- National Slate Museum, Llanberis, Gwynedd, Wales. https://museum.wales/slate
- National Stone Centre, Porter Lane, Wirksworth, Derbyshire. https://www.nationalstonecentre.org.uk
- Natural History Museum London, Cromwell Road, London. https://www.nhm.ac.uk
- Nenthead Mines, Nenthead Smelting Mill, Nenthead, Alston, Cumbria. https://www.nentheadmines.com
- Oxford University Museum of Natural History, Parks Road, Oxford. https://www.oumnh.ox.ac.uk
- Peak District Mining Museum, South Parade, Matlock Bath, Derbyshire. https://peakdistrictleadminingmuseum.co.uk
- Portland Museum, 217, Wakeham, Easton, Portland, Dorset. https://portlandmuseum.co.uk
- Purbeck Mining Museum, Purbeck Park, Nr Corfe Castle, Wareham Dorset. https://purbeckminingmuseum.org
- Rotunda Museum, Vernon Road, Scarborough, N. Yorkshire. https://scarboroughmuseumsandgalleries.org.uk/visit/rotunda-museum
- Saffron Walden Museum, Museum Street, Saffron Walden, Essex. https://www.saffronwaldenmuseum.org
- Sedgwick Museum of Earth Sciences, Downing Street Cambridge. https://sedgwickmuseum.cam.ac.uk
- St Agnes Museum, Penwinnick Road, St Agnes, Cornwall. https://www.stagnesmuseum.org.uk
- The Box, Tavistock Place, Plymouth, Devon. https://www.theboxplymouth.com
- The Cockburn Geological Museum, Grant Institute of Earth Sciences, James Hutton Road, King's Buildings, Edinburgh, Scotland. https://www.ed.ac.uk/visit/museums-galleries/geology
- The Etches Collection, Museum of Jurassic Marine Life, Kimmeridge, Dorset. https://www.theetchescollection.org
- The Hunterian Museum, University of Glasgow, Glasgow, Scotland. https://www.gla.ac.uk/hunterian

- Treasures of the Earth, Corpach, Fort William, Inverness-Shire, Scotland. https://treasuresoftheearth.co.uk
- Tullie, Castle Street, Carlisle, Cumbria. https://tullie.org.uk
- Watchet Market House Museum, The Market House, Market Street, Watchet, Somerset. https://www.watchetmuseum.co.uk
- Whitby Museum, Pannett Park, Whitby, North Yorkshire. https://whitbymuseum.org.uk
- World Museum, William Brown St, Liverpool. https://www.liverpoolmuseums.org.uk/world-museum
- Yorkshire Museum, Museum Gardens, Museum Street, York. https://www.yorkshiremuseum.org.uk

Mindat also maintains a worldwide Directory of Mineral and Geological Museums that can be accessed here: https://www.mindat.org/museums

All links to these sites were functional in January 2026.

The Professor R. A. (Bob) Howie Mineralogical Collection at the Peak District Mining Museum, Matlock Bath, in 2004. G. Morse photograph.

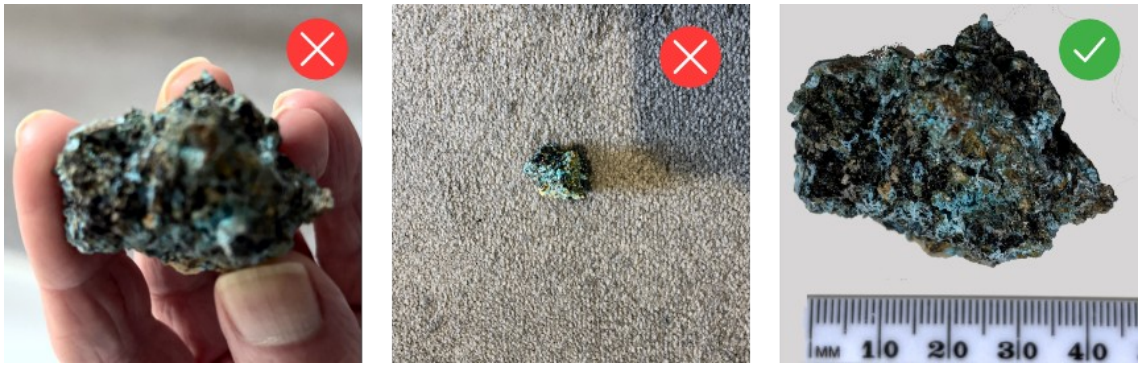
The refurbished Cornwall Museum mineral gallery, Truro, July 2024. Roy Starkey photograph.

Mineral display at the Lapworth Museum of Geology, Birmingham. G. Morse photograph.

Guidelines for Submissions to the JMM

We welcome all contributions that relate in any way to minerals, and mineral collecting suitable for and by our junior members. Articles can be submitted as a Microsoft Word document (.doc, .docx) an OpenDocument Text (.odt) or Rich Text (.rtf) document and sent to the Editor, Gary Morse, via e-mail, to the address below. Do not worry about format or structure, it is your words that we want, the Editor will convert your words into an article formatted for the JMM. A PDF copy will be emailed to you to approve before publication.

If you wish to submit photographs of your specimens or any mineralogical features then please email photographs separately and do not include them in the text. A title and an explanation with full details for the image is very important. Append these at the end of the text. If a specimen is photographed please **do not** hold it in the hand. Take photographs of dry specimens on a plain uncoloured background with a scale (ruler) to show size, if required, or give the size or field of view in the description. Check that the photograph is in focus over all the relevant areas and that the subject fills most of the image. Ideally photograph your specimen in daylight with minimal shadows. The Editor will crop and resize images to fit the JMM article as required if they are published. We cannot accept copyrighted images from other sources.



Finally, when you submit anything to the JMM please confirm that you are happy for us to publish your full name along with your contribution and check that your responsible adults are happy for you to have your name in print. We look forward to your articles, letters and specimen photographs.

Contributions for the next RS Junior Members' Magazine should be sent to the Editor, Gary Morse. The deadlines are, ideally, **January 1st** for the March edition and **July 1st** for the September edition.

Email: newslettereditor@russellsoc.org

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The Society is not responsible for the content of external sites that are linked to from here.

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