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Geologic course for fourth year students (Geology) of

RADIOACTIVE MINERALS

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INTRODUCTION

Uranium oxide has been used since Roman times for yellow pigments in glass. The element was discovered in 1789 by a German chemist, Martin Klaproth, who named it for the newly observed seventh planet. In 1841, French chemist Eugene Peligot extracted pure uranium metal, which caused little interest until March 1, 1869, when French physicist, Henry Becquerel discovered radioactivity in uranium salts.

On a scale arranged according to the increasing mass of their nuclei, uranium is the heaviest of all the naturally-occurring elements (Hydrogen is the lightest). Uranium is 18.7 times as dense as water.

It **occurs in most rocks** in concentrations of 2 to 4 parts per million and is as common in the Earth's crust as tin, tungsten and molybdenum. It occurs in seawater, and could be recovered from the oceans if prices rose significantly. today its slow radioactive decay provides the **main source of heat inside the earth**, causing convection and continental drift.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac**	Rf	Db	Sg	Bh	Hs	Mt	110	111	112	113					
Lanthanides*			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
**Actinides ** **			Th	Pa	**U**	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Atomic number	-	92	Density	g/mL	18.9
Atomic weight	u	238.029	Melting point	K	1405
Atomic radius	A	-	Heat of vaporization	kJ/mol	477
Ionization Potential	V	6.05	Heat of fusion	kJ/mol	8.52
Electronegativity	-	1.38	Specific heat	J/gK	0.12
The oxide is amphoteric.			Crystal are orthorhombic.		

Like other elements, uranium occurs in slightly differing forms known as 'isotopes'. These isotopes (16 in the case of uranium) differ from each other in the number of particles (neutrons) in the nucleus. Natural uranium as found in the Earth's crust is a mixture largely of two isotopes: uranium-238 (U-238), accounting for 99.3% and U-235 about 0.7%.

The isotope U-235 is important because under certain conditions it can readily be split, yielding a lot of energy. It is therefore said to be 'fissile' and we use the expression 'nuclear fission'

Meanwhile, like all radioactive isotopes, they decay. U-238 decays very slowly, its half-life being about the same as the age of the Earth (4500 million years). This means that it is barely radioactive, less so than many other isotopes in rocks and sand. Nevertheless it generates 0.1 watts/tonne as decay heat and this is enough to warm the Earth's core. U-235 decays slightly faster.

Uranium-238 is an α emitter, decaying through the 18-member uranium natural decay series into lead-206 The decay series of uranium-235 (also called actino-uranium) has 15 members that ends in lead-207, protactinium-231 and actinium-227 The constant rates of decay in these series makes comparison of the ratios of parent to daughter elements useful in radiometric dating. Uranium-233 is made from thorium-232 by neutron bombardment.[3]

The isotope uranium-235 is important for both nuclear reactors and nuclear weapons because it is the only isotope existing in nature to any appreciable extent that is fissile, that is, can be broken apart by thermal neutrons.[5] The isotope uranium-238 is also important because it absorbs neutrons to produce a radioactive isotope that subsequently decays to the isotope plutonium-239, which also is fissile.[15]

Uranium abundance

Uranium is a naturally occurring element that can be found in low levels within all rock, soil, and water. Uranium is also the highest-numbered element to be found naturally in significant quantities on earth and is always found combined with other elements. The decay of uranium, thorium and potassium-40 in the Earth's mantle is thought to be the main source of heat[26][27] that keeps the outer core liquid and drives mantle convection, which in turn drives plate tectonics.

Its average concentration in the Earth's crust is (depending on the reference) 2 to 4 parts per million,[4][7] or about 40 times as abundant as silver.[5] The Earth's crust from the surface to 25 km (15 mi) down is calculated to contain 10^{17} kg (2×10^{17} lb) of uranium while the oceans may contain 10^{13} kg (2×10^{13} lb).[4] The concentration of uranium in soil ranges from 0.7 to 11 parts per million (up to 15 parts per million in farmland soil due to use of phosphate fertilizers), and 3 parts per billion of sea water is composed of the element.[7]

It is more plentiful than antimony, tin, cadmium, mercury, or silver, and it is about as abundant as arsenic or molybdenum.[3][7] It is found in hundreds of minerals including uraninite (the most common uranium ore), autunite, uranophane, torbernite, and coffinite.[3] Significant concentrations of uranium occur in some substances such as phosphate rock deposits, and minerals such as lignite, and monazite sands in uranium-rich ores[3] (it is recovered commercially from these sources with as little as 0.1% uranium[5]).

Radioactivity phenomenon

Radioactivity is the spontaneous disintegration of an unstable atomic nucleus and the emission of particles or electromagnetic radiation. All naturally occurring elements with atomic numbers greater than 83, as well as some isotopes of lighter elements, are radioactive. Three different types of radiation are identified.

Alpha particles (**a**) are helium nuclei, containing two protons and two neutrons. They are deflected slightly in an electric of magnetic field. Their penetrating power is very low, being stoppable by a thin sheet of aluminum or paper.

Beta particles (**b**) are electrons capable of travelling at speeds approaching the speed of light. Their low mass allows them to be deflected greatly in an electric or magnetic field, in the opposite direction as the deflection of alpha particles. Their high speed gives them greater penetrating power than alpha particles. Some beta particles can penetrate several centimetres of aluminum. (Some refer to beta particles as "beta negative particles", to distinguish them from beta positive particles -- positrons.) Alpha particle emissions and beta particle emissions change the composition of the nucleus.

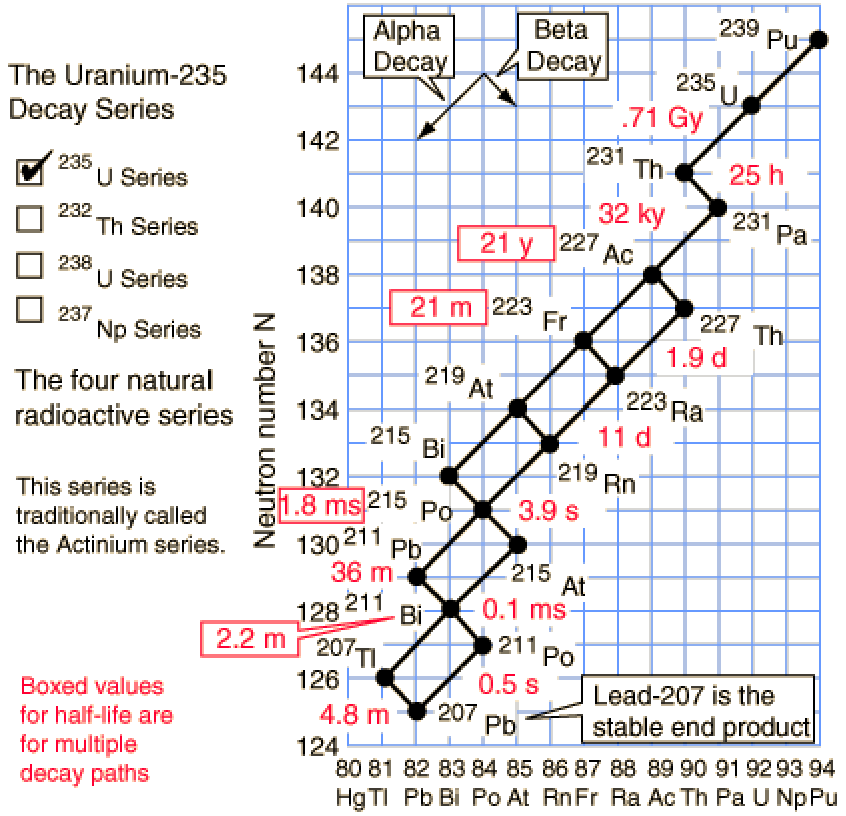
Gamma rays (**g**) are high energy electromagnetic radiation with short wavelengths. Gamma rays, unlike alpha and beta particles, do not change the composition of the nuclide. They have the highest penetrating power, being able to penetrate at least 30 centimetres of lead.

Background radiation comes from a variety of radioactive sources. Cosmic rays penetrating the Earth's atmosphere from outer space usually account for less than 25% of background radiation (but this depends on altitude). Minute quantities of naturally occurring radioactive sources in the surroundings (e.g., soil, air, drinking water, building materials, food, etc.) also contribute to background radiation.

Nuclides radiations affect the emulsion of photographic film, ionize surrounding air molecules, make certain compounds fluoresce, and have certain special biological effects. They undergo radioactive decay. Nuclide charts, with atomic number plotted against neutron number, are used in nuclear physics to illustrate a decay series.

Radioactive Decay (Radioactive Disintegration Series)

The product of a radioactive decay may itself be unstable and undergo further decays, by either alpha or beta emission. Thus, a succession of unstable elements may be produced, the series continuing until a nucleus is produced that is stable. Such a series is known as a radioactive disintegration, or decay, series. The original nucleus in a decay series is called the parent nucleus, and the nuclei resulting from successive disintegrations are known as daughter nuclei.



1μs = 10^{-6}s, 1 ms = 10^{-3}s,1 My = 10^{6}y, 1 Gy = 10^{9}y

Radioactivity Alpha decay Beta decay.

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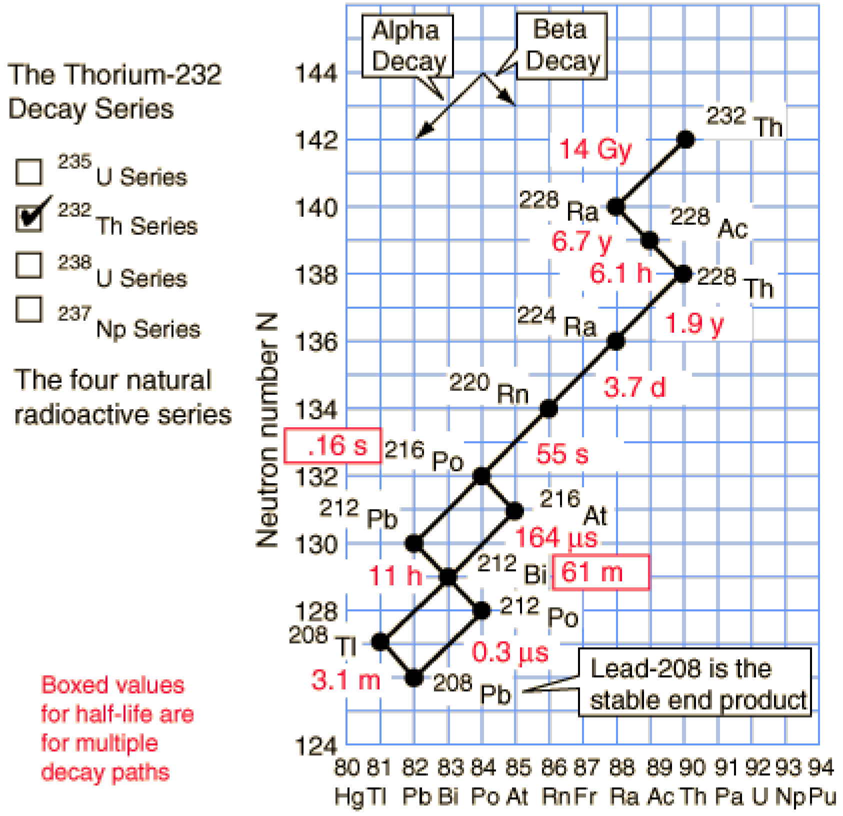

$1 \mu s = 10^{-6}$s, 1 ms = 10^{-3}s,1 My = 10^{6}y, 1 Gy = 10^{9}y

Radioactivity | Alpha decay | Beta decay.

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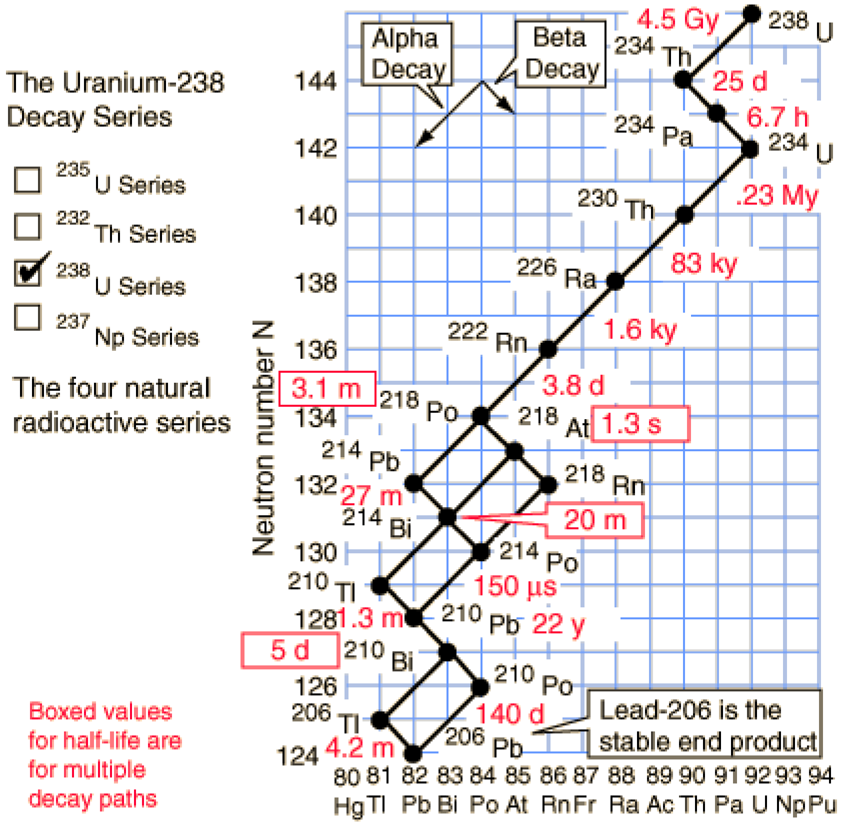

$1\mu\text{s} = 10^{-6}\text{s}$, $1\ \text{ms} = 10^{-3}\text{s}$,$1\ \text{My} = 10^{6}\text{y}$, $1\ \text{Gy} = 10^{9}\text{y}$

Radioactivity Alpha decay Beta decay.

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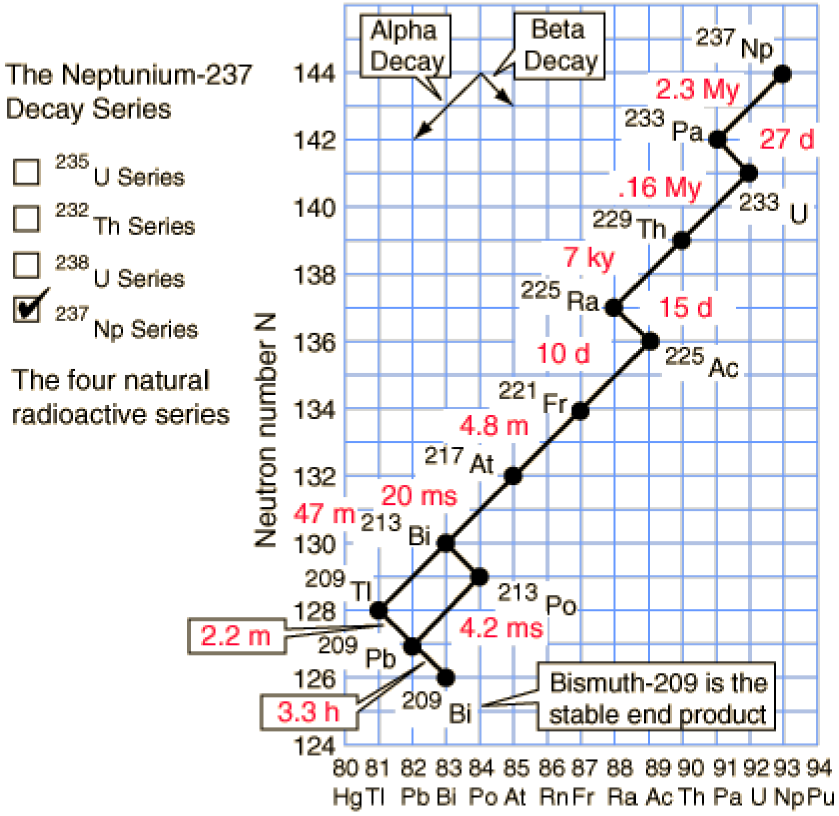

1μs = 10^{-6}s, 1 ms = 10^{-3}s,1 My = 10^{6}y, 1 Gy = 10^{9}y

The members of this series are not presently found in nature because the half-life of the longest lived isotope in the series is short compared to the age of the earth.

Radioactivity Alpha decay Beta decay.

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From uranium ore to reactor fuel

Uranium ore can be mined by underground or open-cut methods, depending on its depth. After mining, the ore is crushed and ground up. Then it is treated with acid to dissolve the uranium, which is recovered from solution. Uranium may also be mined by in situ leaching (ISL), where it is dissolved from a porous underground orebody in situ and pumped to the surface. The end product of the mining and milling stages, or of ISL, is uranium oxide concentrate (U_3O_8). This is the form in which uranium is sold.

Before it can be used in a reactor for electricity generation, however, it must undergo a series of processes to produce a useable fuel.

For most of the world's reactors, the next step in making the fuel is to convert the uranium oxide into a gas, uranium hexafluoride (UF_6), which enables it to be enriched. Enrichment increases the proportion of the uranium-235 isotope from its natural level of 0.7% to 3 - 4%. This enables greater technical efficiency in reactor design and operation, particularly in larger reactors, and allows the use of ordinary water as a moderator.

After enrichment, the UF_6 gas is converted to uranium dioxide (UO_2) which is formed into fuel pellets. These fuel pellets are placed inside thin metal tubes which are assembled in bundles to become the fuel elements or assemblies for the core of the reactor.

The importance of radioactivity phenomenon :

The radioactivity phenomenon can be made use of in prospecting of nuclear raw materials. Several instruments (Geiger and scintillation counters) can detect the intensity of natural radioactivity .

* Where the radioactivity is higher than normal, a naturally occurring radioactive element must be the cause.

* Analyses of the spectrum of the gamma rays of the radioactive material give information concerning the kind of the radioactive elements and their relative abundance in the analysing sample. The method of assaying of radioactive material is known as radiometric spectrometry The instruments used are known spectrometers.

Spectrometers can be carried by hand in ground prospecting ,or mounted in aeroplanes for regional radiometric survey (airborne radiometric survey), or designed as laboratory instruments for more accurate determination of selected samples. Car-borne instruments may be used for rapid ground surveys. The phenomenon of natural radioactivity is also used to determine the absolute ages of rocks in minerals. This branch is known as Geochronology.

Geochemistry of uranium and thorium

* Uranium occurs in nature in several valence states, but two of them, namely tetravalent and hexavalent (U4 & U6) are the most common.

* U4 is isomorphous withTh,Ca, Na, Zr, Mo,Y, Ce, Pb, Fe 2and rare earth (this means that substitution of these elements and uranium can take place in the structure of atoms).

* Compounds of U4 are insoluble in water, green or black colors. The most common of them is UO2 which occur as uraninite.

* U4 is easily oxidized to U6, which combines with two oxygene ions to form the complex uranyl ion (UO2)2+.

*Compounds of U6, or the uranyl ion are quite soluble, exhibit bright yellow color and fluoresence in the ultraviolet light.

*Ions which are isomorphous with U4 can not replace U6, this means that minerals with U6 don’t contain Th, Zr, Ce, …etc., replacing for U because of the large size of the uranyl ion.

* In the zone of oxidation , U4 is readily oxidized to the U6, particularly in the presence of sulphide minerals.

* In this state U6 can be leached out from its ores and migrate for a long distances .

* If the soluble uranyle ions meet reducing environment , U is readily precipitated in the form of uranium oxides with U4. This takes place in the presence of organic material or in closed basins with decaying organic remains.

The uranyl ion can be precipitated by reaction with dissolved silica in ground waters to form the secondary silicate mineral *uranophane* or may be precipitated due to hydration to form *Gummite* (colorful mixture of oxides and hydroxides of U6).

* In the presence of : carbonate ions in alkaline water, or sulphate ions in acidic waters, the uranyl ion form soluble uranyl carbonates and sulphate respectivly. In arid condition, these soluble compounds can be precipitated by evaporation, to give the whole array of secondary carbonate and sulphate minerals. If not precipitated, the soluble carbonate and sulphate compounds are lost in ground waters and ultimately reach the sea .

* The uranyl ion can be precipitated in the form of insoluble compounds in the presence phosphate, vanadate, and arsenate ions to form the whole array of secondary uranium minerals. In this state, it form a great variety of minerals with the following composition :

1- A1+ (UO2)2+ (RO4)3- .x H2o where: A=K, Na, H

2- B2+ (UO2)2+ (RO4)3- .x H2o B= Ca, Ba, Mg, Cu, Fe2,Pb

R= P, As, V

3- B2+ (UO2)2+ (RO4)2- .x H2o

* Thorium occurs mainly in primary minerals. It is rarely leached in weathering processes.

THE URANIUM ORE MINERALS

Lindgren defines an ore mineral as "a mineral which may be used for the extraction of one or more metals." A uranium ore mineral is therefore a mineral possessing such physical and chemical properties and occurring in a deposit in such concentrations that it may be used for the profitable extraction of uranium, either alone or together with one or more other metals. There are only a few of the many uranium minerals that meet these qualifications and still fewer in which uranium is the major constituent. Pitchblende and uraninite contain theoretically up to 85 per cent uranium but actually between 50 and 80 per cent; carnotite, torbernite, tyuyamunite, autunite, uranophane, and brannerite, 45 to 60 per cent. In other minerals, uranium is an important but relatively minor constituent the minerals, davidite, samarskite, and euxenite, for example, contain only 1 to 18 per cent. The majority of uranium-bearing minerals, however, contain uranium in small or trace amounts as an accessory to major constituents.

The uranium content of a mineral does not of itself, however, determine whether it is a uranium ore mineral. If the uranium is present in a mineral in such complex combinations with other elements that it is too costly to extract, or if the mineral does not occur in sufficient quantities to make extraction worthwhile, that mineral is not a uranium ore mineral. Thus, the definition for an ore mineral, like that for an ore deposit, is dependent upon economics and time upon the value of uranium and the results of future exploration and metallurgical progress.

A uranium mineral that is not an ore mineral today may be one tomorrow. Most of the uranium minerals in pegmatites and placers are refractory; that is, the uranium is present in combinations which are extremely difficult to break down chemically in order to recover the uranium. These minerals also usually occur scattered sparsely throughout the deposit so that recovery difficult and expensive. The fact that only a few of the numerous uranium minerals qualify as uranium ore minerals and form uranium ore deposits, whereas uranium in small amounts is widely spread throughout the rocks of the earth's crust, adds greatly to the problem of uranium exploration.

The uranium prospector gets many "nibbles" but few "bites," and to avoid disillusionment and frustration, as well as waste of time, effort, and money, he must know his business well. This is one of the most important factors in searching for uranium.

PRIMARY URANIUM ORE MINERALS

Primary uranium minerals have been found most commonly in veins or pegmatites, although in recent years extensive, flat-lying deposits of pitchblende in sedimentary rocks have also been discovered.The refractory primary uranium minerals are also found in placers.

The primary uranium minerals are generally black or dark brown, noticeably heavy, and often have a shiny or pitch-like luster. When they are exposed to weathering at or near the surface, they are sometimes altered to form the bright-colored secondary uranium minerals. At the present time, there are only three known primary uranium ore minerals, and the most important of these, uraninite and pitchblende, are really varieties of the same mineral.

Oxides

Uraninite and Pichblende

(**combined $UO_2$and UO_3; 50-85 percent U_30_8**)[1]. Uraninite is a naturally occurring uranium oxide with cubic or octahedral crystal form. It has a specific gravity of 8-10.5 (iron = 7.85), a grayish-black color sometimes with a greenish cast and a hardness[2] of 5-6, about the same as steel. Its streak[3] is black. Its most widespread occurrence is in pegrnatites [4], in which it is found in small amounts, throughout the world. However, it is also an important constituent of nearly all important primary deposits, occurring closely associated with its massive variety, pitchblende.

[1] U_30_8 is the symbol for a chemical compound, uranium oxide, composed of three atoms of uranium to eight atoms of oxygen. Most chemical assays for uranium are expressed in terms of U_30_8, and ore purchases are made on that basis. The uranium content equals approximately 85 per cent of the assay expressed in terms of U_30_8.porcelain.

Pitchblende is the massive variety of uraninite, without apparent crystal form, that occurs most abundantly in the rich primary vein deposits of uranium. It is the chief constituent of nearly all high-grade uranium ores and has provided the largest part of all uranium produced throughout the world, forming the principal product of the Shinkolobwe mine, Belgian Congo; the Eldorado mine, Great Bear Lake, Northwest Territories,Canada;and the mines at Joachimsthal, Czechoslovakia.

Pitchblende is somewhat lighter than uraninite, having a specific gravity of between 6 and 9, but its other properties, with the exception of crystal form, are the same. It occurs as irregular masses often with a rounded, layered, botryoidal structure.

 © Rui Nunes 2006	Uraninite Poços de Caldas, Minas Gerais, Southeast Region, Brazil Uraninite mass / field of view 2cms across. Rui Nunes specimen and photo.
 © 2002 John H. Betts	Uraninite Great Bear Lake, Mackenzie District, Northwest Territories, Canada Solid chunk of black uraninite with old label from Ward's Earth Science Estab. Radioactive. Ex. Ward's. Overall size of mineral specimen: 3x1.5x1 cm.
 © M Arliguie	Uraninite, Gummite Great Bear Lake, Mackenzie District, Northwest Territories, Canada Size: 2 X 2 cm Collection and photo: M Arliguie

Uraninite

Bicroft mine, Cardiff Township, Haliburton Co., Ontario, Canada

A 5.3 by 2.8 cms specimen og rough black crystals on and in matrix. Sobolewski specimen and photograph.

© Rob Lavinsky

Uraninite

Katanga (Shaba), Congo (Zaïre)

An extremely sharp, undamaged, lustrous uraninite cube from Katanga Province, Zaire. Uraninite crystals of this quality are RARE from Zaire. 0.8 x 0.6 x 0.6 cm

© P.M. Kartashov

Uraninite (Var: Pitchblende)

Příbram, Central Bohemia Region, Bohemia (Böhmen; Boehmen), Czech Republic

Large collomorphous agregate of pure pithcblende from the classic occurrence. Specimen size is 9x8x3 cm and its Pavel M. Kartashov collection and photo.

© P.M. Kartashov

Uraninite (Var: Pitchblende)

Příbram, Central Bohemia Region, Bohemia (Böhmen; Boehmen), Czech Republic

Large collomorphous agregate of pure pithcblende from the classic occurrence. Associating orange baryte is visible. Specimen size is 9x8x3 cm Pavel M. Kartashov collection and photo.

The principal occurrences of pitchblende are in primary (hydrothermal) vein deposits, usually of the mesothermal (medium temperature and pressure) type, in igneous and metamorphic rocks and in flat-lying bedded deposits in sedimentary rocks. Pitchblende is commonly associated with one or more of the primary ore minerals of iron, copper, cobalt, lead, silver, and bismuth. It is usually accompanied also by bright colored secondary uranium minerals where subjected to weathering or other alteration. The commonly associated gangue[1] minerals are quartz and other silica minerals, carbonates, fluorite, barite, and hydrocarbons. Quartz, calcite, and dolomite are usually the most abundant. Pitchblende, in vein deposits, is most likely to be deposited in existing open spaces in rock formations, rather than by replacement of the rock itself, and the richest deposits occur where large open fractures were available for filling by the mineralizing solutions. There are no important pitchblende replacement deposits like those of copper, lead, zinc, and silver, where rock formations have been substantially replaced by ore through solution of the original constituents and deposition of the ore minerals.

In the recently discovered flat-lying deposits of pitchblende in sedimentary rocks, such as sandstones and conglomerates, the pitchblende is deposited between and around the grains of the rock and in available rock openings. The two most important examples are the "copper-uranium" deposits in southern Utah and northern Arizona, in which pitchblende occurs with a variety of secondary uranium and copper minerals and copper and lead sulfides.

The alteration of the wall rock to form these minerals is known as kaolinization, chloritization, sericitization, and silification. Kaolinization causes the wall rock to become softand clay-like, so that it may be easily gouged with a knife blade or even the fingernail. Chloritization and sericitization cause the rock to become a waxy or greasy green or gray, sometimes soft and flaky. Silification results in a hard flint-like texture.

Pitchblende has also been found in smaller amounts disseminated in volcanic rocks in the southwestern United States, in some of the carnotite deposits of the Colorado Plateau, and in the deposits in limestone in the Grants district, New Mexico.

2- Silicates

Allanite:

$Ca(Ce,La,Y,Ca)Al_2(Fe^{2+},Fe^{3+})(SiO_4)(Si_2O_7)O(OH)$.

Allanite is an epidote mineral that contain a significant amount of rare earth elements. The International Mineralogical Association lists three minerals in the allanite group: allanite-Ce, allanite-La and allanite-Y, depending on the dominant rare earth present.

- **Allanite-(Ce)** the cerium rich allanite, also the most common and in general the one most often referred to as just allanite or orthite.

- **Allanite-(La)** the lanthanum rich allanite.
- **Allanite-(Y)** the yttrium rich allanite.

Allanite, also called orthite, contains up to 20% rare earth elements and is a valuable source of them. Other elements can also substitute in the structure including thorium. Allanite often has a *halo* of radiation damage in the minerals immediately adjacent. Also highly radioactive grains of allanite often have their structure disrupted or are *metamict*.

	Allanite-(Ce) Graphite quarry, Amstall, Mühldorf, Waldviertel, Lower Austria, Austria A very rare specimen of allanite-(Ce) from a classic location in austria. Field of view: 8mm Photo and collection of Martin Slama
 © Brhounds	Allanite-(Ce) Rio de Janeiro, Rio de Janeiro, Southeast Region, Brazil Allanite-Ce fragment. Size 8x5x3cm. Rafael Hernandes Corrêa-Silva Collection.

	Allanite-(Ce) Trimouns Talc Mine, Luzenac, Ariège, Midi-Pyrénées, France Field of view : 2mm, Photo & Collection : JM.Johannet.
	Allanite-(Ce) Trimouns Talc Mine, Luzenac, Ariège, Midi-Pyrénées, France 3 x 1 mm gem crystal - Collection and Picture Jacques VALVERDE - jacques.valverde@tele2.fr

Allanite is usually black in color, but can be brown to brown-violet. It crystallizes in the monoclinic system and forms prismatic crystals usually disseminated in igneous rocks. It has a Mohs hardness of 5.5 and a specific gravity of 3.3 - 4.2.

The radioactivity, as in other radioactive minerals, can manifest itself in a couple of ways. Embedded crystals of allanite are frequently seen with a "halo" or dark ring; evidence of the radioactive effects on nearby minerals. Allanite can also become metamict. This is a condition found in radioactive minerals and results from the destructive effects of its own radiation on its crystal lattice. The effect can destroy a crystal lattice completely while leaving the outward appearance unchanged. The complete destruction of the allanite structure will produce a glassy hydrated substance. The hydration is facilitated by the metamictation. It is classified into three officially recognized minerals:

Allanite is found as an accessory mineral in several igneous rocks such as granites, syenites, diorites and their pegmatites and in a few metamorphic rocks as small embedded grains. It forms tabular crystals that can have excellent form and character.Remember, this is a slightly radioactive mineral and should be stored away from other minerals that are subject to damage from radioactivity, so, human exposure should be limited !

In Mary Kathlene in Australia, allanite of contact marbles and skarns contains finely disseminated pitchblende.

b. Coffinite

Coffinite is a uranium bearing silicate mineral: $U(SiO_4)_{1-x}(OH)_{4x}$.

It is a glass-like black material, dark brown or pale-brown in color, possibly with grayish black streaks. It is named for American geologist Reuben Clare Coffin. It has molecular weight 327.71. It has no good cleavages and a brittle fracture. It is black with a black streak. The hardness of coffinite is between 5 and 6.

It is one of the common primary uranium minerals, especially in the unoxidized ores of the Colorado Plateau.

© P-A Wulser

Coffinite, Montmorillonite

Beverley Mine, Paralana High Plains, North Flinders Ranges, Flinders Ranges, South Australia, Australia

Coffinite nodule in the alpha-mudstone formation (basal level of the Beverley deposit)

© Paul Schumacher

Coffinite

Temple Mountain, San Rafael District (San Rafael Swell), Emery Co., Utah, USA

Coffinite (black) filling spaces between sandstone grains;
Meigi EMTR-2 (30X) & Sony F-717;
Schumacher Collection;
Bohemia, New York, USA

c. ***Zircon:***

Zircon, a naturally occurring gemstone, has colorless, yellow, orange, red, blue, brown and green varieties. In addition, both have been used as diamond substitutes. Zircon has a high refractive index which is responsible for it's diamond like appearance. Zircon can be distinguished from diamond by it's double refraction and by wear and tear of it's edges, as compared to diamond which is very much harder. Yellow zircon is rarely heat treated to improve color. Blue, red and colorless are always heat treated brownish crystals to produce these colors.

© Kristalle and Crystal Classics

Zircon
Konar (Kunar; Konarh; Konarha; Nuristan) Province, Afghanistan

A large, well formed Zircon crystal sits atop a gneissic matrix, creating a lovely display specimen. The Zircon crystal has a fantastic deep red colour with excellent lustre, and has partial translucency around the edges. It measures 3 x 2.5 x 2cm. A very striking specimen.

Size: 85mm x 85mm x 50mm

© Rob Lavinsky

Zircon
Darra-i-Pech (Darra-e-Pech) Pegmatite Field, Nangarhar (Ningarhar) Province, Afghanistan

This is about as red as Zircon gets from most localities. This piece features a sharp, lustrous, translucent, red crystal of Zircon measuring 1.3 cm on Mica/Quartz matrix. A very colorful crystal, but there is a contact on the termination. 7.2 x 4.6 x 3.1cm

© Joseph A. Freilich

Zircon
Darra-i-Pech (Darra-e-Pech) Pegmatite Field, Nangarhar (Ningarhar) Province, Afghanistan

A quite exemplary example of zircon from a region that has certainly produced some of the world's finest specimens. The 20 mm crystal sits on a granitic matrix. 85 x 72 x 50 mm. Crystal-Odyssey specimen. gemcrystals@aol.com

© R. Bottrill 2005

Zircon

Sister's Creek, Boat Harbour, Tasmania, Australia

Zircon crystal from alluvial deposits near Sisters Creek, probably derived from basaltic rocks nearby. Crystal is about 15mm long. Specimen and photographer: Ralph Bottrill.

Zircon, Albite

Aigner Alp, Schellgaden, Murwinkel, Lungau, Salzburg, Austria

0.5 mm long Zircon on Albitite, found on Aigner Alm, Mur valley, by Albert Strasser, photo W. Stoll

Zircon

Goiás, Central-West Region, Brazil

Doubly-terminated reddish-brown zircon crystal with excellent lustrous crystal faces. Bottom incomplete where contacted the matrix, now missing. Fluoresces yellow under UV illumination. Ex. A. Stevenson collection #553. Overall size of mineral specimen: 20x19x19 mm. Size of individual crystals: 20 mm. © 2001 John H. Betts

3- Phosphates

a. *Apatite:* $Ca_5 (PO4)_3 (F, Cl, OH)$.

Apatite is actually three different minerals depending on the predominance of either fluorine, chlorine or the hydroxyl group. These ions can freely substitute in the crystal lattice and all three are usually present in every specimen although some specimens have been close to 100% in one or the other. These minerals are Fluorapatite, Chlorapatite and Hydroxylapatite. It is difficult to distinguish them in hand samples using ordinary methods.

Apatite is widely distributed in all rock types; igneous, sedimentary and metamorphic, but is usually just small disseminated grains or cryptocrystalline fragments. Large well formed crystals though can be found in certain contact metamorphic rocks.Uranium substitutes for Ca, but never exceeds O.O1 %.


© Rob Lavinsky

Apatite
Konar (Kunar; Konarh; Konarha; Nuristan) Province, Afghanistan
This is a HUGE, terminated purple apatite crystal from Afghanistan. It is translucent, and has a nice purple glow to it in good light. The crystal is complete and undamaged all the way around the sides, with pretty bevels beneath the termination. There is a bit of matrix attached as an accent. Impressive for the size, rare in purple apatite! 3.8 ...


© Joseph A. Freilich

Apatite

Konar (Kunar; Konarh; Konarha; Nuristan) Province, Afghanistan

A jet black, lusterous, nicely terminated schorl crystal is host to a group of pink apatite crystals aesthetically situated in various positions. 3.75 x 1.3 inches. Crystal-Odyssey specimen. gemcrystals@aol.com

b. Monazite:

The mineral **monazite** is a reddish-brown phosphate containing rare earth metals and an important source of thorium, lanthanum, and cerium. It occurs usually in small isolated crystals. There are actually at least four different kinds of monazite:

Ce (Ce, La, Pr, Nd, Th, Y)PO_4 , monazite-La (La, Ce, Nd, Pr)PO_4 monazite-Nd (Nd, La, Ce, Pr)PO_4 and monazite-Pr (Pr, Nd, Ce, La)PO_4

Tho2 up to 28%, U is usually low, not more than 1% U.

Lanthanum is the most common rare earth in monazite-La, and so forth. Silica, SiO_2, will be present in trace amounts, as will small amounts of uranium. Due to the alpha decay of thorium and uranium, monazite contains significant amount of helium, which can be extracted by heating.

Monazite is an important ore for thorium, lanthanum, and cerium. It is often found in placer deposits. The deposits in India are particularly rich in monazite. It has a hardness of 5.0 - 5.5 and is relatively dense, about 4.6 to 5.7 g/cm^3. Because of the presence of thorium within monazite, it can be radioactive. If samples are kept, they should be placed away from minerals that can be damaged by radiation.

© S.M. Whittemore

Monazite, Quartz (Var: Smoky Quartz)

Torrington, Clive Co., New South Wales, Australia
Specimen collected by Vic Cloete of Brisbane.
Field of view ~ 1.6 mm

© Harjo

Monazite,

Leffler Brunnen, Gamseck Mt. area, Habach valley, Hohe Tauern Mts, Salzburg, Austria

Monazite crystal between Anatase crystals.
Field of view is 0,5 cm.
Found by Harjo in 2005.

Monazite

Teufelsmühle, Habach valley, Hohe Tauern Mts, Salzburg, Austria
Monazite crystal measuring 0,5 cm.
Found by Harjo in 2005.

Monazite, Quartz

Lohning quarry (Lohninger quarry), Hüttwinkl valley, Rauris valley, Hohe Tauern Mts, Salzburg, Austria
0,6 mm long Monazite crystal from Lohning quarry

© Rob ++++++++

Monazite

Llallagua, Bustillos Province, Potosí Department, Bolivia

A large and rich specimen of the REE-mineral monazite, with tiny ruddy-colored crystals intermixed with quartz crystals, so it is not even all that unattractive! 9.5 x 7.5 x 1.5 cm

© Brhounds

Monazite
Santa Luzia, Paraíba, Northeast Region, Brazil
Nice Monazite crystal. Size 3,5x2,5x2,5cm. Rafael Hernandes Corrêa-Silva Collection.

Monazite

Mendes Pimentel, Minas Gerais, Southeast Region, Brazil

Monazite twinned with 6x4 cm.

The name monazite comes from the Greek *mona`zein* (to be solitary), in allusion to its isolated crystals. Monazite is actually three different minerals technically, but because of a lack of great differences between them they are referred to as one mineral, monazite. The three monazites have differences in the percentages of their chemical makeup and these differences are reflected in their respective names.

The differences in the formula represent the greater percentages of certain elements in the mineral. The first element listed in the parenthesis is the element with the greater percentage in the mineral; so that monazite-(La) is greatly enriched in lanthanum, etc. Monazite-(Ce) is not only enriched in cerium it is also by far the most common of the three and is probably the actual mineral when one encounters a specimen that is simply labeled **monazite.** The general formula represents an aggregate formula for monazite. Silica or SiO4, will often be present in monazite replacing a small percentage of the phosphate groups, but this is not typically shown in monazite's formula. Uranium is also a trace element in some specimens.

The name monazite comes from a Greek word, *monazein*, which means "to be alone". It is an apt name as it is an allusion to the typical crystal habit of primary origin for monazite as isolated individual crystals in phosphatic pegmatites. Monazite is a primary ore of several rare earth metals most notably thorium, cerium and lanthanum. All these metals have various industrial uses and are considered quite valuable. Thorium is a highly radioactive metal and could be used as a replacement for uranium in nuclear power generation. Monazite therefore is an extremely important ore mineral.

Monazite is radioactive, sometimes highly radioactive, and specimens are often metamict. This is a condition found in radioactive minerals and results from the destructive effects of its own radiation on its crystal lattice. The effect can destroy a crystal lattice completely while leaving the outward appearance of the crystal unchanged. Increased metamictation will increase the perfection of the specimens conchoidal fracture. The radioactivity of monazite has been used as an aid in radioactive dating.

Monazite, as already mentioned, forms in phosphatic pegmatites but is actually a standard trace constituent in many ordinary igneous, metamorphic and vein filling rocks. If not too metamict, crystals of monazite are rather durable. They can be weathered out from their host rocks and carried downstream great distances and collect in river deposits and even in ocean beach deposits. Their great density (specific gravity is 4.6 - 5.7) makes it easy for the crystals to be collected into what are called placer deposits. Some monazite beach placers in India alone are so rich that they could supply the entire world's need for monazite for many years to come.

3. *Xenotime*

YPO_4 With UO2 up to about 5%.

Xenotime is one of the very few minerals, let alone words, that starts with the letter X; a good word to remember in some word games. It is a widely spread mineral throughout the world although good crystals and therefore specimens are somewhat hard to find.

Xenotime also will contain traces of silicon dioxide and arsenate replacing the phosphate anion. In fact it forms a solid solution series with the previously mentioned **chernovite-(Y)** whose formula is YAsO4. It is unusual to have a solid solution series involving the principle anions but it is not as complete a solid solution series as the more famous **pyromorphite-vanadinite-mimetesite** series. That is a more complex phosphate-vanadate-arsenate series.

Also of note is that xenotime is one of the few phosphate minerals that does not contain water molecules, hydroxides or chlorides. It belongs to an informal group of phosphates and called the *anhydrous phosphates* along with **monazite, purpurite** and **lithiophyllite**.

 © Stephan Wolfsried	Xenotime-(Y) Hopffeldboden, Hopffeld area, Obersulzbach valley, Hohe Tauern Mts, Salzburg, Austria Picture width 10 mm. Collection and Photograph Stephan Wolfsried
 © Stephan Wolfsried	Xenotime-(Y) Lohning quarry (Lohninger quarry), Hüttwinkl valley, Rauris valley, Hohe Tauern Mts, Salzburg, Austria Picture width 2 mm. Collection and Photograph Stephan Wolfsried
	Xenotime-(Y) Lohning quarry (Lohninger quarry), Hüttwinkl valley, Rauris valley, Hohe Tauern Mts, Salzburg, Austria 1,6 mm size group of Xenotimes found by A.Riess at Lohninger quarry, photo W. Stoll

SECONDARY URANIUM ORE MINERALS

The secondary uranium minerals are by far the most spectacular in appearance of the uranium minerals. Instead of the dull black, gray, and brown colors of the primary minerals, they present an array of bright yellow, orange, green, and all of the combinations and in-between shades of those colors. Some of them also have the property of fluorescence under ultraviolet light, resulting in even more brilliant coloration. Rather than being heavy and massive, they occur as earthy or powdery materials or as fine, delicate, needle-like or platy, flake-like crystals. As a group, they are probably more beautiful than the minerals of any other element. This, of course, is an important factor in their recognition in the field, although the inexperienced prospector may often confuse them with other colorful minerals, such as malachite (copper carbonate), limonite (iron hydroxide), and sulfur.

The secondary uranium ore minerals have represented only a small proportion of the total world uranium production to date. However, their deposits are more numerous and widespread than those of the primary ore minerals and, as a result of intensive prospecting activity, their importance is steadily increasing.

The secondary minerals have two major modes of occurrence:

1. In the weathered or oxidized zones of primary deposits, where they are Formed by decoposition of the primary mineral in place.

2. As irregular, flat-lying deposits in sedimentary rocks, primarily sandstones, but also conglomerates, shales, and limestones, formed by

precipitation from solutions that may have carried the uranium some distance away from the original source.

The secondary uranium ore minerals also occur frequently along with a large variety of other secondary uranium minerals, mainly the uranium phosphates, carbonates, sulfates, hydrous-oxides and silicates, in what may be considered a third type of secondary mineral deposit. These have been referred to as oxidized secondary deposits or simply as oxidized deposits. Most of these deposits are probably oxidized vein deposits, the complete oxidation of the primary minerals in place making it difficult to prove the original primary character. On the other hand, they may be formed by ground-water solutions that have dissolved uranium from a broad area of slightly mineralized rocks and concentrated it by precipitation in veins and fracture zones. These depore numerous throughout arid and semi-arid regions, such as the western and southwestern United States, the west coast of South America, the Mediterranean area, and southern Russia, and, although a few of them have produced ore, they provide most of the troublesome traces or nibbles that often confound uranium prospectors. In some cases they have proved to be the oxidized upper portions of primary deposits from which primary ore has eventually been mined at depth.

The secondary minerals in the weathered zones of primary deposits have at some places contributed significant uranium production, particularly where weathering has been deep, as at Shinkolobwe in the Belgian Congo; at Urgeirica, Portugal; at Marysvale, Utah; and in some of the copper-uranium deposits of the southwestern United States. However, the major significance of such occurrences to the prospector is the indication of the presence of primary mineralization which, at important deposits, produces in the end the preponderance of the uranium. The flat-lying deposits in sedimentary rocks represent the most important occurrence of the secondary minerals, and the most important deposits of this type are the carnotite deposits of the Colorado Plateau area of Colorado, Utah, Arizona, and New Mexico, which have been radium, vanadium, and uranium producers since 1898.

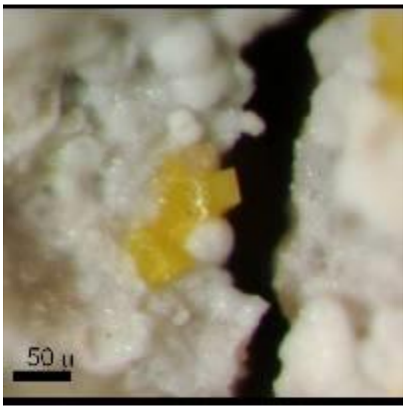
Three-quarters of the more than one hundred uranium minerals are secondary minerals, but of these only six may logically be considered ore minerals. Most of the others, many of them extremely rare, occur primarily as the weathering products in the oxidized zones of primary deposits, but some are found associated with the secondary ore minerals in deposits in sedimentary rocks. Unlike the primary uranium ore minerals, the secondary ore minerals seldom occur singly or only two to a deposit. They usually occur together in groups of several of both the ore and non-ore minerals, although, as in the case of the carnotite deposits, one mineral may be predominant. The dominant colors of the secondary uranium ore minerals are yellow and green, orange being confined primarily to the non-ore minerals. primarily to the non-ore minerals.

Vanadates and Arsenades

***Carnotite*: ($K_20*2UO_3*V_2O_5*nH_20$; 50-55 percent U_3O_8).**

Carnotite, a potassium uranium vanadate, is the most important of the secondary uranium ore minerals, having provided possibly 90 percent of the uranium production from secondary deposits. It is a lemon-yellow mineral with an earthy luster, a yellow streak, and a specific gravity of about 4. It occurs most commonly in soft; powdery aggregates of finely crystalline material or in thin films or stains on rocks or other minerals. Its powdery nature gives the impression of even greater softness than its hardness scale rating of 2-3 would indicate. It can be easily scratched with the fingernail. Carnotite is not fluorescent.

The most noted occurrences of carnotite are in the Colorado Plateau area of the United States, where it was first identified in 1898 and has since provided the major domestic uranium production, on the western edge of the Black Hills, South Dakota, and in the Ferghana basin, U.S.S.R. It occurs in sandstones in flat-lying, irregular, partially bedded ore bodies of from a few tons to a few hundred thousands of tons in size. In the higher-grade deposits (more than one-third of 1 per cent U_3O_8), the carnotite is present in sufficient quantity to color the rock a bright yellow; but in poorer deposits, particularly below 0.20 per cent $U3O_8$, it is often difficult to distinguish it from the sandstone itself. Its color is also often masked by iron staining or by the dark-colored vanadium minerals usually associated with it. Most carnotite deposits range in grade from 0.10 percent to 0.50 per cent U_3O_8.



© PAWulser

Carnotite, Allophane

Beverley Mine, Paralana High Plains, North Flinders Ranges, Flinders Ranges, South Australia, Australia

Carnotite xx on allophane, in the Beverley Clays unit

Carnotite

Radium Hill, Radium Hill area, Mingary, Olary Province, South Australia, Australia

Yellow carnotite micro xls encrustations. Overall size: 2,9 x 2,8 x 1,2 cm. Photo and collection Antonio Borrelli.

© Antonio Borrelli

© Leon Hupperichs

Carnotite

Mashamba West Mine, Kolwezi, Western area, Katanga Copper Zone, Katanga (Shaba), Congo (Zaïre)

Field of view 3 mm.
Specimen and photo Leon Hupperichs.

© Leon Hupperichs

Carnotite

Mashamba West Mine, Kolwezi, Western area, Katanga Copper Zone, Katanga (Shaba), Congo (Zaïre)

Field of view 9 mm.
Specimen and photo Leon Hupperichs.

© Elmar Lackner

Carnotite

Mashamba West Mine, Kolwezi, Western area, Katanga Copper Zone, Katanga (Shaba), Congo (Zaïre)

Picture width is 3mm. Yellow-orange well developed crystals of Carnotite. Depth of field is achieved with CombineZM.

Carnotite

Clara Mine, Rankach valley, Oberwolfach, Wolfach, Black Forest, Baden-Württemberg, Germany

Picture width 3 mm. Collection and foto Stephan Wolfsried

© Stephan Wolfsried

© M.Heintzelman

Carnotite

Mauch Chunk Ridge, Jim Thorpe, Carbon Co., Pennsylvania, USA

Yellow encrustations of Carnotite on conglomerate rock matrix. From the renowned PA Uranyl mineral occurrences at Mauch Chunk (now Jim Thorpe), Carbon Co., Pennsylvania (Dana locale). Originally from an older collection, circa early-mid 20th C. Specimen size: 3.5 x 2.5cm. From the PA Annex of my personal collection, acquired in 2005.

© Charles Creekmur

Carnotite

Gould Lease (Gould 1-3; East Rim; Payday 3-4), Edgemont Uranium District, Fall River Co., South Dakota, USA

A 2 3/4 x 3 1/2 inch slab of sandstone matrix covered with powdery carnotite. In the Charles Creekmur collection.

Although carnotite is the principal mineral in the carnotite deposits, nearly twenty other secondary uranium minerals are found associated with it. The most common of these is the secondary ore mineral, tyuyamunite, described below. All of the other secondary ore minerals, torbernite, autunite, schroeckingerite, and uranophane, have also been found in carnotite deposits. The other associated secondary minerals are the rare oxides, carbonates, arsenates, vanadates, phosphates and silicates. The most common non-uranium minerals found associated with carnotite are the vanadium minerals, corvusite (hydrous-vanadium oxide), hewettite (calcium vanadium oxide), and roscoelite (vanadium mica-silicate). Minerals of the common metals, such as copper, lead, zinc, and manganese, have also been identified in carnotite deposits, as well as pitchblende and uraninite, but their occurrence in most cases is only of academic interest.

One other important association of carnotite should be mentioned, for it has an important bearing on prospecting for these deposits. An evident general affinity of uranium for certain organic materials, which has had some effect on its deposition in almost all types of deposits, is perhaps most clearly displayed in the carnotite deposits of the Colorado Plateau area. In a large number of these deposits, the carnotite is intimately associated with silicified or carbonized wood fossil wood).

Tyuyamunite: ($CaO*2UO_3$ $*V_2O_5*nH_20$; 48-55 percent U_3O_8).

Tyuyamunite is closely related to carnotite as indicated by the chemical formula, which is the same except that calcium substitutes for the potassium of carnotite. The physical properties of tyuyamunite are the same except for a slightly more greenish color than carnotite and, in some cases, a very weak yellow-green fluorescence not found in carnotite.

 © Elmar Lackner	Tyuyamunite, Calcite Rodolfo Mine, Cosquín, Córdoba, Argentina Picture width is 5mm. Yellow crystals of Tyuyamunite on Calcite. Depth of field is achieved with CombineZM.

 © Martins da Pedra	Tyuyamunite Zelenaya Cave, Tyuya-Muyun Cu-V-U Deposit, Tyuya-Muyun Hill, Fergana Valley, Osh Oblast, Kyrgyzstan Crust on goethite matrix - Overall size 4x3x1,5cm - December of 2004 - From Luís Miguel collection
 © David Aldridge 06	Tyuyamunite, Calcite Margaritas #1 Mine, Sierra Peña Blanca, Peña Blanca District, Mun. de Aldama, Chihuahua, Mexico Beautiful microcrystals of vividly yellow tyuyamunite sprayed across calcite. Specimen is about 4cm across. In the collection of the photographer.
 © Rob Lavinsky	Tyuyamunite Santa Eulalia District, Mun. de Aquiles Serdán, Chihuahua, Mexico A rich specimen of the rare uranium mineral tyuyumunite, with bright yellow color. Old scott williams co. label. 6.8 x 4 x 3 cm
	Tyuyamunite Santa Eulalia District, Mun. de Aquiles Serdán, Chihuahua, Mexico Field of view 8 mm. Collection M. Kampf No 80-013.

© 2005 M. Kampf	
 © Chris Tucker	Tyuyamunite, Fluorite, Calcite Carbon Co., Montana, USA Tyuyamunite with Calcite on Fluorite, Dandy Mine, Carbon County, Montana. Small calcite crystals rest on a matrix of dark purple fluorite with scattered microcrystals of vivid tyuyamunite. Measures 4.5x5x2.5cm
 © Chris Tucker	Tyuyamunite, Calcite Carbon Co., Montana, USA Tyuyamunite on Calcite, Dandy Mine, Carbon County, Montana. Milky white calcite that has a dark red rusty coating and then a coating of powdery yellow tyuyamunite. Measures 7x5x4cm

Tyuyamunite is found in small amounts in almost any deposit or with any occurrence of carnotite. It is, as one would suspect, more abundant where there is an appreciable amount of calcium, usually in the form of calcite or limestone. Tyuyamunite first obtained importance as an ore mineral because of its occurrence in a deposit in southeastern Turkistan, U.S.S.R., near the town of Tyuya Muyun, for which it was named. It occurs there, and at other localities in the region, associated with other secondary uranium minerals, particularly carnotite and torbernite, in fractures in limestones, dolomites, and shales.

Phosphates

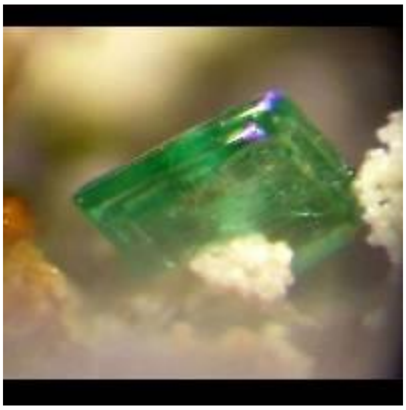
Torbernite and Meta-torbernite:

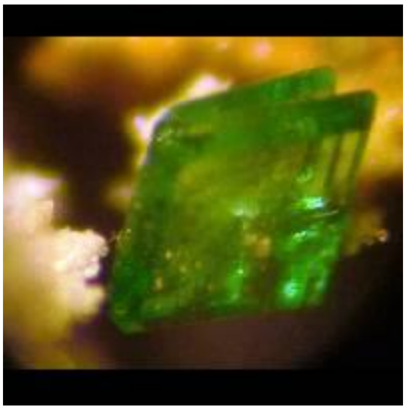
($CuO*2UO_3$ $*P_2O_5*$ nH_20; 60 percent U_3O_8) .

Torbernite and meta-torbernite are hydrous copper uranium phosphates, the only difference between the two being the number of water molecules present; their physical properties are identical. They have a bright emerald color, a pearly luster, hardness of 2-2 1/2 (about the same as the fingernail), and specific gravity of about 3.5 (a little heavier than quartz). They occur in flat, square, translucent crystals which usually fluoresce With a faint green color.

Torbernite and meta-torbernite are the most common of the secondary uranium minerals that are found associated with primary deposits where oxidation has occurred.

They are common in nearly all such deposits except pegmatites, which usually do not contain the necessary copper to form them. They are most noted for their abundance in the oxidized zones at Shinkolobwe, Joachimsthal, and in the copper-uranium deposits of Utah and Arizona.

 © viccloete	Torbernite Monakoff Mine, Cloncurry District, Mt Isa - Cloncurry area, Queensland, Australia Another neat micro <1mm from this site, ex 2005 trip

 © viccloete	Torbernite Monakoff Mine, Cloncurry District, Mt Isa - Cloncurry area, Queensland, Australia One of several pristine but micro ~1mm Torbernite crystals Collected 2005
 © viccloete	Torbernite, Fluorite Monakoff Mine, Cloncurry District, Mt Isa - Cloncurry area, Queensland, Australia While not being prismatic, the association of Torbernite and Fluorite must be most unusual! Field of view ~1.5mm
 © 2003 John H. Betts	Torbernite Mt Painter area, North Flinders Ranges, Flinders Ranges, South Australia, Australia Foliatated, green crystals of torbernite with brownish limonite staining. Radioactive. Ex. Robert C. Linck (1905-1970). Overall size of mineral specimen: 26x18x14 mm. Size of individual crystals: 5-12 mm.

In addition, they occur with the other secondary uranium minerals in the oxidized secondary deposits whenever copper has been present in the depositing solutions or surrounding rocks. They are associated with tyuyamunite in Turkistan and with autunite at Bukhova, Bulgaria, and at Mt. Painter, South Australia. The principal non uranium minerals associated with torbernite are the clay minerals, limonite, quartz, pyrite, and the copper sulfides and carbonates.

Elsewhere in this book these two minerals will be referred to simply as torbernite, although actually the most common of the two is probably Meta-torbernite.

Autunite and Meta-autunite:

($CaO*2UO_3* P_2O_5* nH_2O$; 60 percent U_30_8.)

Reference to the chemical formula will show that these two minerals have the same composition as torbernite, with calcium substituting for copper. Because of this similarity, they are commonly found together, the proportion of torbernite being dependent upon the amount of copper available to the uranium-bearing solutions. In some instances, where copper is completely lacking, only autunite or meta-autunite is formed. Like torbernite and meta-torbernite, autunite and meta-autunite are identical in their physical properties, the distinction being made on the basis of the number of water molecules present. Also, as in the case of torbernite, meta-autunite is probably the most common. For simplification,however, they will be referred to as autunite. The physical properties of autunite are similar to those of torbernite, except for its color, which is predominantly lemon or sulfur-yellow. although occasionally apple-green, and its brilliant yellow to greenish-yellow fluorescence in ultraviolet light. Autunite has a hardness of 2-2 1/2, is slightly heavier than quartz (specific gravity, 3.1), has a colorless to pale yellow or green streak, and occurs in small square, rectangular, or octagonal flat, translucent crystals or as thin coatings or stains on rock or other mineral surfaces.

	Autunite Palermo No. 1 Mine, Groton, Grafton Co., New Hampshire, USA Bright yellow-green autunite in a fresh exposure. View is about 5 mm across. P. Cristofono specimen and photo, field-collected 2004.
 © Stephan Wolfsried	Autunite Foote Lithium Co. Mine (Foote Mine), Kings Mountain District, Cleveland Co., North Carolina, USA Picture width 2 mm. Collection and photo Stephan Wolfsried
 © Charles Creekmur	Autunite, Uranophane Chalk Mountain Mine, Spruce Pine, Spruce Pine District, Mitchell Co., North Carolina, USA A 5x2 1/2 inch piece of pegmatite matrix with autunite and uranophane on it. In the Creekmur collection.

It is seldom found in large masses but rather as small spots scattered throughout the enclosing rocks. A good autunite exposure is a brilliant sight at night under ultraviolet light, and the inexperienced prospector is apt to overestimate the grade of a deposit seen under those conditions.Autunite is found in varying amounts in almost all deposits of the other secondary uranium minerals. It is an oxidation product of pitchblende and uraninite and most of the other primary minerals, and may also be derived from some other secondary minerals, like gummite and uranophane. As such it is an important constituent of the oxidized zones at Shinkolobwe and other important primary ore deposits and is a common secondary uranium mineral in most pegmatites. It is present in small amounts in many of the carnotite deposits of the Colorado Plateau area and in larger amounts in the tyuyaunite deposits of Turkistan.

The greatest significance of autunite to the prospector lies in the fact that it is the most common uranium mineral in the oxidized secondary deposits in igneous rocks of arid regions, both those related to primary mineralization and those of unknown origin. It is an important constituent of the oxidized ores at Urgeirica, Portugal, and at Marysvale, Utah, and the most prominent mineral in the White Signal, New Mexico, district, at Mt. Painter, South Australia, and in the numerous low-grade secondary occurrences in the Mojave Desert and at other localities in southern California and Nevada. The associated non-uranium minerals are the same as for torbernite, except that the copper minerals may be absent.

SILICATES

Uranophane:

($CaO*2UO_3*2SiO_2*6H_2O$; 65 percent U_30_8

Uranophane is a hydrated calcium uranium silicate containing silica in place of the phosphate of autunite. It is slightly lighter in color and somewhat heavier than autunite (specific gravity 3.85) and has a different crystalline form; it may occur as stains or coatings without apparent crystal form or as finely fibrous or radiating crystal aggregates.

 © Element51.com	Uranophane Madawaska Mine (Faraday Mine), Faraday Township, Bancroft District, Hastings Co., Ontario, Canada The spray on the left measures 1cm from top to bottom
 © Rob Lavinsky	Uranophane Madawaska Mine (Faraday Mine), Faraday Township, Bancroft District, Hastings Co., Ontario, Canada A GORGEOUS specimen with unusually large acicular crystals for the species, arranged in radial tufts protected within a vuggy matrix. For what it is, this is one of the best examples I have seen from the region. 6.7 x 4.8 x 2.7 cm
 © Antonio Borrelli	Uranophane Madawaska Mine (Faraday Mine), Faraday Township, Bancroft District, Hastings Co., Ontario, Canada Spray of yellow acicular crystals. Overall size: 2,7 x 1,8 x 2,1 cm. Photo and collection Antonio Borrelli.

© O. Dziallas

Uranophane

Shinkolobwe Mine (Kasolo Mine), Shinkolobwe, Central area, Katanga Copper Zone, Katanga (Shaba), Congo (Zaïre)

Picture width 3mm. Photographer and collection O. Dziallas.

© Stephan Wolfsried

Uranophane

Shinkolobwe Mine (Kasolo Mine), Shinkolobwe, Central area, Katanga Copper Zone, Katanga (Shaba), Congo (Zaïre)

Picture width 5 mm. Collection and photo Stephan Wolfsried

© ARLIGUIE M

Uranophane, Spherocobaltite

Kalongwe deposit, Western area, Katanga Copper Zone, Katanga (Shaba), Congo (Zaïre)

Sample size: 6 X 5 cm
Uranophane crystals: 4 mm max

Collection and photo: M Arliguie

© Dick Dionne

Uranophane

Le Boucheron, Davignac, Corrèze, Limousin, France
Sprays of uranophane crystals. 50x micro photo, field of view 2mm. Dionne collection. ex Simkev specimen.

© Dick Dionne

THE 2013 IAEA CLASSIFICATION OF URANIUM DEPOSITS

Fifteen types of deposit have been retained in the new IAEA classification scheme [2, 3, 44]. In contrast to the ordering of previous IAEA classifications, the economics parameter has not been taken into account. Instead, the deposits are listed in a geologically meaningful order, ranging from deep, primary magmatic deposits to sedimentary and surficial deposits. The classes are as follows:

(1) Intrusive; (2) Granite-related; (3) Polymetallic iron oxide breccia complex; (4) Volcanic-related; (5) Metasomatite; (6) Metamorphite; (7) Proterozoic unconformity; (8) Collapse breccia pipe; (9) Sandstone; (10) Palaeo quartz-pebble conglomerate; (11) Surficial; (12) Lignite–coal; (13) Carbonate; (14) Phosphate; (15) Black shale.

Type 1. Intrusive:

Deposits included in this type are contained in intrusive rocks of many different petrochemical compositions (granite, pegmatite, monzonite, peralkaline syenite and carbonatite). Two main subtypes are recognized: (i) intrusive anatectic deposits associated with partial melting processes (Rössing and Rössing South, Namibia, and deposits in the Bancroft area, Canada), and (ii) intrusive plutonic deposits related to magmatic differentiation. Examples of this latter type include the uranium occurrences in the porphyry copper deposits of Bingham Canyon and Twin Buttes (USA), the Kvanefjeld deposit (Greenland) and the Phalabora carbonatite complex (South Africa).

Type 2: Granite-related deposits

Deposits related to granite include: (i) true veins composed of ore and gangue minerals in granite or adjacent (meta-) sedimentary rocks and (ii) disseminated mineralization occurring in granite as episyenite bodies. Uranium mineralization occurs within, at the contact or peripheral to the intrusion. In the Hercynian Belt of Europe and other parts of the world, these deposits are generally associated with large, peraluminous two mica granite complexes (leucogranites). Resources range from small to large in size and grades vary from low to high. Two subtypes are distinguished on the basis of their spatial setting with respect to the granitic pluton and the host country rock.

Type 3: Polymetallic iron oxide breccia complex deposits

This type of deposit has been assigned to a broad category of iron oxide–copper–gold deposits occurring around the world, although Olympic Dam (Australia) is the only known representative of this type with significant by-product uranium resources. This deposit is the world's largest individual uranium resource and contains with more than 2 Mt of uranium at low grade (230 ppm). Deposits of this group occur in haematite-rich granite breccias (Olympic Dam, Gawler Craton) or in metasedimentary–metavolcanic breccias (Salobo, Carajas district, Brazil) and contain disseminated uranium in association with copper, gold, silver and rare earth elements. At Olympic Dam, this breccia is hosted within a Mesoproterozoic, highly potassic granitic intrusion that exhibits regional Fe–K metasomatism.

Type 4: Volcanic-related deposits

Uranium deposits of this type are located within and near volcanic calderas filled with mafic to felsic volcanic lavas or, more commonly, pyroclastic rocks and intercalated clastic sediments. Uranium mineralization is largely controlled by structures such as veins and stockworks with minor stratiform lodes. This mineralization occurs at several stratigraphic levels within the volcanic and sedimentary units and may extend deeply into the underlying basement where it is found in fractured granite and metamorphic rocks. Uranium minerals (pitchblende, coffinite, hexavalent uranium minerals and, less commonly, brannerite) are associated with molybdenum-bearing sulphides and pyrite. Other anomalous elements include As, Bi, Ag, Li, Pb, Sb, Sn and W. Associated gangue minerals consist of violet coloured fluorite, carbonates, baryte and quartz. The most significant deposits are located within the Streltsovska caldera in the Russian Federation.

Type 5: Metasomatite deposits

Deposits of this type are generally confined to Precambrian Shields (an exception being Coles Hill, USA) in orogenic belts affected by intense Na- or K-metasomatism, which produced albitized or illitized rocks along deeply rooted fault systems. In Ukraine, these deposits are developed within a variety of basement rocks, including granite, migmatite, gneiss and ferruginous quartzite which produced albitite, aegirinite, alkali amphibolite, as well as carbonate and ferruginous rocks. The principal uranium phases are uraninite, brannerite and other titaniferous and uraniferous minerals, pitchblende, coffinite and hexavalent uranium minerals. The resources range in size from medium to very large. Examples include the Michurinskoye, Vatutinskoye, Severinskoye, Zheltorechenskoye, Novokonstantinovskoye deposits (Ukraine), deposits of the Elkon district (Russian Federation), Espinharas and Lagoa Real (Brazil), Valhalla (Australia), Kurupung (Guyana), Coles Hill (USA), Lianshanguan (China), Michelin (Canada) and several small deposits in the Arjeplog region of northern Sweden. Three subtypes of metasomatite deposits are distinguished on the basis of precursor rock lithology and type of metasomatism: Na-metasomatite, K-metasomatite and skarn deposits.

Type 6: Metamorphite deposits

Metamorphite deposits consist of disseminations, impregnations, veins and shear zones within metamorphic rocks of various ages with no relation to granitic intrusions. These deposits are highly variable in size, resources and grades. Two subtypes are recognized:

Type 7: Proterozoic unconformity deposits

Unconformity-related deposits are associated with and occur immediately below, above, or spanning an unconformable contact that separates Archaean–Palaeoproterozoic crystalline basement from overlying, red bed clastic sediments of Proterozoic age. In most cases, the basement rocks immediately below the unconformity are strongly haematized and clay altered, possibly as a result of palaeoweathering and/or diagenetic/hydrothermal alteration. Deposits consist of pods, veins and semimassive replacements comprising mainly pitchblende. Strong quartz dissolution is generally associated with them. They are preferentially located in two major districts, the Athabasca Basin (Canada) and the Pine Creek Orogen (Australia). The Proterozoic unconformity deposits include three subtypes of variable importance: unconformity-contact, basement-hosted and stratiform structurecontrolled deposits.

Type 8: Collapse breccia pipe deposits

Deposits in this group occur in sedimentary basins within cylindrical, vertical pipes filled with fragments from overlying lithological units filling karst solution cavities excavated in the thick, underlying carbonate strata. The uranium is concentrated as primary, tetravalent uranium minerals, mainly pitchblende, in the permeable breccia matrix and in the arcuate, ring fracture zone surrou-nding the pipe. The pitchblende is associated with numerous sulphide and oxide minerals containing Cu, Fe, V, Zn, Pb, Ag, Mo, Ni, Co, As and Se. Type examples are the deposits of the Arizona Strip north of the Grand Canyon and those immediately south of the Grand Canyon (USA). Resources are small to medium (300–2500 tU) and of relatively high grade (0.20–0.80% U).

Type 9: Sandstone deposits

Sandstone-hosted uranium deposits occur in medium- to coarse-grained sandstones deposited in continental fluvial or marginal marine sedimentary environments. Volcanic ash may represent a major uranium sources within the sandstone (Arlit district, Niger; Lodève Basin, France; Wyoming, USA). Uranium is precipitated by reduction processes caused by the presence of a variety of possible reducing agents within the sandstone. These include carbonaceous material (mainly detrital plant debris), sulphides (pyrite), ferro-magnesian minerals (chlorite), bacterial activity, migrated fluids from under-lying hydrocarbon reservoirs and others. Sandstone uranium deposits can be divided into five main subtypes with frequent transitional types between them.

Type 10: Palaeo quartz-pebble conglomerate deposits

Detrital uranium oxide ores are found in quartz-pebble conglomerates deposited as basal units (Elliot Lake district, Canada or intraformational conglomerates (Witwatersrand Basin, South Africa) in fluviolacustrine braided stream systems older than 2400–2300 Ma. The conglomerate matrix is pyritic, and gold, as well as other accessory oxide and sulphide detrital minerals, are often present in minor quantities. Examples include deposits of the Witwatersrand Basin, South Africa, where uranium is mined as a by-product of gold, as well as deposits in the Blind River/Elliot Lake area of Canada. Two economic subtypes are distinguished.

Type 11: Surficial deposits

Surficial uranium deposits are broadly defined as young (Tertiary–Recent), near surface uranium concentrations hosted in sediments and soils. The largest of the surficial uranium deposits are found in calcrete (calcium and magnesium carbonates) and they are mainly located in Australia (Yeelirrie) and Namibia (Langer Heinrich). These calcrete hosted deposits mainly occur in valley fill sediments along Tertiary drainage channels and in playa lake sediments in areas of deeply weathered, uraniferous 23 granites. Carnotite is the main uranium mineral. Surficial deposits also occur less commonly in peat bogs, karst caverns and soils.

Type 12: Lignite–coal deposits

Elevated uranium contents occur in lignite or coal mixed with mineral detritus (silt, clay) and in immediately adjacent carbonaceous mud and siltstone–sandstone horizons. Pyrite and ash contents are high. Lignite–coal seams are often interbedded or overlain by felsic pyroclastic rocks. Examples include deposits in the southwestern Williston Basin (USA), Koldjat and Nizhne Iliskoye (Kazakhstan), Freital (Germany), Ambassador (Australia) and the Serres Basin (Greece). Two subtypes are recognized: stratiform lignite–coal deposits and fracture-controlled lignite–coal deposits.

Type 13: Carbonate deposits

Deposits are hosted in carbonate rocks (limestone, dolostone). Mineralization can be syngenetic and stratabound or, more commonly, structure related within karsts, fractures, faults and folds. Three types of carbonate hosted uranium deposits are recognized: stratabound, cataclastic and karst.

Type 14: Phosphate deposits

Phosphate deposits are principally represented by marine phosphorite of continental shelf origin containing synsedimentary, stratiform, disseminated uranium in fine-grained apatite. Phosphorite deposits constitute very large uranium resources (millions of tonnes) but of very low grade (0.005– 0.015% U). Uranium can be recovered as a by-product of phosphate production. Examples include the Land Pebble district, Florida (USA), Gantour (Morocco) and Al-Abiad (Jordan). Another type of phosphorite deposit consists of organic phosphate, including argillaceous marine sediments enriched in fish remains that are uraniferous (Melovoe, Kazakhstan). Deposits in continental phosphates are not common. Three types of uranium-bearing phosphate deposits are identified: organic, minero-chemical and continental.

Type 15: Black shale deposits

Black shale related uranium mineralization includes marine, organic-rich shale and coal-rich pyritic shale, containing synsedimentary, disseminated uranium adsorbed onto organic material and clay minerals, and fracture-controlled mineralization hosted within or adjacent to black shale horizons. Examples include the uraniferous alum shale in Sweden and Estonia, the Chattanooga Shale (USA), the Chanziping deposit (China) and the Gera-Ronneburg deposit (Germany).