Uranium Ore Deposits

There is a very wide geological variety of uranium deposits. The currently most important mineralization styles are unconformity-related Proterozoic deposits (mainly in Canada and Australia), roll-front deposits in Mesozoic-Cenozoic sandstone (Kazakhstan and USA), and IOCG („Iron Oxide-Copper-Gold") deposits in hematitic granite breccias where uranium is a by-product of copper mining (Olympic Dam, Australia). The uranium deposit spectrum is controlled by the high aqueous solubility of uranium in the hexavalent state, and low solubility in the tetravalent state. This geochemical background is reflected in large-scale leaching of uranium by oxidized meteoric or formation waters, and precipitation of uraninite (UO_2) at redox fronts. Evapotranspiration under arid climate conditions can lead to uranium enrichment in near-surface calcrete deposits (Namibia and Australia). Paleoplacers (quartz-pebble conglomerates), restricted to Late Archean to Early Proterozoic age, contain a large low-grade resource of clastic uraninite (South Africa, Canada). The currently known uranium resources are sufficient to sustain current and future nuclear power generation for the next 100 years. Advanced fast neutron technologies would extend the resource life time to more than 1000 years.

Introduction

Uranium is essentially used for electricity generation in nuclear reactors, after a first period from 1945-1960 when military demand for nuclear bombs was prevailing. Civilian nuclear power started in the 1960s, with strong growth during 25 years, but levelled out after the Chernobyl accident in the Soviet Union in 1986. About 35 % of the European Union's electricity are produced from nuclear energy today, but no new reactors were built since twenty years. There is currently renewed interest because nuclear energy is neutral in terms of its greenhouse effect and is capable of generating large amounts of power at low cost compared to rival non-nuclear energies. AREVA, the French world nuclear energy leader, is currently constructing two third-generation nuclear reactors in China, and another one in Finland, known as „European Pressurised Water Reactor" (EPR). And there are projects in the major industrialized countries to develop fourth-generation fast neutron nuclear reactors which will have an efficiency many times superior to the current technology. ▶
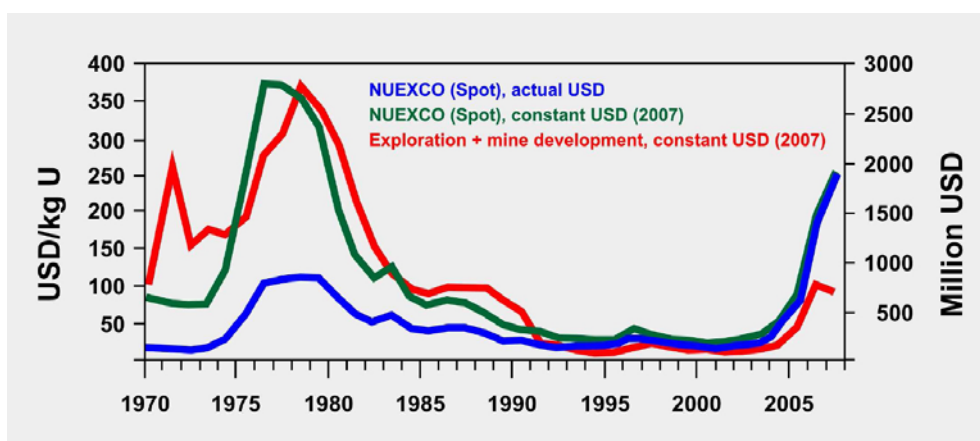

Fig. 1: *Uranium spot price and expenditures for exploration and mine development. (Source: Nuclear Energy Agency 2008)..*

Such nuclear energy systems are set to play a key role in a sustainable long-term world energy balance.

There is currently a boom in uranium exploration, with a global expenditure of about 720 million USD in 2007 for exploration and mine development (**Fig. 1**), still much below the exploration budgets in the late 1970s.

Natural uranium consists essentially of two isotopes, ^{238}U with an abundance of 99.3 % and ^{235}U with an abundance of 0.7 % which slowly decay to ^{206}Pb and ^{207}Pb, respectively ($T_{1/2}$ ^{238}U 4.5 Ga; $T_{1/2}$ ^{235}U 710 Ma). Only ^{235}U can be used in conventional fission reactors, and most reactors (Light Water Reactors) use enriched uranium where the proportion of the ^{235}U isotope has been increased from the present-day natural composition at 0.7 % to about 3 % or up to 5 % (for comparison, uranium used for nuclear weapons has to be enriched to at least 90 % ^{235}U). The world consumption of uranium (non-enriched) for the total of 439 operating reactors (September 2008) is about 65,000 t U per year from which 2600 TWh (1 TWh = 1 billion kWh) electricity are generated, equivalent of 16 % of total world electricity generation.

The mine production of uranium in 2007 is shown in **Figure 2**, with Canada (23 %), Australia (21 %) and Kazakhstan (16 %) standing out. Germany contributed 0.1 % from treatment of mine waters from former uranium mining areas in eastern Germany. Historically, eastern Germany and the Czech Republic during the times of the GDR and Czechoslovakia, respectively, were significant providers for the Soviet nuclear arsenal. There is a difference between uranium demand (65,000 t/yr) and mine production (41,300 t/yr) which is covered from the large military inventories of the USA and Russia, and from recycling of nuclear waste (**Fig. 3**)

The currently identified uranium resources are adequate to meet the requirements during the lifetime of the current

nuclear plants, as well as an expansion of up to 80 % expected by 2030, although supply shortfalls could develop given the long lead time typically required to bring new resources into production, and given the long period of stagnation of the uranium market at very low uranium prices in the recent past, which were insufficient to sustain investment in exploration and development. Deployment of advanced reactor and fuel cycle technology could extend the long-term availability of nuclear energy from a century to thousands of years. Such technology would use fast neutrons which are able to fission ^{238}U, and therefore use the other 99.3 % of natural uranium which are currently wasted or stockpiled. ▶
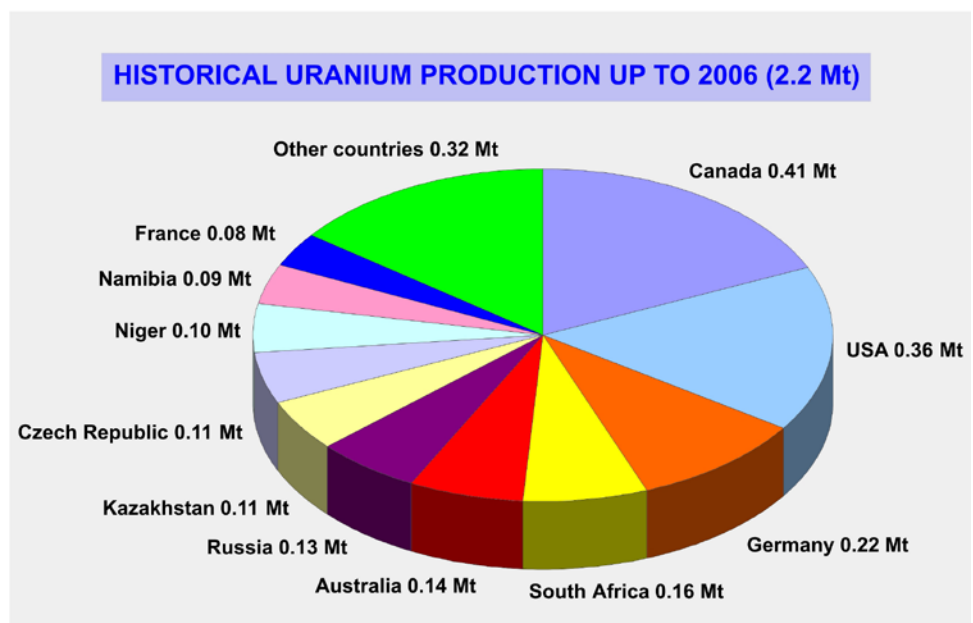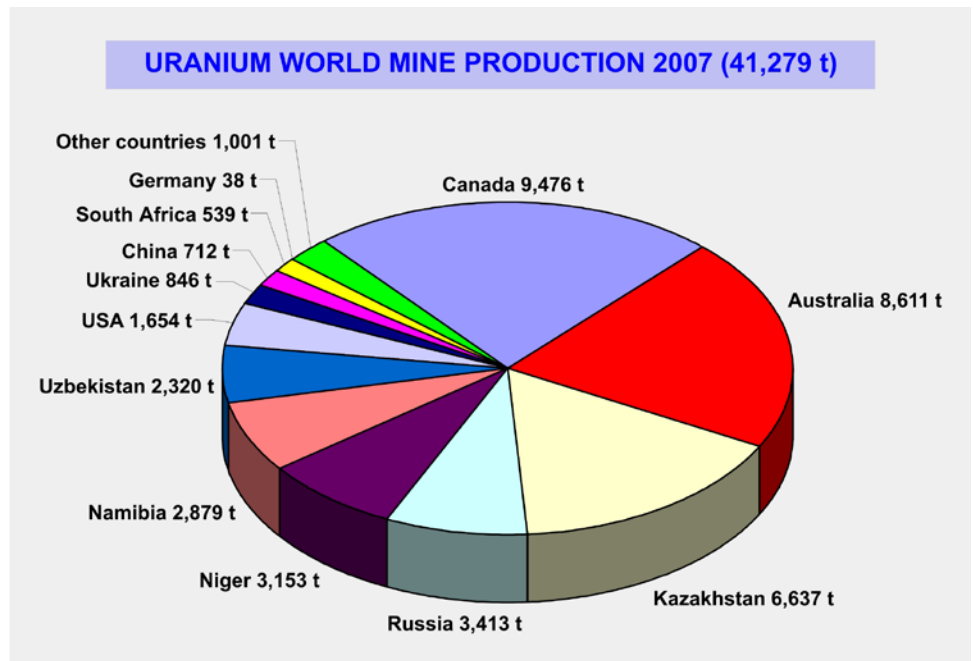

URANIUM WORLD MINE PRODUCTION 2007 (41,279 t)

Other countries 1,001 t
Germany 38 t
South Africa 539 t
China 712 t
Ukraine 846 t
USA 1,654 t
Uzbekistan 2,320 t
Namibia 2,879 t
Niger 3,153 t
Russia 3,413 t
Kazakhstan 6,637 t
Canada 9,476 t
Australia 8,611 t

HISTORICAL URANIUM PRODUCTION UP TO 2006 (2.2 Mt)

Other countries 0.32 Mt
France 0.08 Mt
Namibia 0.09 Mt
Niger 0.10 Mt
Czech Republic 0.11 Mt
Kazakhstan 0.11 Mt
Russia 0.13 Mt
Australia 0.14 Mt
South Africa 0.16 Mt
Germany 0.22 Mt
USA 0.36 Mt
Canada 0.41 Mt

Fig. 2:
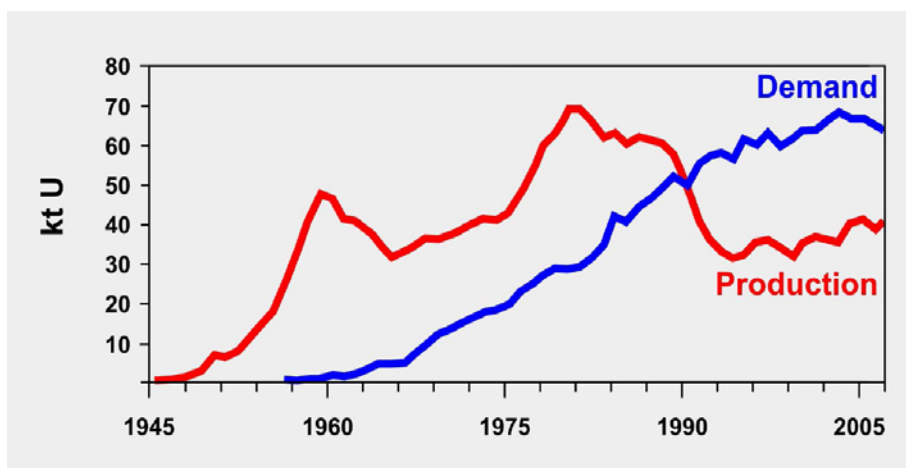*Present-day and historical world uranium mine production..*

Fig. 3: *Uranium mine production and civilian demand since 1945. Note the difference between demand and mine production since the 1990s which is mainly covered by recycled uranium from military inventories. (Source: Nuclear Energy Agency 2008).*

Uranium was discovered in pitchblende ore from Johanngeorgenstadt in the Erzgebirge by the Berlin pharmacist Klaproth in 1789, and only gained wider interest 150 years later, when Hahn and Strassmann, again in Berlin, discovered nuclear fission of ^{235}U in 1938. This process liberates more neutrons than it consumes which allows a chain reaction provided a critical mass of several kg ^{235}U is assembled. It then took only four years to construct the first nuclear reactor in Chicago, and another three years to test the first atomic bomb in Nevada, and to destroy the cities of Hiroshima and Nagasaki with a uranium (60 kg ^{235}U) and a plutonium (8 kg ^{239}Pu) bomb, respectively. This development started a frantic and very costly arms race of about 30 years in which several countries tested and developed a wide range of nuclear technology and stockpiled thousands of nuclear warheads, part of which are now reconverted for fuel in power plants. Ironically, half of the US commercial reactor fuel today is from Russian nuclear warheads.

Geochemical background

The upper 10 km of the Earth's continental crust have an average abundance of 2.7 g/t U (Rudnick & Gao 2003). The grade of uranium ore deposits ranges from a few hundred g/t U to more than 20 % U. Therefore, an ore-forming process is required which enriches uranium over its global geochemical background by a factor of 100 to 10,000. Such enrichment is possible by leaching of large rock volumes by oxidized warm water and precipitation of uranium (commonly in the form of uraninite, UO_2, also known as pitchblende, due to its black color) in such places where the solubility of uranium changes. Uranium exists in two oxidation states. Uranium in the 6^+ state is highly soluble, while uranium in the 4^+ state is highly insoluble. This can be condensed into the general geochemical formulation:

U^{6+} (aqueous) + 2 e$^-$ = U^{4+}↓ (precipitation)

Or, in a natural system,

$UO_2(CO_3)_2^{2-}$ + 2 H$^+$ = UO_2 + ½ O_2 + 2 CO_2 + H_2O　　　　(1)

Note that there are many other possible uranium complexes in nature, but the underlying theme is the dissolved U species in the 6^+ state, while the precipitated U species is in the 4^+ state. The solubility of U^{4+} at low temperatures is extremely low, similar to thorium as Th^{4+}.

However, thorium, as opposed to uranium, has no oxidized species which is why it is not enriched in low-temperature hydrothermal deposits. Only under high-temperature conditions, particularly in silicate melts, uranium and thorium can become enriched synchroneously due to their common large ionic radius and high charge and then can form U-Th deposits in pegmatites and alkaline granites.

Equation (1) describes sufficiently both the formation of hydrothermal uranium ore deposits (reaction from the left to the right side), as well as their mining by in-situ solution techniques (reaction from right to left).

The solubility of uranium as described in (1) can then be formulated as

$\log K = \log [UO_2(CO_3)_2^{2-}] + 2 \log [H^+] - ½ \log [O_2] - 2 \log [CO_2]$
$\log [UO_2(CO_3)_2^{2-}] = \log K + 2 pH + ½ \log [O_2] + 2 \log [CO_2]$

This equation describes the solubility of uranium as a function of pH, oxidation state, and CO_2 fugacity. Given a situation where pH is buffered by rocks, the solubility of uranium will be controlled by the concentration of CO_2 and O_2 in the solution. A practical example for this relationship is given in **Figure 4**, where the change from an oxidized environment with U soluble to a reduced environment with U insoluble can be read directly from the rock. Uranium ore formation by precipitation as uraninite from oxidized solutions marks the transition from oxidized to reduced environments. ▶

In-situ solution mining reverses this process by forcing an oxidized environment on the reduced uranium ore deposit whereby uraninite is dissolved.

Hydrothermal mobility of uranium requires an oxidized environment of fluid circulation. Note that the term „hydrothermal" refers to any kind of warm water, without a genetic connotation. Oxidized conditions exist only since about 2.4 Ga when the Earth's atmosphere first developed oxygen levels in the percent range. There are no hydrothermal uranium deposits prior to this period, but there are magmatic enrichments of uranium in granites and granite pegmatites throughout the history of Earth. Uranium behaves as incompatible element in felsic melt systems, i.e. is not incorporated into the major silicate minerals, and becomes enriched in residual melts. Prior to 2.4 Ga, uraninite with high thorium content from erosion of such rocks was an insoluble heavy mineral and became enriched in fluviatile placers, such as the Witwatersrand, South Africa, or Blind River/Elliott Lake district, Canada. Such uranium placers only formed in the Archean oxygen-free environment. Under recent atmospheric conditions, uraninite dissolves easily in rain water, and the erosion of uranium deposits, or even uranium-rich granites (10-20 g/t U), produces broad secondary dispersion halos which are used for finding uranium ore. The high solubility of uranium under oxidizing conditions even at low temperatures allows enrichment under arid to semi-arid weathering conditions where uranium can be precipitated due to evapotranspiration. In this environment, hexavalent uranium is fixed commonly together with potassium and vanadium, and then forms a number of deep yellow to green minerals such as carnotite [$K_2(UO_2)V_2O_8 \cdot 3H_2O$] and tyuyamunite [$Ca(UO_2)V_2O_8 \cdot 5$-$8½ H_2O$] (**Fig. 5**). The predominance of uranium vanadates in these deposits is due to the low solubility of U-V compounds compared to all other $(UO_2)^{2+}$ minerals.

Uranium is variably enriched in igneous rocks due to its large ionic size and charge which does not allow incorporation of uranium into the major rock-forming minerals during crystallization. Uranium is similar in its physicochemical properties to thorium, and both elements become enriched in residual melts during crystal fractionation. Particularly granitic rocks are enriched in both elements and provide a reservoir for leaching by warm water.

However, thorium is much less soluble than uranium which is why hydrothermal uranium deposits have low Th contents. There are also igneous rocks which are so highly fractionated that uranium (and thorium) reach ore grade, i.e. a few hundred g/t. Such rocks are pegmatites and leucogranites, as well as highly alkaline rocks.

Major uranium deposit types

Uranium deposits form in a very wide range of geological environments. Historically, vein-type deposits were the most important, as well as paleoplacers. These mineralization styles tend to be relatively low grade (commonly < 1 % U), and the discovery of high-grade unconformity- ▶

Fig. 4: Uranium ore from the Bertholène deposit (mined out) in the Massif Central, France. This granite breccia consists of hematitized granite fragments (red), cemented by thin uraninite rims (black), followed by pyrite (yellowish), and demonstrates the change in oxidation state of the system from oxidized (hematite) to reduced (pyrite). Uraninite is precipitated during this change in redox conditions. The ore occurs near the unconformity of weathered Hercynian granite of Carboniferous age and overlying Permian coal-bearing strata of Permian age. (Sample collection Lehmann).
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Fig. 5: Uranium ore from weathering and evapotranspiration: Tyuyamunite, a hydrated Ca-U-vanadate, in Carboniferous limestone, Prior Mountains, Wyoming, USA. (Sample collection Lehmann)..

related deposits in Canada during the 1960s, and of very-high-grade deposits up to around 20 % U in the same setting in the 1980s changed the economics of uranium. Nevertheless, there are currently still many low-grade and very-low grade (< 0.05 % U) deposits profitably mined, either due to cheap extraction techniques (such as in-situ leaching) or due to co-production of copper and gold (such as in IOCG deposits). **Figure 6** gives an overview of the more important mineralization styles in terms of tonnage and grade. The high end in terms of grade is represented by unconformity-related deposits, the low end by paleoplacers and the giant Olympic Dam IOCG deposit in Australia.

Three major types of hydrothermal uranium ore deposits provide about 85 % of the present-day world uranium mine production. These are (1) unconformity-related uranium deposits, (2) sandstone-hosted or „roll front" deposits, and (3) IOCG („Iron Oxide-Copper-Gold) deposits. All three types form at redox fronts where oxidized basinal brines or meteoric water meet reducing lithologies or methane-bearing fluids. The basic process is large-scale leaching of U^{6+} from average or slightly uranium-enriched rocks under oxidizing conditions, and fixation in the U^{4+} state (uraninite; UO_2). This ore formation requires large amounts of oxidized warm water, such as available in intracratonic basins with km-thick sequences of red sandstone (±gypsum).

Large-scale fluid circulation can leach both the sedimentary basin sequence as well as the underlying metamorphic basement.

The reduction can be achieved by interaction of such water with reduced lithologies (for instance, graphite schist) or with hydrocarbons. The textbook example for this situation is the Athabasca basin in northern Saskatchewan, Canada, where several large mines work (or are developed to mine) ore with up to 20 % U (McArthur River, Cigar Lake) (**Fig. 7 and 8**).

These high-grade deposits occur near the unconformity of the Archean to Paleoproterozoic metamorphic basement and the overlying 1.9 Ga-old Athabasca sandstone, and are therefore commonly termed unconformity-related uranium deposits. The uranium mineralization is spatially associated with sheared graphite-bearing meta-sedimentary units in the basement, which have transmitted their reduced environment via hydrothermal halos into the overlying sandstone (**Fig. 9**). This control is important for exploration of hidden ore bodies by electrical geophysical methods.

A similar example are the classical sandstone or roll-front deposits in the western USA where uranium is concentrated in sandstone aquifers where the lithology changes from oxidized to reduced (**Fig. 10**). ▶
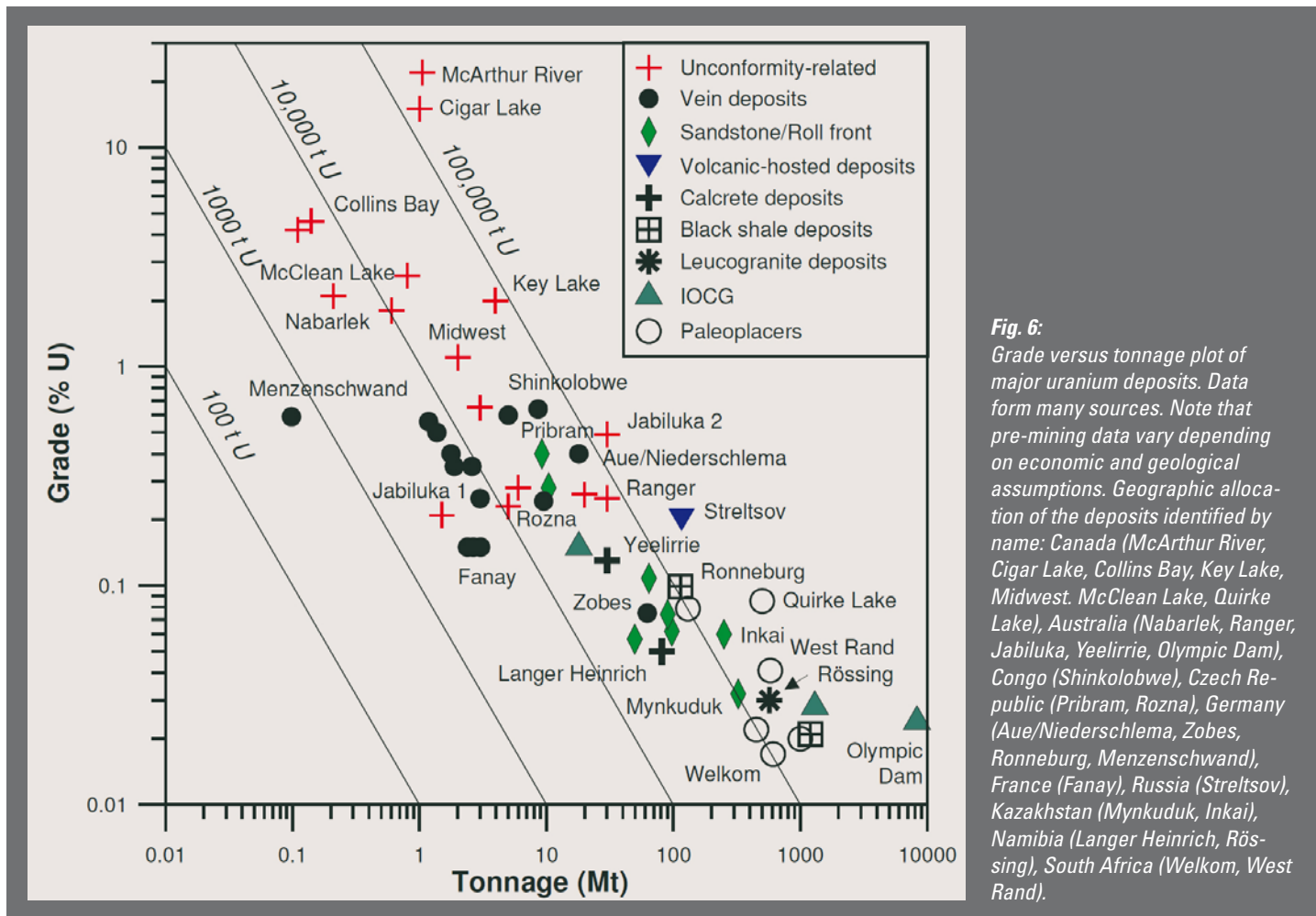

Fig. 6:
Grade versus tonnage plot of major uranium deposits. Data form many sources. Note that pre-mining data vary depending on economic and geological assumptions. Geographic allocation of the deposits identified by name: Canada (McArthur River, Cigar Lake, Collins Bay, Key Lake, Midwest. McClean Lake, Quirke Lake), Australia (Nabarlek, Ranger, Jabiluka, Yeelirrie, Olympic Dam), Congo (Shinkolobwe), Czech Republic (Pribram, Rozna), Germany (Aue/Niederschlema, Zobes, Ronneburg, Menzenschwand), France (Fanay), Russia (Streltsov), Kazakhstan (Mynkuduk, Inkai), Namibia (Langer Heinrich, Rössing), South Africa (Welkom, West Rand).

Fig. 7: Unconformity-related uranium ore in the Athabasca sandstone: Drill core from the Pod 2 area of the McArthur River deposit, Saskatchewan, Canada. DDH 301 consists over several meters of very-high-grade (> 50 % U) friable uraninite and argillic minerals. (Photo: Lehmann).
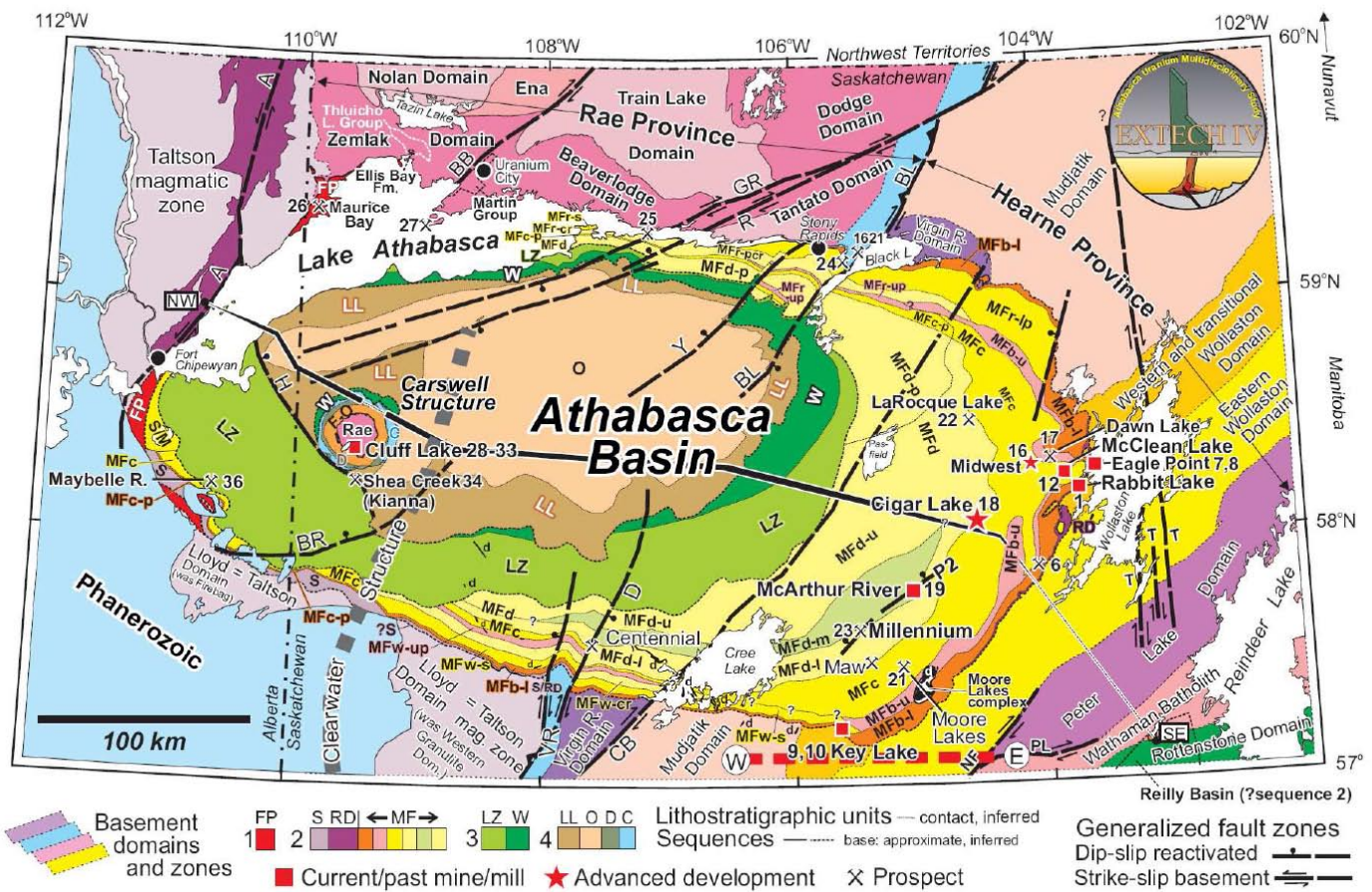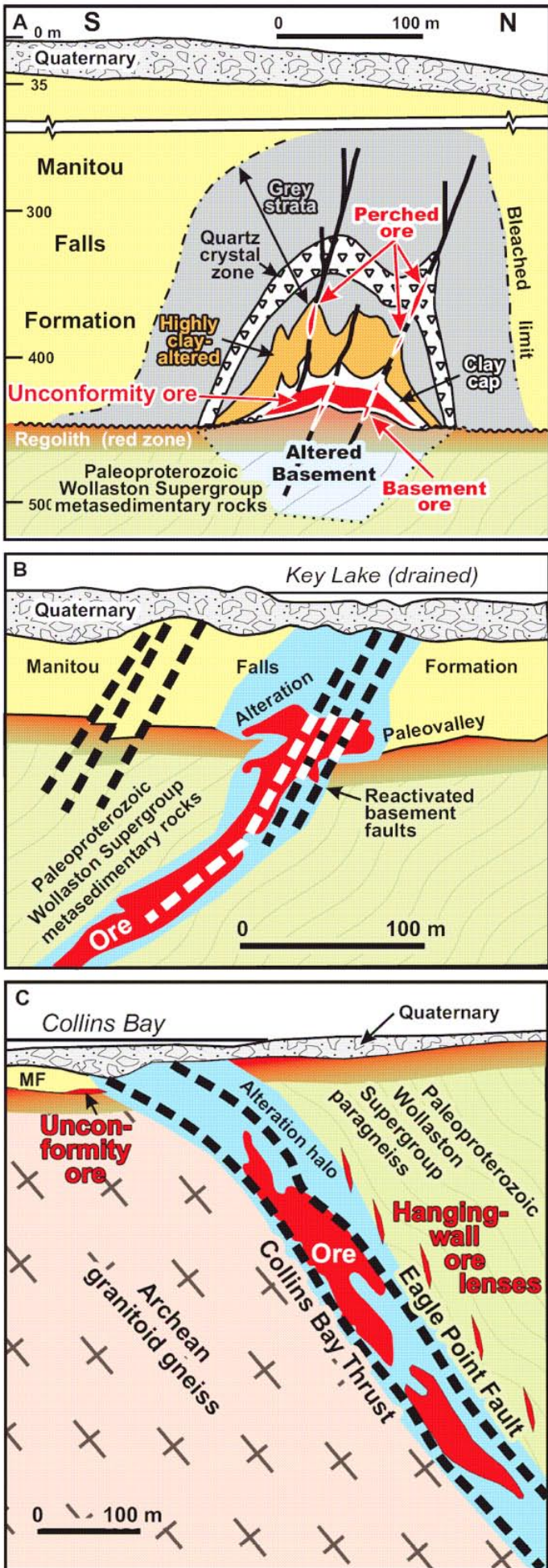

Fig. 8: Geological setting of the unconformity-type uranium deposits of the Athabasca Basin in Saskatchewan which has a current total resource of about 600,000 t U at and average grade of about 2 %. „MF" refers to the mid-Proterozoic Manitou Falls Formation which is the lower unit of the sedimentary Athabasca basin sequence. The major deposits are near the 200 km long southeastern border of the clastic sandstones and their Paleo-Proterozoic and Archean metamorphic basement. The major deposits are Key Lake (70,000 t U, 2 %, mined out), McArthur River (proven 80,000 t U, 15 %, + probable 62,600 t U, 22 %, active mining), Cigar Lake (87,000 t U, 21 % U, in development). From Jefferson et al. (2007: 276).

Fig. 9:
Three examples of major unconformity-associated uranium deposits in the southeastern part of the Athabasca Basin.

(A) Cigar Lake (underground mine development) is mainly immediately above the unconformity in hydrothermally altered sandstone.

(B) Deilmann (open pit, mined out) at Key Lake is both basement-hosted and unconformity ore.

(C) Eagle Point is mostly basement hosted (originally mined by open pit and underground; hanging-wall lenses still being developed and mined underground).

All mineralization styles are related to sheared graphite-bearing metasedimentary rock units in the basement. Vertical scale=horizontal scale. From Jefferson et al. (2007: 287).
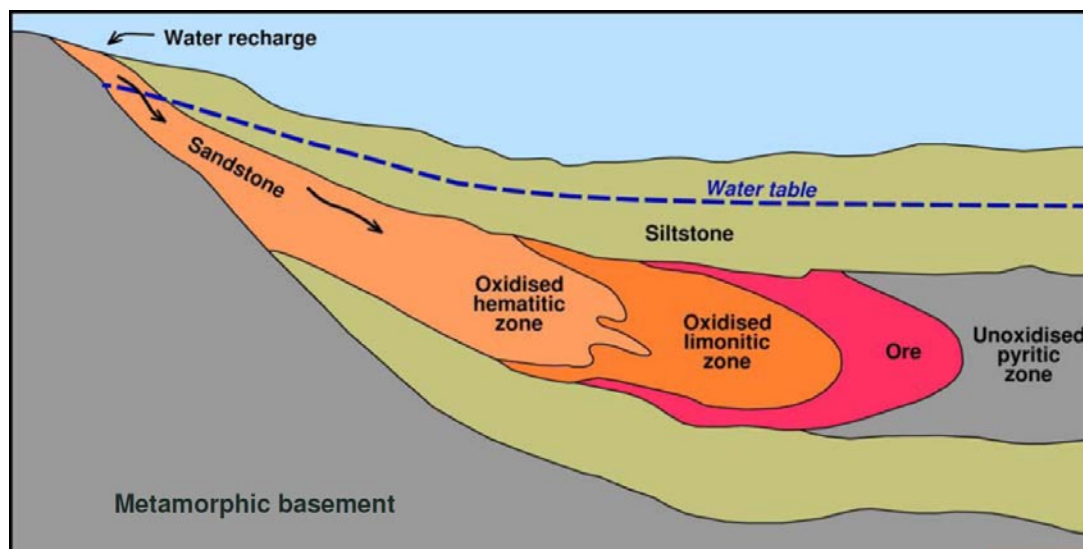
The reducing environment is here commonly induced by organic components or sedimentary-diagenetic pyrite in the sandstone. An even more effective means of reduction can be provided by oil or gas (methane), given the right hydraulic gradients. Such a situation seems to be given in central Kazakhstan, where many small to intermediate size uranium deposits in Late Cretaceous to Tertiary sandstone form a giant uranium province which is associated with gas fields in the same area. These deposits are low-grade (~ 0.03 - 0.05 % U), but host a huge resource of about 1.1 Gt U and can easily be exploited by in-situ leach techniques because the unconsolidated sand and sandstone aquifers have a good permeability (**Fig. 11**). ▶

Fig. 10:
Schematic representation of a roll-front deposit where a crescent-shaped uranium ore body forms at the dynamic reaction front in the sandstone aquifer between oxidized and reduced lithologies. The redox front moves with meteoric water flow more and more inside the original reduced rock unit, driven by hydraulic head.
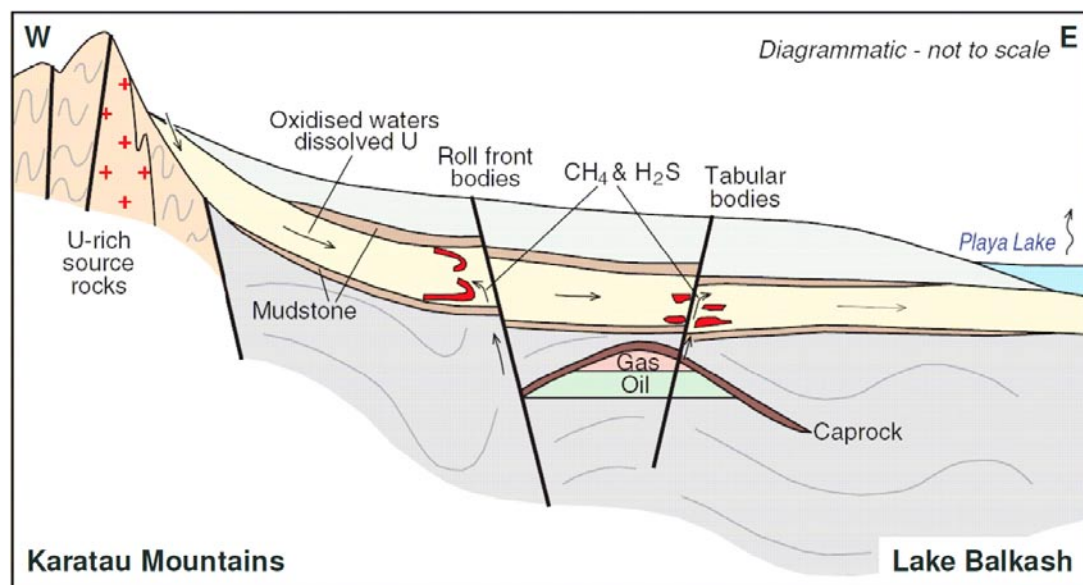

Fig. 11:
Schematic W-E crosss section over 500 km from the Karatau Moutains to Lake Balkash (Central Kazakhstan). Sandstone-hosted uranium deposits formed where regional-scale oxidized groundwater flow in Cretaceous-Tertiary aquifers encountered methane and hydrogen sulfide released from underlying gas fields. These deposits host around 1.1 Gt U at a low grade of ~0,03-0.05 % U easily extracted by ISL („In-Situ Leach") mining. Modified from Jaireth et al. (2008).

The IOCG („Iron oxide-Copper-Gold") deposit style is mainly known from the Gawler craton in southern Australia, with the supergiant Olympic Dam deposit standing out. The latest total resource figures make this deposit the largest uranium deposit known, although uranium is only a by-product of copper mining: 8.3 Gt @ 0.88 % Cu, 0.24 kg/t U, 0.31 g/t Au, 1.50 g/t Ag (BHP Billiton Annual Report 2008). Mining is currently still underground, but a multi-billion open-pit project with exceptional dimensions is under way. The Olympic Dam Cu-U-Au deposit consists of a huge Mesoproterozoic (~ 1590 Ma) granite breccia complex with abundant hematite (up to 90 %) and minor magnetite, as well as sulfides, and its formation is not well understood. This deposit has produced 3,500 t U in the past year (1 July 2007 to 30 June 2008, as to BHP Billiton reporting style), and is the only important uranium deposit of the IOCG style.

There is a variety of other uranium ore deposits of currently less economic importance. These cover all geological environments. The hydrothermal environment has classical vein type and shear-zone related deposits which were important in the early days of uranium mining. A large part of the European uranium production came from such veins systems in the Hercynian fold- and thrust-belts of the Bohemian Massif/Erzgebirge (Czech Republic and Germany) and the French Massif Central. An important part of the East German uranium production came from Early Paleozoic black shales in the Ronneburg district which picked up much uranium at a synsedimentary redox front (euxinic environment) which then probably became upgraded on weathering. This deposit style is known from other regions, particularly from the Cambrian alum shale in Sweden, where the uranium grade around 0.1 % U is below current economic feasibility (**Fig. 6**). ▶

Fig. 12: *Paleoplacer gold-uranium ore, Ventersdorp Contact Reef, Witwatersrand, South Africa. This typical sample shows milky-white quartz pebbles in a fine-grained matrix of chlorite and pyrite (yellowish). Uraninite and gold are visible under the microscope only. Average grade of the 3.1 Ga Witwatersrand paleoplacers is about 10 g/t Au + 210 g/t U, while the very similar Blind River/Ellott Lake paleoplacers in Canada have 900 g/t U, but no gold. (Sample collection Lehmann).*

Uraninite is a heavy mineral (density of 9.0 - 9.7 g/cm³) which can be enriched in placers under reducing conditions. Such conditions do not exist on the present-day Earth with a 20 % oxygen atmosphere. However, oxygen content in the atmosphere prior to about 2.4 Ga was very low ($<<$ 1 % O_2), which allowed enrichment of uraninite and pyrite as a clastic heavy mineral in the exogene environment. There are huge uranium paleo-placers, also known as quartz-pebble meta-conglomerates, in the 3.1-2.7 Ga Witwatersrand basin of South African, and in the 2.45 Ga Blind River/Elliott Lake district in Ontario, Canada. The clastic uraninite has a high thorium content of several weight-percent which indicates an origin from granitic or pegmatitic sources. Part of the uranium component has reacted with bitumen to amorphous „thucholite" (synthetic name from the Th-U-CHO association). Under the microscope, the uraninite pebbles display minute inclusions of galena, derived from radiogenic lead. This observation allowed a first ore microscopy-based age estimate of the mineralization, later refined by microanalytical isotope measurements.

Uranium is variably enriched in igneous rocks due to its large ionic size and charge which do not allow incorporation of uranium into the major rock-forming minerals during crystallization. Uranium is similar in its physicochemical properties to thorium, and both elements become enriched in residual melts during crystal fractionation. Particularly granitic rocks are enriched in both elements and provide a reservoir for leaching by warm water. However, thorium is much less soluble than uranium which is why hydrothermal uranium deposits have low Th contents. There are also igneous rocks which are so highly fractionated that uranium (and thorium) reach ore grade, i.e. a few hundred g/t. Such rocks are pegmatites and leucogranites, as well as highly alkaline rocks. The currently only example of an economic deposit of this type is the very large Rössing deposit in Namibia which produced about 3,000 t U in 2007 from low-cost open-pit production at a grade of about 300 g/t U. ▶

Natural nuclear reactors

It is interesting to know that nuclear reactors are not only man made, but also occurred in nature in a specific time window when two conditions were met: (1) Enough oxygen was in the atmosphere to allow mobilization and transport of uranium by warm water, and local precipitation of uraninite, as today in high-grade unconformity- and sandstone-type U deposits; (2) The proportion of ^{235}U in natural uranium was about $\geq$ 3.5 % which was realized at about 2 Ga and beyond, given the about six times shorter half-life of ^{235}U compared to ^{238}U. These two conditions bracket the natural formation of a critical mass of uranium at the time of about 2.0 - 2.4 Ga. Natural nuclear reactors were discovered in the 2 Ga Franceville basin in eastern Gabon in 1972 where 16 natural nuclear reactors are known so far. These reactors operated based on ore concentrations in sandstone of $\geq$ 20 % U with then 3.7 % ^{235}U, and water acted as moderator to slow down high-energy neutrons to be able to be absorbed by ^{235}U atoms and trigger fission. As the chain reaction proceeds, however, it generates heat which boils away the water, dries up the reactor and shuts it off. Similar to a geyser in a geothermal field, the process then starts up again after recharge by cold groundwater. Fissiogenic Xe and Kr trapped in alumino-phosphate minerals allows a detailed reconstruction of the life cycles of these reactors which operated over 150,000 years, with probably 30-min active pulses separated by 2.5-h dormant periods for water recharge (Meshik et al. 2004). The energy released during the life time of these reactors is estimated at ~15 GWyr, and about 50 % of this energy came from „breeding", i.e. internal production of ^{239}Pu from neutron capture of ^{238}U, and α-decay of ^{239}Pu to ^{235}U. Even more astonishing, these open-system breeder reactors did not contaminate large areas, but their toxic and radiogenic components behaved essentially immobile over their 2 Ga history until today, due to the reducing and argillic nature of the country rocks. This natural analogon of a nuclear waste repository is relevant for the current discussion on safety of waste storage. ▶
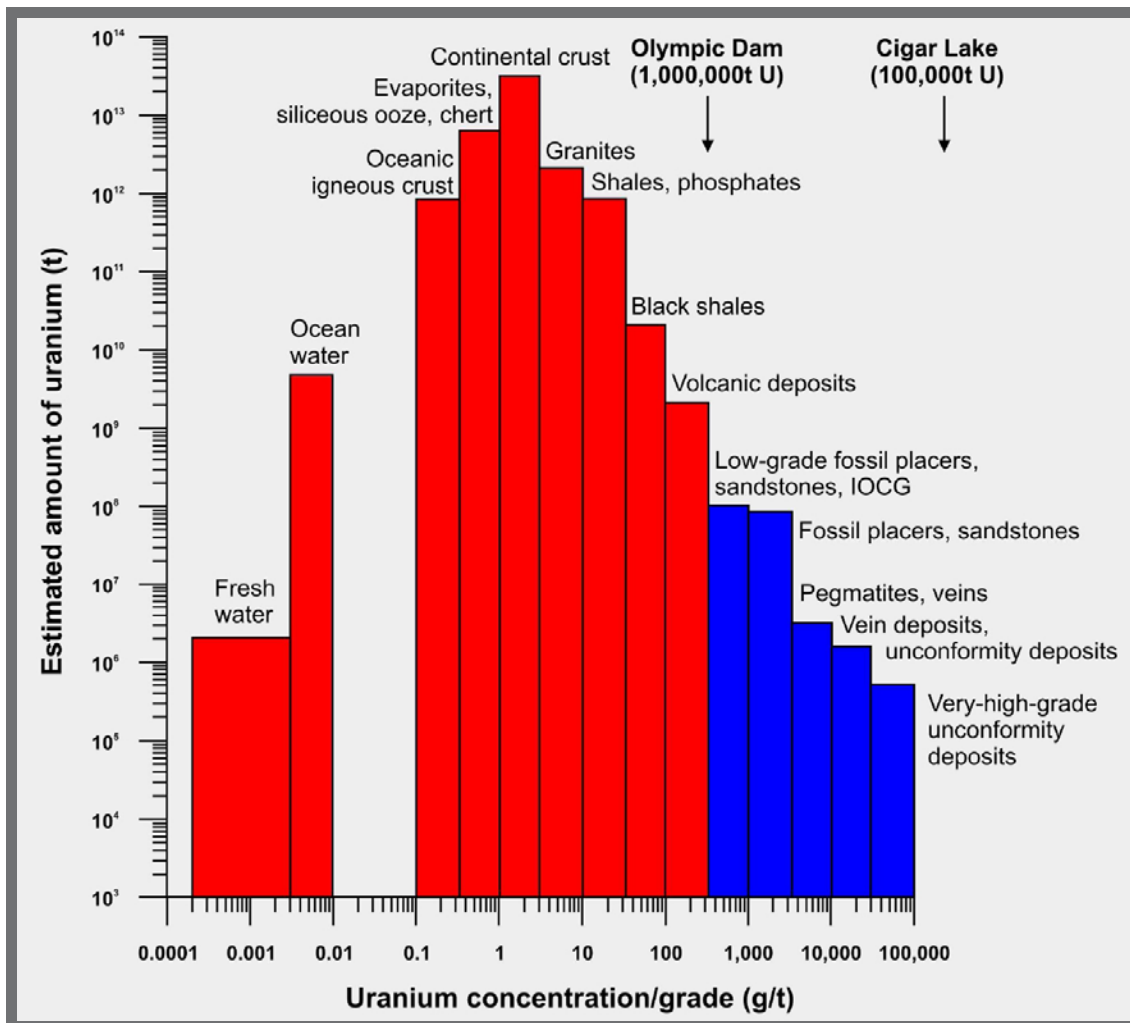

Fig. 13:
Uranium distribution in the Earth's crust. The bars represent various categories of uranium deposits (in blue) or geological repositories of uranium (in red). The currently mined uranium deposits have a very large grade range from a few hundred g/t to about 20 %. The arrows locate the grade at the extremes of this range, with the giant and low-grade Olympic Dam Cu-U-Au mine in Australia, and the very-high-grade unconformity-type U deposit of Cigar Lake in Canada (in development). Adapted from Deffeyes and MacGregor (1980).

Resource perspective

The resource distribution of uranium in the Earth's crust is of more than passing interest, because nuclear reactors may become the preferred source of electricity generation in the future, once climate change and oil/gas shortages are widely perceived as particularly unpleasant. **Figure 13** gives an overview on the availability of uranium in the Earth's lithosphere and hydrosphere. The amount of uranium in the several types of uranium deposits increases progressively as the grade decreases. The data in **Figure 13** show that at the present rate of mining the amount of uranium in ore with more than 0.1 % U will last more than 1000 years. Much of this amount is uneconomic at the current price. The uranium resouces recoverable at a price of up to 130 USD/kg U are estimated at 5.5 Mt (NEA 2008).

Average seawater has an abundance of 3.2 ppb (ng/g) U, and there are about 4.5 Gt U in the form of uranyl-tricarbonate $[UO_2(CO_3)_3^{4-}]$ in the oceans which have a total mass of seawater of 1.4 x 1018 t. Uranium extraction by adsorption has been experimentally tested, and seawater mining could be done powered by ocean currents. Industrial-scale production was, however, never tested and is estimated to become profitable at a price of about 400-1200 USD/kg U (Macfarlane & Miller 2007).

Economic perspective

The production cost of electric energy from nuclear power plants in 2005 was 1.7 US ct/kWh, compared to 2.2 US ct for coal, 7.5 ct for natural gas, and 8.1 ct for oil (operation, fuel and maintenance; US data in NEA 2008). Given that the cost of natural uranium constitutes only 3 - 5 % of the cost of a kilowatt-hour of nuclear-generated electricity, compared to 78 % for coal, 94 % for natural gas and 91 % for oil, large increases in the price of natural uranium have much less impact than price hikes for coal, gas or oil. Therefore, nuclear-generated electricity will be more and more competitive with other electricity sources, in spite of the high initial investment cost.

A simple back-of-the-envelope calculation can estimate the influence of price fluctuations of raw materials for various energy sources: The relationship between the energy output from equal amounts of natural uranium and steam coal is about 10,000, and the relationship between the present-day price of equal amounts of natural uranium (150 USD/kg U) and steam coal (150 USD/t coal) is 1000. Therefore, an increase in the current price of uranium by a factor of 2 (when very-low-grade uranium enriched rocks become mineable, and also seawater mining may be feasible) would have only 10 % of the impact on electricity price

compared to the same amount of price increase for steam coal. The same calculation is, of course, much in favor of solar energy for which solar radiation comes free, but the price of large-scale conversion into electricity is currently still prohibitive.

There is an enormous potential of cheap electric energy from nuclear power, limited not by natural resources, but by political and environmental issues. A particularly intriguing perspective is added by new breeder technology which could provide all energy requirements on Earth in a sustainable manner (i.e. no depletion), as already pointed out by Cohen in 1983.

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