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Uranium ore

Uranium ore deposits are economically recoverable concentrations of uranium within the Earth's crust. Uranium is one of the more common elements in the Earth's crust, being 40 times more common than silver and 500 times more common than gold. It can be found almost everywhere in rock, soil, rivers, and oceans. The challenge is to find those areas where the concentrations are adequate to form an economically viable deposit.

Globally, the distribution of uranium ore deposits is widespread on all continents, with the largest deposits found in Australia, Kazakhstan, and Canada. To date, high-grade deposits are only found in the Athabasca Basin region of Canada.

Uranium deposits are generally classified based on host rocks, structural setting, and mineralogy of the deposit. The most widely used classification scheme was developed by the International Atomic Energy Agency (IAEA) and subdivides deposits into 15 categories.

1) Uranium

Uranium is a silvery-gray metallic weakly radioactive chemical element. It has the chemical symbol U an atomic number 92. The most common isotopes in natural uranium are ^{238}U (99.27%) and ^{235}U (0.72%). All uranium isotopes present in natural uranium are radioactive and fissionable, and ^{235}U is fissile (will support a neutron-mediated chain reaction). Uranium, thorium, and potassium are the main elements contributing to natural terrestrial radioactivity.

Uranium has the highest atomic weight of the naturally occurring elements and is approximately 70% denser than lead, but not as dense as tungsten, gold, platinum, iridium, or osmium. It is always found combined with other elements. Along with all elements having atomic weights higher than that of iron, it is only naturally formed in supernova explosions.

2) Uranium minerals

Uranium Minerals ^{[7][8]}	
Primary uranium minerals	
Name	Chemical Formula
uraninite or pitchblende	UO_2
coffinite	$\text{U}(\text{SiO}_4)_{1-x}(\text{OH})_{4x}$
brannerite	UTi_2O_6
davidite	$(\text{REE})(\text{Y,U})(\text{Ti,Fe}^{3+})_{20}\text{O}_{38}$
thucholite	Uranium-bearing pyrobitumen
Secondary uranium minerals	
Name	Chemical Formula
autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \times 8-12 \text{ H}_2\text{O}$
carnotite	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \times 1-3 \text{ H}_2\text{O}$
gummite	gum like amorphous mixture of various uranium minerals
saleeite	$\text{Mg}(\text{UO}_2)_2(\text{PO}_4)_2 \times 10 \text{ H}_2\text{O}$
torbernite	$\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \times 12 \text{ H}_2\text{O}$
tyuyamunite	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \times 5-8 \text{ H}_2\text{O}$
uranocircite	$\text{Ba}(\text{UO}_2)_2(\text{PO}_4)_2 \times 8-10 \text{ H}_2\text{O}$
uranophane	$\text{Ca}(\text{UO}_2)_2(\text{HSiO}_4)_2 \times 5 \text{ H}_2\text{O}$
zeunerite	$\text{Cu}(\text{UO}_2)_2(\text{AsO}_4)_2 \times 8-10 \text{ H}_2\text{O}$

The primary uranium ore mineral is uraninite (UO₂) or pitchblende. A range of other uranium minerals can be found in various deposits. These include carnotite, tyuyamunite, torbernite and autunite. The davidite-brannerite-absite type uranium titanates, and the euxenite-fergusonite-samaraskite group are other uranium minerals.

A large variety of secondary uranium minerals are known, many of which are brilliantly coloured and fluorescent. The most common are gummite, autunite (with calcium), saleeite (magnesium) and torbernite (with copper); and hydrated uranium silicates such as coffinite, uranophane (with calcium) and sklodowskite (magnesium).

3) Ore genesis

There are several themes of uranium ore deposit formation, which are caused by geological and chemical features of rocks and the element uranium. The basic themes of uranium ore genesis are host mineralogy, reduction-oxidation potential, and porosity.

Uranium is a highly soluble, as well as a radioactive, heavy metal. It can be easily dissolved, transported and precipitated within ground waters by subtle changes in oxidation conditions. Uranium also does not usually form very insoluble mineral species, which is a further factor in the wide variety of geological conditions and places in which uranium mineralization may accumulate.

Uranium is an incompatible element within magmas, and as such it tends to become accumulated within highly fractionated and evolved granite melts, particularly alkaline examples. These melts tend to become highly enriched in uranium, thorium and potassium, and may in turn create internal pegmatites or hydrothermal systems into which uranium may dissolve.

4) Classification schemes

Uranium Deposit Classification ^[9]	
Uranium Transport / Precipitation Conditions	Deposit Type
Surface Processes / synsedimentary	Surficial deposits
	Quartz-pebble conglomerate deposits
	Phosphorite deposits
	Lignite
	Black shales
Diagenetic	Sandstone deposits
Diagenetic – Hydrothermal?	Unconformity-related deposits
	Vein deposits
	Collapse breccia pipe deposits
Magmatic – Hydrothermal?	Breccia complex deposits
	Volcanic deposits
	Metasomatite deposits
	Vein deposits
	Intrusive deposits
Metamorphic – Hydrothermal?	Metamorphic deposits

4.1) IAEA Classification (1996)

The International Atomic Energy Agency (IAEA) assigns uranium deposits to 15 main categories of deposit types, according to their geological setting and genesis of mineralization, arranged according to their approximate economic significance:

1. Unconformity-related deposits
2. Sandstone deposits
3. Quartz-pebble conglomerate deposits
4. Breccia complex deposits
5. Vein deposits
6. Intrusive deposits (Alaskites)
7. Phosphorite deposits
8. Collapse breccia pipe deposits
9. Volcanic deposits
10. Surficial deposits
11. Metasomatite deposits
12. Metamorphic deposits
13. Lignite
14. Black shale deposits
15. Other types of deposits

4.2) Alternate scheme

The IAEA classification scheme works well, but is far from ideal, as it does not consider that similar processes may form many deposit types, yet in a different geological setting. The following table groups the above deposit types based on their environment of deposition.

5) Deposit types (IAEA Classification)

5.1) Unconformity-related deposits

Unconformity-type uranium deposits host high grades relative to other uranium deposits and include some of the largest and richest deposits known. They occur in close proximity to major unconformities between relatively quartz-rich sandstones comprising the basal portion of relatively undeformed sedimentary basins and deformed metamorphic basement rocks. These sedimentary basins are typically of Proterozoic age, however some Phanerozoic examples exist.

Phanerozoic unconformity-related deposits occur in Proterozoic metasediments below an unconformity at the base of overlying Phanerozoic sandstone. These deposits are small and low-grade (Bertholene and Aveyron deposits, in France).

The two most significant areas for this style of deposit are currently the Athabasca Basin in Saskatchewan, Canada, and the McArthur Basin in the Northern Territory, Australia.

5.1.1) Athabasca Basin

Athabasca Basin in Canada, including the two largest high grade uranium deposits in the world, Cigar Lake with 217 million pounds (99,000 t) U₃O₈ at an average grade of 18% and McArthur River with 324 million pounds (147,000 t) U₃O₈ at an average grade of 17%. These deposits occur below, across and immediately above the unconformity. Additionally, another high grade discovery

is in the development stage at Patterson Lake (Triple R deposit) with an estimated mineral resource identified as; “Indicated Mineral Resources” estimated to total 2,291,000 tons at an average grade of 1.58% U₃O₈ containing 79,610,000 pounds of U₃O₈. “Inferred Mineral Resources” are estimated to total 901,000 tons at an average grade of 1.30% U₃O₈ containing 25,884,000 pounds of U₃O₈.

5.1.2) McArthur Basin

The deposits of the McArthur River basin in the East Alligator Rivers region of the Northern Territory of Australia (including Jabiluka, Ranger, and Nabarlek) are below the unconformity and are at the low-grade end of the unconformity deposit range but are still high grade compared to most uranium deposit types. There has been very little exploration in Australia to locate deeply concealed deposits lying above the unconformity similar to those in Canada. It is possible that very high grade deposits occur in the sandstones above the unconformity in the Alligator Rivers/Arnhem Land area.

5.2) Sandstone deposits

Sandstone deposits are contained within medium to coarse-grained sandstones deposited in a continental fluvial or marginal marine sedimentary environment. Impermeable shale or mudstone units are interbedded in the sedimentary sequence and often occur immediately above and below the mineralised horizon. Uranium is mobile under oxidising conditions and precipitates under reducing conditions, and thus the presence of a reducing environment is essential for the formation of uranium deposits in sandstone.

Primary mineralization consists of pitchblende and coffinite, with weathering producing secondary mineralization. Sandstone deposits constitute about 18% of world uranium resources. Orebodies of this type are commonly low to medium grade (0.05–0.4% U₃O₈) and individual orebodies are small to medium in size (ranging up to a maximum of 50,000 t U₃O₈).

Sandstone hosted uranium deposits are widespread globally and span a broad range of host rock ages. Some of the major provinces and production centers include:

1. The Wyoming basins
2. The Grants District of New Mexico
3. Deposits in Central Europe and
4. Kazakhstan

Significant potential remains in most of these centers as well as in Australia, Mongolia, South America, and Africa.

This model type can be further subdivided into the following sub-types:

- tabular
- roll front
- basal channel
- structurally related

Many deposits represent combinations of these types.

5.2.1) Tabular

Tabular deposits consist of irregular tabular or elongate lenticular zones of uranium mineralisation within selectively reduced sediments. The mineralised zones are oriented parallel to the direction of groundwater flow, but on a small scale the ore zones may cut across sedimentary features of the host sandstone. Deposits of this nature commonly occur within palaeochannels cut in the underlying basement rocks.

Tabular sandstone uranium deposits contains many of the highest grades of the sandstone class, however the average deposit size is very small.

5.2.2) Roll front

Roll-front uranium deposits are generally hosted within permeable and porous sandstones or conglomerates. The mechanism for deposit formation is dissolution of uranium from the formation or nearby strata and the transport of this soluble uranium into the host unit. When the fluids change redox state, generally in contact with carbon-rich organic matter, uranium precipitates to form a 'front'.

The Rollfront subtype deposits typically represent the largest of the sandstone-hosted uranium deposits and one of the largest uranium deposit types with an average of 21 million lb (9,500 t) U₃O₈. Included in this class are the Inkai deposit in Kazakhstan and the Smith Ranch deposit in Wyoming. Probably more significant than their larger size, rollfront deposits have the advantage of being amenable to low cost in-situ leach recovery.

Typical characteristics:

- roll-front deposits are crescent-shaped bodies that transect the host lithology
- typically the convex side points down the hydraulic gradient.
- the limbs or tails tend to be peneconcordant with the lithology.
- most ore-bodies consist of several interconnected rolls.
- individual roll-front deposits are quite small but collectively can extend for considerable distances.

5.2.3) Basal channel (palaeochannel)

Basal channel deposits are often grouped with tabular or rollfront deposits, depending on their unique characteristics. The model for formation of palaeochannel deposits is similar to that for roll-front deposits, above, except that the source of uranium may be in the watershed leading into a stream, or the bed load of the palaeochannel itself. This uranium is transported through the groundwaters.

and is deposited either at a reduced boundary, or in ephemeral drainage systems such as those in deserts of Namibia and Australia, it is deposited in calcretised evaporation sites or even in saline lakes as the ground water evaporates.

Some particularly rich uranium deposits are formed in palaeochannels which are filled in the lower parts by lignite or brown coal, which acts as a particularly efficient reductive trap for uranium. Sometimes, elements such as scandium, gold and silver may be concentrated within these lignite-hosted uranium deposits.

The Frome Embayment in South Australia hosts several deposits of this type including Honeymoon, Oban, Beverley and [Four Mile] (which is the largest deposit of this class). These deposits are hosted in palaeochannels filled with Cainozoic sediments and sourced their uranium from uranium-rich

Palaeo- to Mesoproterozoic rocks of the Mount Painter Inlier and the Olary Domain of the Curnamona Province.

5.2.4) Structurally related

Tectonic-lithologic controlled uranium deposits occur in sandstones adjacent to a permeable fault zone which cuts the sandstone/mudstone sequence. Mineralisation forms tongue-shaped ore zones along the permeable sandstone layers adjacent to the fault. Often there are a number of mineralised zones 'stacked' vertically on top of each other within sandstone units adjacent to the fault zone.

5.3) Quartz-pebble conglomerate deposits

Quartz pebble conglomerate hosted uranium deposits are of historical significance as the major source of primary production for several decades after World War 2. This type of deposit has been identified in eight localities around the world, however the most significant deposits are in the Huronian Supergroup in Ontario, Canada and in the Witwatersrand Supergroup of South Africa. These deposits make up approximately 13% of the world's uranium resources.

Two main sub-types have been identified:

- Elliot Lake
- Witwatersrand

Quartz pebble conglomerate hosted uranium deposits formed from the transport and deposition of uraninite in a fluvial sedimentary environment and are defined as stratiform and stratabound paleoplacer deposits. Host rocks are typically submature to supermature, polymictic conglomerates and sandstones deposited in alluvial fan and braided stream environments. The host conglomerates of the Huronian deposits in Canada are situated at the base of the sequence, whereas the mineralized horizons in the Witwatersrand are arguably along tectonized intraformational unconformities.

Uranium minerals were derived from uraniferous pegmatites in the sediment source areas. These deposits are restricted to the Archean and early Paleoproterozoic and do not occur in sediments younger than about 2200 million years when oxygen levels in the atmosphere reached a critical level, making simple uranium oxides no longer stable in near-surface environments.

Quartz pebble conglomerate uranium deposits are typically low grade but characterized by high tonnages. The Huronian deposits in Canada generally contain higher grades (0.15% U₃O₈) and greater resources (as shown by the Denison and Quirke mines), however some of the South African gold deposits also contain sizeable low grade (0.01% U₃O₈) uranium resources.

5.3.1) Witwatersrand sub-type

In the Witwatersrand deposits ores are found along unconformities, shale and siltstone beds, and carbonaceous seams. The West Rand Group of sediments tend to host the most uranium within the Witwatersrand Supergroup. The uranium rich Dominion Reef is located at the base of the West Rand Supergroup. The Vaal Reef is the most uranium rich reef of the Central Rand Group of sediments. Structural controls on the regional scale are normal faults while on the deposit scale are bedding parallel shears and thrusts. Textural evidence indicates that the uranium and gold have been remobilized to their current sites; however the debate continues if the original deposition was detrital or was entirely hydrothermal, or alternatively related to high grade diagenesis.

Uranium minerals in the Witwatersrand deposits are typically uraninite with lesser uranothorite, brannerite, and coffinite. The uranium is especially concentrated along thin carbonaceous seams or

carbon leaders. Strong regional scale alteration consists of pyrophyllite, chloritoid, muscovite, chlorite, quartz, rutile, and pyrite. The main elements associated with the uranium are gold and silver. Gold contents are much higher than in the Elliot Lake type with U: Au ranging between 5:1 and 500:1, which indicates that these gold-rich ores are essentially very low grade uranium deposits with gold.

5.3.2) Elliot Lake sub-type

Sedimentological controls on the Huronian deposits of the Elliot Lake district appear to be much stronger than in the Witwatersrand deposits. Ores grade from uranium through thorium to titanium-rich with decreasing pebble size and increasing distance from their source. While evidence of post-diagenetic remobilization has been identified, these effects appear far subordinate to the sedimentological controls.

Ore consists of uraninite with lesser brannerite and thucholite. These occur in thin beds exhibiting graded bedding reminiscent of placer sorting. Alteration is nonexistent to very weak at best and the weak chlorite and sericite are believed to be mainly post-ore effects. Other postdepositional alteration includes pyritization, silicification, and alteration of titanium minerals. The most prominent geochemical associations with the uranium are thorium and titanium.

It should be noted that this schematic model represents the original depositional setting. The Huronian underwent mild post-depositional folding during the Penokean orogeny around 1.9 billion years. The main regional structure is the Quirke syncline along the margins of which the majority of the known deposits are situated. Due to this structural overprint ore bodies range from subhorizontal to steeply dipping.

5.4) Breccia complex deposits (IOCG-U)

See also: Iron oxide copper gold ore deposits Only one iron-ore-copper-gold (IOCG) deposit of this type is known to contain economically significant quantities of uranium. Olympic Dam in South Australia is the world's largest resource of low-grade uranium and accounts for about 66% of Australia's reserves plus resources.

Uranium occurs with copper, gold, silver, and rare earth elements (REE) in a large hematite-rich granite breccias complex in the Gawler Craton overlain by approximately 300 metres of flat-lying sedimentary rocks of the Stuart Shelf geological province.

Another example for the Breccia type is the Mount Gee area in the Mount Painter Inlier, South Australia. Uranium mineralised quartz-hematite breccia is related to Palaeoproterozoic granites with uranium contents of up to 100 ppm. Hydrothermal processes at about 300 million years ago remobilised uranium from these granites and enriched them in the quartz-hematite breccias. The breccias in the area host a low grade resource of about 31,400 t U₃O₈ at 615 ppm in average.

5.5) Vein deposits

Vein deposits play a special role in the history of uranium: the term "pitchblende" ("Pechblende") originates from German vein deposits when they were mined for silver in the 16th century. F.E. Brückmann made the first mineralogical description of the mineral in 1727 and the vein deposit Jachymov in the Czech Republic became the type locality for uraninite. In 1789 the German chemist M. H. Klaproth discovered the element of uranium in a sample of pitchblende from the Johanngeorgenstadt vein deposit. The first industrial production of uranium was made from the Jachymov deposit and Marie and Pierre Curie used the tailings of the mine for their discovery of polonium and radium.

Vein deposits consist of uranium minerals filling in cavities such as cracks, veins, fractures, breccias, and stockworks associated with steeply dipping fault systems. There are three major subtypes of vein style uranium mineralisation:

- intragranitic veins (Central Massif, France)
- veins in metasedimentary rocks in exocontacts of granites
 - + quartz-carbonate uranium veins (Erzgebirge Mts, Germany/Czech Republic; Bohemian Massif, Czech Republic)
 - + uranium-polymetal veins (Erzgebirge Mts Germany/Czech Republic; Saskatchewan, Canada)
- mineralised fault and shear zones (central Africa; Bohemian Massif, Czech Republic)

Intragranitic veins form in the late phase of magmatic activity when hot fluids derived from the magma precipitate uranium on cracks within the newly formed granite. Such mineralisation contributed much to the uranium production of France. Veins hosted by metasedimentary units in the exocontact of granites are the most important sources of uranium mineralisation in central Europe including the world class deposits Schneeberg-Schlema-Alberoda in Germany (96,000 t uranium content) as well as Příbram (50,000 t uranium content) and Jáchymov (~10,000 t uranium content) in the Czech Republic. Also they are closely related to the granites, the mineralization is much younger with a time gap between granite formation and mineralisation of 20 million years. The initial uranium mineralisation consists of quartz, carbonate, fluorite and pitchblende. Remobilisation of uranium occurred at later stages producing polymetal veins containing silver, cobalt, nickel, arsenic and other elements. Large deposits of this type can contain more than 1,000 individual mineralized veins. However, only 5 to 12% of the vein areas carry mineralization and although massive lenses of pitchblende can occur, the overall ore grade is only about 0.1% uranium.

The Bohemian Massif also contains shear zone hosted uranium deposits with the most important one being Rozna-Olsi in Moravia northwest of Brno. Rozna is currently the only operating uranium mine in central Europe with a total uranium content of 23,000 t and an average grade of 0.24%. The formation of this mineralization occurred in several stages. After the Variscan Orogeny, extension took place and hydrothermal fluids overprinted fine grained materials in shear zones with a sulphide-chlorite alteration. Fluids from the overlying sediments entered the basement mobilising uranium and while uprising on the shear zone, the chlorite-pyrite material caused precipitation of uranium minerals in form of coffinite, pitchblende and U-Zr-silicates. This initial mineralisation event took place at about 277 million to 264 million years. During the Triassic a further mineralisation event took place relocating uranium into quartz-carbonate-uranium veins. Another example of this mineralisation style is the Shinkolobwe deposit in Congo, Africa, containing about 30,000 t of uranium.

5.6) Intrusive associated deposits

Intrusive deposits make up a large proportion of the world's uranium resources. Included in this type are those associated with intrusive rocks including alaskite, granite, pegmatite and monzonites. Major world deposits include Rossing (Namibia), Ilimaussaq intrusive complex (Greenland) and Palabora (South Africa).

5.7) Phosphorite deposits

Marine sedimentary phosphorite deposits can contain low grade concentrations of uranium, up to 0.01–0.015% U₃O₈, within fluorite or apatite. These deposits can have a significant tonnage. Very large phosphorite deposits occur in Florida and Idaho in the United States, Morocco, and some middle eastern countries.

5.8) Collapse breccia pipe deposits

Collapse breccia pipe deposits occur within vertical, circular solution collapse structures, formed by the dissolution of limestone by groundwater. Pipes are typically filled with down-dropped coarse fragments of limestone and overlying sediments and can be from 30 to 200 metres (100 to 660 ft) wide and up to 1,000 metres (3,300 ft) deep.

Primary ore minerals are uraninite and pitchblende, which occur as cavity fills and coatings on quartz grains within permeable sandstone breccias within the pipe. Resources within individual pipes can range up to 2500 tonnes U₃O₈ at an average grade of between 0.3 and 1.0% U₃O₈.

The best known examples of this deposit type are in Arizona, USA, where several of these deposits have been mined.

5.9) Volcanic deposits

Volcanic deposits occur in felsic to intermediate volcanic to volcanoclastic rocks and associated caldera subsidence structures, comagmatic intrusions, ring dykes and diatremes.

Mineralization occurs either as structurally controlled veins and breccias discordant to the stratigraphy and less commonly as stratabound mineralization either in extrusive rocks or permeable sedimentary facies. Mineralization may be primary, that is magmatic-related or as secondary mineralization due to leaching, remobilization and re-precipitation. The principal uranium mineral in volcanic deposits is pitchblende, which is usually associated with molybdenite and minor amounts of lead, tin and tungsten mineralization.

Volcanic hosted uranium deposits occur in host rocks spanning the Precambrian to the Cenozoic but because the shallow levels at which they form, preservation favors younger age deposits. Some of the more important deposits or districts are Streltsovskoye, Russia; Dornod, Mongolia; and McDermitt, Nevada.

The average deposit size is rather small with grades of 0.02% to 0.2% U₃O₈. These deposits make up only a small proportion of the world's uranium resources. The only volcanic hosted deposits currently being exploited are those of the Streltsovskoye district of eastern Siberia. This is in fact not a single stand-alone deposit, but 18 individual deposits occurring within the Streltsovsk caldera complex. Nevertheless, the average size of these deposits is far greater than the average volcanic type.

5.10) Surficial deposits (calcretes)

Surficial deposits are broadly defined as Tertiary to Recent near-surface uranium concentrations in sediments or soils. Mineralization in calcrete (calcium and magnesium carbonates) are the largest of the surficial deposits. They are interbedded with Tertiary sand and clay, which are usually cemented by calcium and magnesium carbonates. Surficial deposits also occur in peat bogs, karst caverns and soils.

Surficial deposits account for approximately 4% of world uranium resources. The Yeelirrie deposit is by far the world's largest surficial deposit, averaging 0.15% U₃O₈. Langer Heinrich in Namibia is another significant surficial deposit.

5.11) Metasomatite deposits

Metasomatite deposits consist of disseminated uranium minerals within structurally deformed rocks that have been affected by intense sodium metasomatism. Ore minerals are uraninite and brannerite. Th/U ratio in the ores is mostly less than 0.1. Metasomatites are typically small in size and generally

contain less than 1000 t U₃O₈. Giant (up to 100 thousands t U) U deposits in sodium metasomatites (albitites) are known in Central Ukraine and Brazil.

Two subtypes are defined based on host lithologies:

- metasomatized granite; ex. Ross Adams deposit in Alaska, USA, Novokostantynivka deposit in Kirovogradska oblast, Ukraine.
- metasomatised metasediment; ex. Zhovta Richka and Pervomayske deposits in Dnipropetrovska oblast, Ukraine and Valhalla deposit in northwestern Queensland, Australia.

5.12) Metamorphic deposits

Metamorphic deposits those that occur in metasediments or metavolcanic rocks where there is no direct evidence for mineralization post-dating metamorphism. These deposits were formed during regional metamorphism of uranium bearing or mineralized sediments or volcanic precursors.

The most prominent deposits of this type are Mary Kathleen, Queensland, Australia, and Forstau, Austria.

5.13) Lignite

Lignite deposits (soft brown coal) can contain significant uranium mineralization. Mineralization can also be found in clay and sandstone immediately adjacent to lignite deposits. Uranium has been adsorbed onto carbonaceous matter and as a result no discrete uranium minerals have formed. Deposits of this type are known from the Serres Basin, in Greece, and in North and South Dakota in the USA. The uranium content in these deposits is very low, on average less than 0.005% U₃O₈, and does not currently warrant commercial extraction.

5.14) Black shale deposits

Black shale mineralisations are large low-grade resources of uranium. They form in submarine environments under oxygen-free conditions. Organic matter in clay-rich sediments will not be converted to CO₂ by biological processes in this environment and it can reduce and immobilize uranium dissolved in seawater. Average uranium grades of black shales are 50 to 250 ppm. The largest explored resource is Ranstad in Sweden containing 254,000 t of uranium. However, there are estimates for black shales in the USA and Brasil assuming a uranium content of over 1 million tonnes, but at grades below 100 ppm uranium. The Chattanooga Shale in the southeastern USA for example is estimated to contain 4 to 5 million tonnes at an average grade of 54 ppm.

produced significant amounts of uranium with one exception: the Ronneburg deposit in eastern Thuringia, Germany. The Ordovician and Silurian black shales at Ronneburg have a background uranium content of 40 to 60 ppm. However, hydrothermal and supergene processes caused remobilisation and enrichment of the uranium. The production between 1950 and 1990 was about 100,000 t of uranium at average grades of 700 to 1,000 ppm. Measured and inferred resources containing 87,000 t uranium at grades between 200 and 900 ppm are left.

5.15) Other types of deposits

- There are also uranium deposits, of other types, in the Jurassic Todilto Limestone in the Grants District, New Mexico, USA.

- The Freital/Dresden-Gittersee deposit in eastern Germany produced about 3.700 t of uranium from Permian hard coal and its host rocks. The average ore grade was 0.11%. The deposit formed in a combination of syngenetic and diagenetic processes.
- In some countries like China trials are underway to extract uranium from fly ash.

6) Occurrence

Uranium is a naturally occurring element that can be found in low levels within all rock, soil, and water. Uranium is the 51st element in order of abundance in the Earth's crust. Uranium is also the highest-numbered element to be found naturally in significant quantities on Earth and is almost always found combined with other elements. Along with all elements having atomic weights higher than that of iron, it is only naturally formed in supernovae. The decay of uranium, thorium, and potassium-40 in the Earth's mantle is thought to be the main source of heat that keeps the outer core liquid and drives mantle convection, which in turn drives plate tectonics.

Uranium's average concentration in the Earth's crust is (depending on the reference) 2 to 4 parts per million, or about 40 times as abundant as silver. The Earth's crust from the surface to 25 km (15 mi) down is calculated to contain 10¹⁷ kg (2×10¹⁷ lb) of uranium while the oceans may contain 10¹³ kg (2×10¹³ lb). 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 its concentration in sea water is 3 parts per billion.

Uranium is more plentiful than antimony, tin, cadmium, mercury, or silver, and it is about as abundant as arsenic or molybdenum. Uranium is found in hundreds of minerals, including uraninite (the most common uranium ore), carnotite, autunite, uranophane, torbernite, and coffinite. 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 (it is recovered commercially from sources with as little as 0.1% uranium).

Some bacteria, such as *Shewanella putrefaciens*, *Geobacter metallireducens* and some strains of *Burkholderia fungorum*, use uranium for their growth and convert U(VI) to U(IV).

Some organisms, such as the lichen *Trapelia involuta* or microorganisms such as the bacterium *Citrobacter*, can absorb concentrations of uranium that are up to 300 times the level of their environment. *Citrobacter* species absorb uranyl ions when given glycerol phosphate (or other similar organic phosphates). After one day, one gram of bacteria can encrust themselves with nine grams of uranyl phosphate crystals; this creates the possibility that these organisms could be used in bioremediation to decontaminate uranium-polluted water. The proteobacterium *Geobacter* has also been shown to bioremediate uranium in ground water. The mycorrhizal fungus *Glomus intraradices* increases uranium content in the roots of its symbiotic plant.

In nature, uranium(VI) forms highly soluble carbonate complexes at alkaline pH. This leads to an increase in mobility and availability of uranium to groundwater and soil from nuclear wastes which leads to health hazards. However, it is difficult to precipitate uranium as phosphate in the presence of excess carbonate at alkaline pH. A *Sphingomonas* sp. strain BSAR-1 has been found to express a high activity alkaline phosphatase (PhoK) that has been applied for bioprecipitation of uranium as uranyl phosphate species from alkaline solutions. The precipitation ability was enhanced by overexpressing PhoK protein in *E. coli*.

Plants absorb some uranium from soil. Dry weight concentrations of uranium in plants range from 5 to 60 parts per billion, and ash from burnt wood can have concentrations up to 4 parts per million. Dry weight concentrations of uranium in food plants are typically lower with one to two micrograms per day ingested through the food people eat.

7) Production and mining

Worldwide production of U_3O_8 (yellowcake) in 2013 amounted to 70,015 tonnes, of which 22,451 t (32%) was mined in Kazakhstan. Other important uranium mining countries are Canada (9,331 t), Australia (6,350 t), Niger (4,518 t), Namibia (4,323 t) and Russia (3,135 t).

Uranium ore is mined in several ways: by open pit, underground, in-situ leaching, and borehole mining (see uranium mining). Low-grade uranium ore mined typically contains 0.01 to 0.25% uranium oxides. Extensive measures must be employed to extract the metal from its ore. High-grade ores found in Athabasca Basin deposits in Saskatchewan, Canada can contain up to 23% uranium oxides on average. Uranium ore is crushed and rendered into a fine powder and then leached with either an acid or alkali. The leachate is subjected to one of several sequences of precipitation, solvent extraction, and ion exchange. The resulting mixture, called yellowcake, contains at least 75% uranium oxides U_3O_8 . Yellowcake is then calcined to remove impurities from the milling process before refining and conversion.

Commercial-grade uranium can be produced through the reduction of uranium halides with alkali or alkaline earth metals. Uranium metal can also be prepared through electrolysis of KUF_5 or UF_4 , dissolved in molten calcium chloride (CaCl_2) and sodium chloride (NaCl) solution. Very pure uranium is produced through the thermal decomposition of uranium halides on a hot filament.

7.1) Mining techniques

- Open pit
- Underground uranium mining
- Heap leaching
- In-situ leaching
- Recovery from seawater

8) Resources and reserves

It is estimated that 5.5 million tonnes of uranium exists in ore reserves that are economically viable at US\$59 per lb of uranium, while 35 million tonnes are classed as mineral resources (reasonable prospects for eventual economic extraction). Prices went from about \$10/lb in May 2003 to \$138/lb in July 2007. This has caused a big increase in spending on exploration, with US\$200 million being spent worldwide in 2005, a 54% increase on the previous year. This trend continued through 2006, when expenditure on exploration rocketed to over \$774 million, an increase of over 250% compared to 2004. The OECD Nuclear Energy Agency said exploration figures for 2007 would likely match those for 2006.

Australia has 31% of the world's known uranium ore reserves and the world's largest single uranium deposit, located at the Olympic Dam Mine in South Australia. There is a significant reserve of uranium in Bakouma a sub-prefecture in the prefecture of Mbomou in Central African Republic. Some nuclear fuel comes from nuclear weapons being dismantled, such as from the Megatons to Megawatts Program.

An additional 4.6 billion tonnes of uranium are estimated to be in sea water (Japanese scientists in the 1980s showed that extraction of uranium from sea water using ion exchangers was technically feasible). There have been experiments to extract uranium from sea water, but the yield has been low due to the carbonate present in the water. In 2012, ORNL researchers announced the successful development of a new absorbent material dubbed HiCap which performs surface retention of solid or gas molecules, atoms or ions and also effectively removes toxic metals from water, according to results verified by researchers at Pacific Northwest National Laboratory.

9) Applications

9.1) Military

The major application of uranium in the military sector is in high-density penetrators. This ammunition consists of depleted uranium (DU) alloyed with 1–2% other elements, such as titanium or molybdenum. At high impact speed, the density, hardness, and pyrophoricity of the projectile enable the destruction of heavily armored targets. Tank armor and other removable vehicle armor can also be hardened with depleted uranium plates. The use of depleted uranium became politically and environmentally contentious after the use of such munitions by the US, UK and other countries during wars in the Persian Gulf and the Balkans raised questions concerning uranium compounds left in the soil (see Gulf War Syndrome).

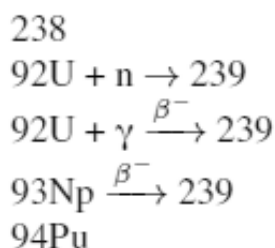
Depleted uranium is also used as a shielding material in some containers used to store and transport radioactive materials. While the metal itself is radioactive, its high density makes it more effective than lead in halting radiation from strong sources such as radium. Other uses of depleted uranium include counterweights for aircraft control surfaces, as ballast for missile re-entry vehicles and as a shielding material. Due to its high density, this material is found in inertial guidance systems and in gyroscopic compasses. Depleted uranium is preferred over similarly dense metals due to its ability to be easily machined and cast as well as its relatively low cost. The main risk of exposure to depleted uranium is chemical by uranium oxide rather than radioactivity (uranium being only a weak alpha emitter).

During the later stages of World War II, the entire Cold War, and to a lesser extent afterwards, uranium-235 has been used as the fissile explosive material to produce nuclear weapons. Initially, two major types of fission bombs were built: a relatively simple device that uses uranium-235 and a more complicated mechanism that uses plutonium-239 derived from uranium-238. Later, a much more complicated and far more powerful type of fission/fusion bomb (thermonuclear weapon) was built, that uses a plutonium-based device to cause a mixture of tritium and deuterium to undergo nuclear fusion. Such bombs are jacketed in a non-fissile (unenriched) uranium case, and they derive more than half their power from the fission of this material by fast neutrons from the nuclear fusion process.

9.2) Civilian

The main use of uranium in the civilian sector is to fuel nuclear power plants. One kilogram of uranium-235 can theoretically produce about 20 terajoules of energy (2×10^{13} joules), assuming complete fission; as much energy as 1500 tonnes of coal.

Commercial nuclear power plants use fuel that is typically enriched to around 3% uranium-235. The CANDU and Magnox designs are the only commercial reactors capable of using unenriched uranium fuel. Fuel used for United States Navy reactors is typically highly enriched in uranium-235 (the exact values are classified). In a breeder reactor, uranium-238 can also be converted into plutonium through the following reaction:



Before (and, occasionally, after) the discovery of radioactivity, uranium was primarily used in small amounts for yellow glass and pottery glazes, such as uranium glass and in Fiestaware.

The discovery and isolation of radium in uranium ore (pitchblende) by Marie Curie sparked the development of uranium mining to extract the radium, which was used to make glow-in-the-dark paints for clock and aircraft dials. This left a prodigious quantity of uranium as a waste product, since it takes three tonnes of uranium to extract one gram of radium. This waste product was diverted to the glazing industry, making uranium glazes very inexpensive and abundant. Besides the pottery glazes, uranium tile glazes accounted for the bulk of the use, including common bathroom and kitchen tiles which can be produced in green, yellow, mauve, black, blue, red and other colors.

Uranium was also used in photographic chemicals (especially uranium nitrate as a toner), in lamp filaments for stage lighting bulbs, to improve the appearance of dentures, and in the leather and wood industries for stains and dyes. Uranium salts are mordants of silk or wool. Uranyl acetate and uranyl formate are used as electron-dense “stains” in transmission electron microscopy, to increase the contrast of biological specimens in ultrathin sections and in negative staining of viruses, isolated cell organelles and macromolecules.

The discovery of the radioactivity of uranium ushered in additional scientific and practical uses of the element. The long half-life of the isotope uranium-238 (4.51×10^9 years) makes it well-suited for use in estimating the age of the earliest igneous rocks and for other types of radiometric dating, including uranium-thorium dating, uranium-lead dating and uranium-uranium dating. Uranium metal is used for X-ray targets in the making of high-energy X-rays.

10) Uranium Exploration Activities in Egypt

Before the 1996, the exploration works resulted in the discovery of some low grade U- occurrences which related to various geologic formations such as; vein-type (G. El-Missikat), metasomatized granites (G. Um Ara), shear zones in calc-alkaline granite and inter-mountain basin (G. Gattar) and surfacial type U-deposit in sedimentary rocks (Abu Zeneima ,Sinai).

After the 1996, NMA exploration activities for uranium resources were focusing on the south Eastern Desert of Egypt, these works resulted in the discovery of three U-resources These resources (from south to north) include vein-types (G. El-sella & Abu Rusheid area) and metamorphosed sandstone-type (Sikait area).

Egypt has an ongoing program in the Sinai and Eastern Deserts to extract uranium ore through heap leach mining. Egypt asserts that none of the uranium ore concentrate produced is of a purity or composition to require IAEA safeguarding, but transferred some of the material to NMA headquarters in Cairo for IAEA review during the agency's 2005 investigations.

Egypt began investigating conventional uranium occurrences in the Bahariya Oasis, Western Desert, Eastern Desert, and Sinai Peninsula in the 1950s. Egypt also explored unconventional uranium resources contained in phosphate deposits in the Western Desert, Nile Valley, and the Red Sea Coast. These phosphate deposits contain substantial uranium (estimated at 33,000 tons), but extraction would be difficult and expensive. From 2001 to 2005, the NMA suffered substantial budget cuts, effectively crippling further phosphate exploration plans. As a result, the NMA decided to explore and evaluate only the most promising sites in the Sinai and Eastern Desert.

Presently, exploration is focusing on conventional granite-based uranium resources in the inter-mountain basins, while evaluation of potential uranium resources continues in the El Sella and Kab Amiri areas of the Eastern Desert. Attention is being concentrated on several mineralized vein-type deposits (Gabal Gattar, El Miskat/El Erediya, Um Ara, and El Atshan) and a siltstone deposit in the Sinai (Wadi Nasib). Egypt also discovered another uranium bearing area, Gabal Kadabora, in the central eastern desert. Generally, operations in the Eastern Desert have included deep trenching, tunneling, core and percussion drilling, and laboratory analysis.

Western intelligence sources believe that in January 2005, Egypt and China formed an agreement for Chinese assistance in mining uranium deposits on the Sinai Peninsula. The status of this project is unclear.

Uranium resources in Egypt may be classified as:

- vein-type (G. El-Missikat), (G. El Sella) and (Abu Rusheid Area).
- metamorphosed sandstone-type (Sikait area).
- shear zones in calc-alkaline granite and inter mountain basin (G. Gattar).
- surfacial type U-deposit in sedimentary rocks (Abu Zeneima).

Location map showing the uranium occurrences in Egypt

