# Uranium geology and mining

**Ranger 1 open-pit uranium mine in Australia**

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**Introduction:**

Uranium is a strategic resource that is the basis for both nuclear power and nuclear weapons. Nuclear power accounts for around 16% of the world's electricity and uses uranium as a fuel to drive steam turbines.

The large scale use of uranium started around 1940 with the Manhattan project and the development of nuclear bombs, but later started to be focused more and more on power generation with nuclear reactors.

### Top ten uranium reserve holders and their production

| Country | Amount [tons] | Share of total | Production [tons] | Share of total |
|---|---|---|---|---|
| Australia | 701 000 | 36.0% | 8 980 | 21.8% |
| Canada | 287 200 | 14.7% | 11 800 | 28.6% |
| Kazakhstan | 278 840 | 14.3% | 4 175 | 10.1% |
| Niger | 172 866 | 8.9% | 3 400 | 8.2% |
| Brazil | 139 900 | 7.2% | 340 | 0.8% |
| South Africa | 88 548 | 4.5% | 848 | 2.1% |
| Namibia | 62 186 | 3.2% | 3 000 | 7.3% |
| Uzbekistan | 59 743 | 3.1% | 2 300 | 5.6% |
| Russia | 57 530 | 3.0% | 3 275 | 7.9% |
| Jordan | 30 375 | 1.6% | 0 | 0% |

**Source:** BGR - Reserves, Resources and Availability of Energy Resources 2005

**Creation of uranium:**

Uranium is originally created in stars, especially dying stars in a process that is called stellar nucleosynthesis. When the star dies in a supernova or planetary nebula huge amounts of neutrons are created. By repeated capture in iron and similar elements the atomic number can be increased and elements heavier than iron can be obtained. Later on this uranium ended up in the interstellar clouds that formed the solar system and the earth and ultimately became a part of different geological formations.

**Uranium compounds:**

Phase relationships in uranium-oxygen systems are very complex. Uranium dioxide (UO2) and uranium trioxide (UO3) are formed from the two most important oxidation states IV and VI. A wide array of other oxidation states are also possible and uranium monoxide (UO), diuranium pentoxide (U2O5) and even uranium peroxide (UO4*2H2O) are known to exist in nature during special conditions.

The most common uranium oxides in nature are the triuranium octaoxide (U3O8) and uranium dioxide (UO2). Both of them are solids with low solubility in water and stability over a wide range of different chemical/environmental conditions. U3O8 is the most stable compound and the most common in nature.

## Uranium minerals:

The two primary ore minerals are uraninite (basically UO2) and pitchblende (U3O8), but a range of other uranium minerals can be found in ore deposits. These include carnotite, a uranium-potassium-vanadium compound, davidite-brannerite-absite type of uranium titanates and the euxenite-fergusonite-samarskite group of niobates of uranium and rare earth elements.

Brannerite is also important since it occurs in up to 30% of the mineralisation at Olympic Dam and over 20% at Valhalla near Mount Isa in Australia and in some other places in the world. It will not dissolve easily in sulphuric acid and it therefore not largely recovered. Research is undertaken to improve the recovery rate and if successful it will have significant implications for the recoverable low-cost resources of uranium in the world.

*Pitchblende (left) and uraninite (right)*

A number of secondary uranium minerals are known and many of them are brilliantly coloured and fluorescent. The most common is gummite, a general term for limonite for mixtures of hydrated uranium oxides with impurities. Hydrated uranium phosphates of phosouranylite type include autunite, saleeite and torbernite. Hydrated uranium silicates such as coffinite, uranophane and sklodowskite can also be found in some places.

*Autunite (left) and torbernite (right)*

## Different types of uranium deposits:

The deposits of uranium in the world are subdivided into 13 major categories of different types based on the geology of the deposits according to Nuclear Energy Agency (NEA, an agency within the OECD organization) and the International Atomic Energy Agency (IAEA).

### *Unconformity deposits:*

This type of deposits occurs close to major unconformities. An unconformity is a buried erosion surface that separates two rock masses or strata of different age, indicating a non-continuous sediment deposition. Often the oldest layer was exposed to erosion for some time before the younger unit was deposited. Below the unconformity the metasedimentary rocks are often faulted and brecciated. The mineralization of uranium can take place in this region and results in ore formations with high uranium concentration.

Unconformity-related deposits make up around 33% of the worlds uranium resources and include some of the richest and largest formations. The dominating minerals are uraninite and pitchblende, but other minerals can also be found in smaller extent.

The largest deposits of this type can be found in Canada, more specifically in the Athabasca basin, Sasketchewan and Thelon basin in the Northwest Territories. Also Australia has a large number of important unconformity formations with uranium near the Alligator Rivers region and the Rudall River area. Unconformity-related deposits constitute around 20% of the total uranium resources of Australia and much of the total production since 1980 has been mined from two of these deposits, Ranger 1 & 3 together with the now depleted Nabarlek mine. Some other major deposits in production from the Alligator Rivers are Jabiluka, Koongarra and Ranger 68.

Currently all of Canadas uranium production is from unconformity-related deposits. Key Lake, Rabbit Lake, Cluff Lake are all now depleted but were very important mines earlier. McClean Lake and McArthur River are other important mining regions in uranium deposits of this type.

Cigar Lake in Sasketchewan is an unconformity deposits, which contains exceptionally high grade ores (averaging 20% $U_3O_8$ and in some zones over 50% $U_3O_8$). The ore body is located at 430 meters depth and gives no traces of radioactivity on the surface due to a thick clay layer surrounding the formation which effectively stops all radioactive substances from migrating to the surface. Sadly the mine is currently water filled after an accident and production has been halted.

*Mining tunnel in Cigar Lake*

The Canadian deposits occur below, across and immediately above the unconformity with the highest grade ores located at or just above the unconformity. In Australia the known deposits are below the unconformity and generally contain much lower grade uranium ores.

It should be mentioned that uranium exploration in Alligator River and Arnhem Land regions in Australia, both containing many unconformities, has been restricted since 1970s due to political and environmental factors. Much of these regions has therefore only been subjected to a superficial exploration designated to detect outcropping deposits and extensions of known deposits. Jabiluka 2 was for instance found by drilling along structures from Jabiluka 1. Since there has been very little work done to detect deeply concealed deposits similar to Cigar Lake, it is possible that very high grade deposits remains to be discovered in Alligator Rivers and Arnhem Land.

***Breccia complex deposits:***

This is a type of uranium formations that occur near breccias. Breccia comes from the Italian word for breach and means rock that is composed of rock or mineral fragments in a matrix that is a cementing material, which may be similar or different in composition to the fragments. A wide array of different types is possible and sedimentary breccias, tectonic breccias, igneous breccias, impact breccias and hydrothermal breccias are the most common.

*The Olympic Dam underground uranium mine*

The most important deposit of this type in the world is the Olympic Dam in Australia. It accounts for about 66% of Australia's uranium reserves and resources. The uranium content is 0.05 % on average but the formation is enormous. The deposit occurs in hematite-rich granite covered by about 300 meters of flat-lying sedimentary rocks. The mining operations take place under ground.

The core of Olympic Dam is a complex of barren hematite-quartz breccias with several diatreme structures flanked by intermingled hematite-rich breccias and granitic breccias. These zones are approximately one kilometre wide and five km long. Nearly all of the copper-uranium mineralization is found in these hematite-rich breccias. Broad zones of granitic breccias with lower contents of ore minerals extend up to 3 km beyond the other limits of the hematite-rich breccias.

Olympic Dam also contains iron, copper, gold, silver, fluorine, lanthanum and cerium and more rare earth elements. Only copper, uranium, gold and silver are recovered. Copper grades average 2.7% and gold grades vary between 0.3-1.0 grams per ton.

Many details of the origin of Olympic Dam are still withheld, classified or unknown. The principal mechanisms forming the breccia structure have likely to have been hydraulic fracturing, tectonic faulting, chemical corrosion and gravity collapse. Much of the brecciating occurred near a surface in an eruptive environment in a crater complex during boiling and explosive interactions between water and magma.

Other important breccia formations containing uranium can be found in USA in Arizona. Here uranium mineralization took place in breccias pipes related to old volcanoes.

***Sandstone deposits:***

Marginal marine sedimentary or continental fluvial environments, where medium to coarse-grained sandstones are deposited can yield structures with significant uranium ores. Impermeable shale or mudstone units are mixed into the sedimentary sequence and often occur near the mineralized sandstone. A variety of reducing agents within the sandstone can react with uranium and cause formation of uranium minerals. Common reducing agents in sandstone are carbonaceous material such as detrital plant debris, amorphous humate and marine algae, but also sulphides, hydrocarbons and interbedded basic volcanic with abundant ferro-magnesian minerals.

Sandstone deposits make up about 18% of the worlds uranium resources. Ore bodies of this type commonly have low to medium (0.05-0.4%) grade uranium content and the individual ore bodies range up to 50 000 ton. The main primary uranium minerals are uraninite and coffinite. The traditional mining/milling operation with removal of rock material has now often been replaced by cheaper in situ leaching mining methods.

USA has large formations of uranium bearing sandstone in the Western Cordillera region and most of the American production has been from these deposits. The Powder River Basin in Wyoming, the Colorado Plateau and the Gulf Coast Plain in south Texas are major sandstone uranium provinces. In the world major sandstone deposits can be found in Niger, Kazakhstan, Uzbekistan, Gabon and South Africa.

Sandstone deposits accounts for about 7% of Australia’s total resources of uranium. Frome Embayment contains six uranium deposits of sandstone type. At Mulga Rock uranium mineralisation in peat layers interbedded with sand and clay can be found in a buried channel structure.

*Uranium sandstone from Kazakhstan*

Sandstone deposits contain three different subclasses.

- *Rollfront deposits* which are bodies of crosscut sandstone bedding.
- *Tabular deposits* which are irregular, elongated lenticular bodies parallel to depositional trend, typically occurring in palaeochannels incised into underlying basement rock.
- *Tectonic/lithologic deposits* that occur in sandstones adjacent to permeable fault zones are the final subclass.

***Surface deposits:***

This type of uranium deposits are broadly defined as young near-surface concentrations of uranium in sediments or soils. They typically contain a secondary cementing mineral such as calcite, gypsum, dolomite, ferric oxide and halite. Calcrete with a high uranium content accounts for the largest share of surface deposits in the world. Uranium mineralizations are confined to fine-grained surficial sand and clay, cemented by calcium and magnesium carbonates.

About 4% of the world's uranium resources can be found in surface deposits. Calcrete deposits represent 5% of the Australian total uranium supplies. They were formed when uranium-rich granite was deeply weathered in a semi-arid to arid climate. The Yeelirrie deposits are by far the world's largest surficial formation. Other significant deposits in Australia include Lake Way, Centipede, Thatcher Soak and Lake Maitland. The Central Namib Desert deposit in Namibia is another very important surface formation.

*Uranium pit mine*

***Volcanic deposits:***

Near volcanic formations uranium deposits are formed. Thus, faults and shear zones within acid volcanic rocks can lead to mineralisation of uranium-rich ores. Molybdenum and fluorine are often associated with uranium in this type of deposits.

Only a small portion of the world's uranium is made up from volcanic deposits. Significant resources of this type can be found in Mexico, China, Kazakhstan and Russia.

In USA and Canada uranium is found in some volcanic ash deposits. Especially near the western margin of North America, where volcanic activity was significant, houses a number of volcanic uranium deposits. The south and west margin of the Canadian Shield formed a leading edge of uranium mineralisation from the Proterozoic to present.

Kazakhstan has plans for a major increase in its uranium production from around 4000 tons annually to 15 000 tons by 2010. The Chu-Sarysu basin contains more than half of the known resources in Kazakhstan.

***Intrusive deposits:***

This type includes formations associated with intrusive rocks such as alaskite, granite, pegmatite and monzonites. Intrusion is the process where a body of igneous rock crystallizes from molten magma beneath the surface. If the conditions are suitable, formation of high grade uranium ores are possible from these magmas.

Some important deposits of this type are the Rössing formation in Namibia, Ilimaussaq on Greenland and Palabora in South Africa.

The intrusive deposit near Radium Hill in Australia was mined from 1954-62 (until it was depleted). Large bodies with low grade mineralisation at Crocker Well and Mount Victoria in Australia are also important, especially in the future if higher uranium prices will make them more interesting to develop.

*The Rössing uranium mine in the deserts of Namibia*

***Metasomatite deposits:***

Uranium can accumulate and form minerals near structurally deformed rocks that already have been altered by metasomatic processes, usually by the introduction of sodium, potassium or calcium into these rocks. Major examples of this type include Espinharas deposits in Brazil, the Zheltye Vody deposit in Ukraine and some mines near Mount Isa in Australia.

***Metamorphic deposits:***

In metamorphic rocks uranium and rare earth metals can form minerals. An example of this is the Mary Kathleen mine 60 km east of Mount Isa in Australia. The mine was in operation during the periods 1958-63 and 1976-82. The mined ore body occurs in a calcium-rich zone of Proterozoic metamorphic rock.

***Quartz-pebble conglomerate deposits:***

A conglomerate is a sedimentary rock that is made up from of rounded grains, coarser than sand, which has been cemented together by a suitable material in sedimentary conditions. Quartz pebbles are here cemented by a quartz-rich matrix. Uranium bearing minerals are also found in the conglomerate together with gold and other minerals.

About 13% of the world's uranium resources is found in this type of deposit. Important examples are the Witwatersrand gold-uranium deposit in South Africa and the Elliot Lake deposit in Canada. The mining at Elliot Lake have been closed down in recent years since the deposit is uneconomic under current market conditions.

### *Vein deposits:*

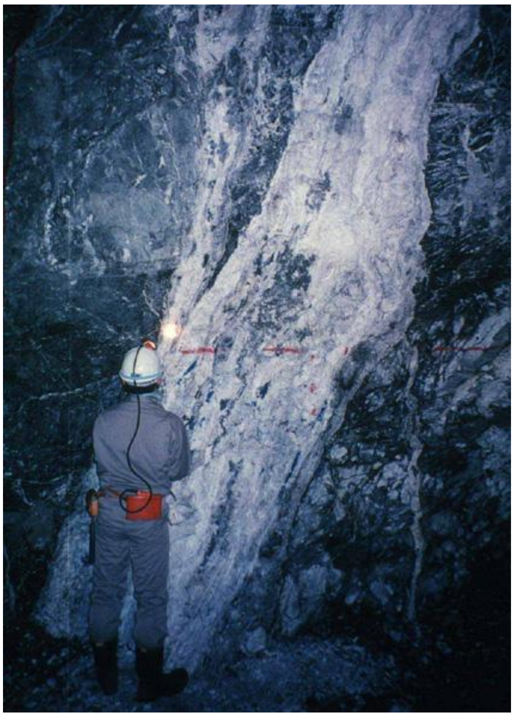
A vein deposits is a fairly well defined zone with mineralisation, typically narrow compared to its length and depth. Most veins occur in fault or fissure openings or in shear zones within the country rock.

Veins are formed as hot hydrothermal fluids rise towards to surface from cooling intrusive rocks. As the fluids pass through fractures, fault, brecciated rocks, porous layers and other channels they will cool or react chemically with the surroundings. This can lead to the formation of minerals if the temperature, pressure and chemical conditions are favourable.

About 9% of the world's uranium is found in vein deposits all over the globe. Some important formations are Jachymov in Czech Republic and Shinkolobwe in Zaire.

Jachymov, also known as Joachimsthal in German, is also famous due to Marie Curie and her work. The radioactive element radium was first separated from uraninite ore from the Jachymov mines. In fact Jachymov was the only known source of uranium in the world until after the First World War.

Shinkolobwe provided the uranium that the Americans used in the Hiroshima bomb. The owner of the mine has sold 1 200 tons of uranium to the government of the USA since 1939. Uranium from Shinkolobwe was also involved in a smuggling deal with Iran according to an UN report from 2006.



*Uranium vein in an underground mine*

## Uranium mining:

Since uranium often is found in low concentration associated mining operations tend to be very volume-intensive. A significant amount of rock must be moved and crushed to obtain the uranium, but there are however some methods that can extract the uranium without having to process large volumes of material.

Traditional methods include open pit mining and underground mining. In open pit mining the top soil that covers a shallow deposit of uranium is first removed by blasting, draglines and giant excavators. The ore is then extracted. Water is extensively sprayed on the uranium ore to suppress airborne dust and thus limit the radioactive exposure.

Underground mining takes place in tunnels and shafts dug to access the uranium ore formation. Radon gas associated with the uranium ore is a hazard to the miners and requires extra ventilation. Room-and-pillar mining and drift tunnel mining are the dominating methods of underground mining. Some of the ore must be left to support the roof and prevent the mine from caving-in.

In principle the traditional uranium mining methods are no different from ordinary hard rock mining of other metals, such as copper, gold and lead. It is only a matter of moving rock.

### *Leaching methods:*

Uranium can also be extracted by other methods than the traditional rock mining. These methods utilize different forms of solvents, often acids. The solvents are injected directly into the ore body or sprinkled on heaps of ore.

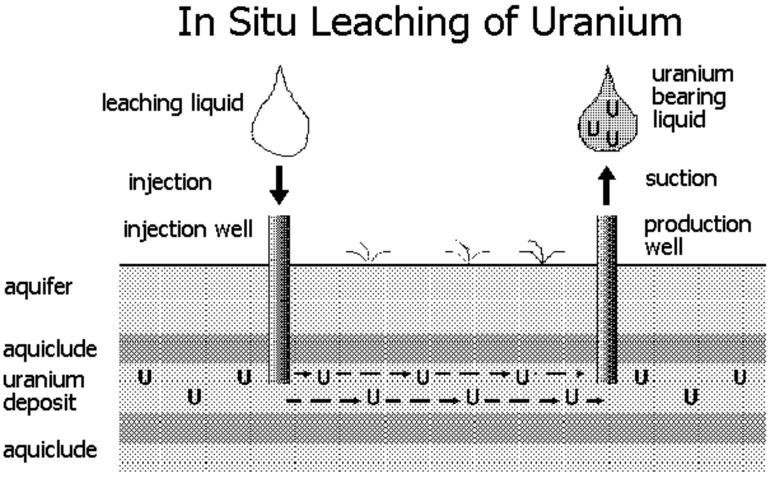
Leaching is also employed for many other minerals and metals, for instance copper and silver. It can only be employed in certain deposits where the porosity is suitable. Two different subclasses of leaching-based mining exist, *heap leaching* and *in-situ leaching*.

***Heap leaching:***
If a traditional mining operation generates huge amounts of waste rock with concentration too low to be economic for normal processing, these waste rocks can be subjected to heap leaching for recovery of the uranium. Waste rocks with elevated concentration of radioisotopes typically occur in removed overburden near the primary uranium ore or in tunnels outside the main ore body. The grade of the waste rock is too low for direct ore processing. The waste rocks are also a threat to environment due to their release of radon gas and radioactive seepage water.

The waste rock is piled up in heaps and a leaching liquid is introduced on the top. Typical leaching liquids are sulphuric acid or hydrochloric acid. The liquid will percolate down until it reaches a liner or collection pit below the pile. The liquid now contains uranium and other dissolved minerals. Finally the fluid is pumped to a processing plant where the uranium is extracted by chemical reactions.

Heap leaching is seldom used in the industrialised world due to the extreme damage to the near environment, but is still employed in some countries where the environmental laws are less strict.

***In-site leaching (ISL):***
This is a mining method that is also referred to as in-situ recovery or solution mining. Weakly acid or alkaline solutions (depending on the calcium concentration in the ore) are introduced on one side of the deposit in injection wells. The injected fluid will pass through the ore body and react with it chemically. The fluid and the dissolved uranium will later be pumped up through recovery wells on the opposite side of the deposit.



*Principle scheme for an in-situ leaching operation*

ISL is very cost-effective because it avoids excavation costs and can be deployed very quickly compared to traditional mining methods. The only drawback is the fact that it can only be performed on deposits where the rock is permeable to liquids, typically in sandstone formations.

The environmental impact is much smaller as the fluids are weaker and never will be near the surface. However the ground water can be affected. ISL is the only type of uranium mining currently undertaken in the USA (as of 2006).

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**Web resources:**

http://www.uic.com.au/nip40.htm
http://www.uraniumsa.org/