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Unconventional resources in IAEA Uranium DEPOsit Database (UDEPO)

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INTRODUCTION

Unconventional resources are defined in the 2016 version of the Red Book as "Resources from which uranium is only recoverable as a minor by-product, such as uranium associated with phosphate rocks, non-ferrous ores, carbonatite, black shale and lignite"[1].

Unconventional resources of uranium are recorded in UDEPO, the IAEA Uranium DEPOsit Database [2, 3]. They correspond to low to very low grade, generally very large geological resources where uranium can only be extracted as a co- or by-product of other mining production. In most cases, this cannot currently be done economically with existing technologies.
In the IAEA geological classification of uranium deposits [4, 5], most unconventional resources are associated with the following deposits types and subtypes: intrusive plutonic, polymetallic iron-oxide breccias complexes (IOCG-U), volcanic-related, Au-rich paleo quartz-pebble conglomerate, placers, lignite-coal, phosphorite and black shale. The largest unconventional resources are in sea water with resources estimated at 4 billion tonnes at an average grade of 3.3 ppb (3.3 mg/m3). This resource is not included here.

UNCONVENTIONAL URANIUM RESOURCES IN UDEPO

In 2017, UDEPO total geological uranium resources stand at 62 674 137 tU hosted within 2755 deposits with known or estimated resources. There repartition is a follow:

- Conventional uranium resources of 11 857 089 tU, hosted within 2475 deposits with known/estimated resources,
- Unconventional resources of 50 817 048 tU, hosted within 280 deposits with known/estimated resources. Deposits such as Olympic Dam (IOCG-U) are included in the UDEPO unconventional resources category, which explains some of the differences in the figures when compared for example with Red Book data.

UDEPO is firstly a geological database, thus there is no economic connotation taken into consideration. Unconventional resources or deposits are those that cannot be mined solely for uranium (co- and/or by-product). They include:

- very large (generally > 1 Mt U), low grade (20-200 ppm) resources such as those in volcanic formations (Northern Latium province, Italy), lignite-coal (Northern Great Plains, USA), phosphorites (Morocco basins) and black shale formations (Baltoscandian district),
- large (10 000–100 000 t U), low grade (50-250 ppm) resources located within peralkaline plutonic intrusions (Kvanefjeld, Greenland) and carbonatites (Palabora, South Africa), polymetallic iron-oxide breccia complexes (Olympic Dam, Australia) and Au-rich paleo quartz-pebble conglomerates (Witwatersrand Basin deposits, South Africa),
- very low grade ("background") uranium (10-30 ppm U) in porphyry copper deposits (Bingham Canyon, USA), volcano-sedimentary formations (El Boleo, Mexico) and base metal deposits (Talvivaara mine, Finland),

- placer deposits.

In UDEPO, 12 of these unconventional resources contain more than 1 million tonnes of uranium:

- Phosphoria Formation (USA): 7 Mt, 0.005-0.015% (Phosphorite)
- Tarfaya basin (Morocco): 6.4 Mt, 0.008% (Black shale)
- Baltoscandian district (Estonia): 5.667 Mt, 0.0085% (Black shale)
- Chattanooga Shale (USA): 5 Mt, 0.006% (Black shale)
- Northern Great Plains (USA): 5 Mt, 0.006% (Coal-lignite)
- Oulad Abdoum basin (Morocco): 3.2 Mt, 0.012% (Phosphorite)
- Olympic Dam (Australia): 2.125 Mt, 0.023% (IOCG-U)
- Timahdit (Morocco): 2.1 Mt, 0.005% (Black shale)
- Meskala basin (Morocco): 2 Mt, 0.010% (Phosphorite)
- Randstad Inlier (Sweden): 1.7 Mt, 0.021% (Black shale)
- Gantour basin (Morocco): 3.2 Mt, 0.012% (Phosphorite)
- Northern Latium province (Italy): 1 Mt, 0.005% (Volcanic-related, volcano sedimentary)

Other than the Olympic Dam deposit which is an operating mine, precise estimation of these large geological resources is very difficult due to the size of the formations and the poorly characterized distribution of uranium grades. For example, the Phosphoria Formation (USA) covers an area of about 350 000 km2, with a thickness of 60-150 m for the mineralized phosphatic layers and uranium grades are estimated around 50-150 ppm. Thus, depending of the parameters used, the calculated content of uranium ranges between 5 and 60 Mt U (7 Mt in UDEPO from historical USA data). Historically, 184 tU was extracted from localized enriched areas with tenors reaching up to 1% U.

REPARTITION OF THE UNCONVENTIONAL RESOURCES

In detail, unconventional resources are associated with several deposit types and subtypes:

- Type 1: Intrusive, plutonic subtype, with 3 classes (quartz monzonite, peralkaline complex and carbonatite). Resources: 1.907 Mt in 33 deposits;
- Type 3: Polymetallic iron-oxide breccia complex (IOCG-U). Resources: 2.760 Mt in 18 deposits ;
- Type 4: Volcanic-related, volcano-sedimentary subtype. Resources: 1.204 Mt in 2 deposits,
- Type 10: Paleo quartz-pebble conglomerate, Au-rich subtype. Resources: 1.860 Mt in 100 deposits. Also, in South Africa, 16 areas with large tailings resources contain an estimated 175 500 tU;
- Type 11: Surficial, placer subtype. Resources: 67 000 t in 13 deposits ;
- Type 12: Lignite-coal, stratiform subtype. Resources: 7.223 Mt in 21 deposits;
- Type 14: Phosphate, minerochemical phosphorite subtype. Resources: 14.148 Mt in 48 deposits ;
- Type 15: Black shale, stratiform subtype. Resources: 21.473 Mt in 29 deposits.

However, the types and subtypes listed above also contain deposits previously mined for uranium and those which could be mined in the future for uranium only owing to their grades (generally $>$ 0.05% U). In those instances the deposits are not considered unconventional in UDEPO. Examples include the coal-lignite deposits mined in the past in Germany (Freital district), the black shale deposits of Uzbekistan and the organic phosphorite deposits mined in Kazakhstan.

- Type 1. Intrusive, subtype 1.2 plutonic: all quartz monzonite (porphyry copper), and most peralkaline complexes and carbonatites correspond to unconventional resources where low to very low (10-250 ppm) grade uranium is associated with Cu, Ag, Au, Mo, REE, Th, Nb, Ta, Zn and Zr. Some exceptions are Bokan Mountain (USA) and Poços de Caldas (Brazil) where uranium was mined in the past as a primary commodity. Uranium was produced in the past at Bingham Canyon (USA), Twin Buttes (USA) and Palabora (South Africa). Uranium production is planned in the near future at the Kvanefjeld project (Greenland) in association with REE and Zn.
- Type 3. Polymetallic iron-oxide breccia complex (IOCG-U): deposits of this type, with grades of 30-250 ppm U, correspond to large to very large iron–copper–gold–silver deposits occurring on the Gawler Craton (Australia) and in the Carajas Province (Brazil). Uranium is extracted as a co-product along with copper–gold–silver at Olympic Dam, the largest world uranium deposit with resources of 2.2 Mt. Deposits from the Mount Painter area in South Australia which have grades of 0.05–0.20% U are considered conventional. Some of these deposits have already been mined in the past for radium or uranium alone.

- Type 4. Volcanic-related, stratabound and volcano-sedimentary subtypes: Quaternary alkaline volcanics of northern Latium (Italy) contain in average 20-70 ppm U representing geological resources of more than 1 Mt. Sub-marginal resources in the volcano-sedimentary formations are in the range 5-10 000 t U at a grade of 300-600 ppm U. The El Boleo project (Mexico), a Cu-Co-Ni-Mn mine, is planning the extraction of very low grade (10 ppm) uranium.
- Type 10. Paleo quartz-pebble conglomerate, Au-rich subtype: uranium is mined as a by-product of gold in the Witwatersrand Basin (South Africa). Average grade is around 250 ppm and uranium geological resources exceed 2 Mt. In addition, there are plans to extract uranium and gold from low to very low grade (35–75 ppm U) tailings which are a legacy of gold mining over the past 130 years. Total resources in 16 areas are estimated to be of the order of 175 500 tU.
- Type 11. Surficial, placer subtype: placer deposits are accumulations of heavy minerals formed by gravity separation during sedimentary processes. The principal minerals containing thorium and uranium are zircon, monazite and xenotime. India has very large resources of monazite from which uranium could be extracted in addition to Th and REE.
- Type 12: Lignite–coal: most coal and lignite deposits contain very low grades, of the order of U, on the order of 1–5 ppm. However, some coal deposits (such as those in South Africa, Kazakhstan, Kyrgyzstan, the Russian Federation and Ukraine) record unusually high uranium contents (0.05–0.15% U) and these are not classified as unconventional in UDEPO. In the past, uranium was extracted from fracture-controlled coal deposits in the former German Democratic Republic (Freital district). Very large quantities of tailings from coal processing around the world are enriched in uranium (5-20 ppm) representing significant unconventional resources.
- Type 14: Phosphate: Phosphorites typically cover very large surface areas and represent large low grade (50-150 ppm) resources of uranium. Total world phosphate resources are estimated at 300 billion tones and assuming an average grade of 100 ppm U, would contain about 30 Mt U. Between 1978 and 2000, 17 225 t U were extracted from the phosphorite formations in Florida. Continental phosphate deposits (Central African Republic) and organic phosphorites (Kazakhstan, Russian Federation) are listed as conventional resources due to their grade (0.05-0.3%). Some of the Kazakhstan organic phosphorite deposits were historically mined for uranium as a major product,
- Type 15: Black shale: in UDEPO, the uranium resources of black shales are currently estimated at 21.5 million tU, with stratiform black shale formations hosting the largest geological, low-grade (20–200 ppm U) uranium resources in the world. The uranium is associated with various other metals such as Ni, Co, Cu, Zn and V. Historically, uranium was mined as the primary product from this type of deposit in the Gera-Ronneburg district (former German Democratic Republic).

PLANNED AND POTENTIAL MINING PROJECTS

In 2018, several operating mines or new mining projects could produce uranium as a by- co-product:

- Chuquicamata (Chile): Cu-Mo (porphyry-copper), potential production of 85 t U/year from ore containing 5-10 ppm U,
- Kvanefjeld (Greenland): REE-Zn (peralkaline complex), planned production of 400 t U/year from ore containing 200-250 ppm U,
- Round Top (USA): REE-Be (peralkaline complex), planned production of 115 t U/year from ore containing 20-50 ppm U,
- El Boleo (Mexico): Cu-Ni-Co-Mn mine (volcanic-related), potential production of 60 t U/year from ore containing 10-20 ppm U,
- Talvivaara (Finland): Cu-Ni-Co-Mn mine (black shale), potential production of 350 t U/year from ore containing 10-15 ppm U,
- Haggan (Sweden): Mo-Ni-Zn-V (black shale), planned production of 385 t U/year from ore containing 120-150 ppm U,
- MMS Vicken (Sweden): Zn-Ni-Cu (black shale).

SUMMARY

Currently 280 uranium deposits and resources listed in UDEPO are classified as unconventional resources associated with eight deposit types and containing geological resources in the order of 51 Mt U. Considering the number of analogous geological host rock examples worldwide, potential additions of unconventional deposits and resources to the UDEPO database can be estimated in the order of 5-6000:

- Type 1. Intrusive plutonic deposits: 1660 occurrences worldwide (33 deposits in UDEPO);
- Type 3. Polymetallic iron-oxide breccia complex (IOCG-U) deposits, 50 occurrences worldwide (18 deposits in UDEPO);

- Type 11. Surficial placer deposits: 500-1000 occurrences worldwide (13 deposits in UDEPO) ;
- Type 12. Lignite-coal deposits: about 1600 occurrences worldwide (21 deposits in UDEPO);
- Type 14. Phosphate deposits: 1635 occurrences worldwide (48 deposits in UDEPO) ;
- Type 15. Black shale deposits: around 1000 occurrences worldwide (29 deposits in UDEPO).

This indicates that potential geological unconventional resources of uranium worldwide are enormous. Of course, most of these resources will never produce uranium due to their very low grades, their environmental impact and their economic conditions. However, unconventional uranium resources in conjunction with the concept of "comprehensive extraction"will probably play an important role in future world uranium production.

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