

Uranium and Thorium: The Extreme Diversity of the Resources of the World's Energy Minerals

123

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4

Abstract

Uranium and thorium represent two elements which can be used for the production of energy. The types of uranium deposits, the mechanisms driving their genesis and their resources are relatively well known because extensive exploration programs and scientific research projects have been developed worldwide since the early 1950s. However, there are still several types of U deposits which have been underexplored such as those related to Na-metasomatism, and several others with low uranium grade but large tonnages such as phosphates, which mining has been discontinued, may become significant resources in the future depending of the evolution of the U prices. At the opposite, the types of Th deposits, their genesis and their resources are poorly known because of the extremely limited commercial use of this commodity. Recent evaluations of the Th resources show however that they may be as important as identified U resources, but a better evaluation of the cost of Th extraction for most of these resources is crucially needed. But as the Th cycle does not need the costly enrichment process and that the totality of Th can be burned in a nuclear power station, at least theoretically, the cost of thorium extraction can probably be higher than that of U.

U deposits are extremely diverse and may be formed at nearly all steps of the geological cycle, whereas Th deposits dominantly result from concentration during two major types of processes: magmatic fractionation of peralkaline complexes, associated carbonatites as an incompatible element and associated fluid fractionation from these types of melt, and as heavy mineral accumulation in placer-type deposits, essentially as monazite.

Uranium is already widely used for energy production, but only a very small part of it is burned in the present nuclear reactors. A great variety of nuclear materials are produced during the U nuclear cycle: depleted U,

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33 spent fuel, reprocessed U, reprocessed Pu and military highly enriched U
 34 and Pu, which ~~begins to be reprocessed to be~~ transformed to usable fuel in
 35 the present and future generations of nuclear power stations for a sustain-
 36 able use of these resources. The present review of available and potentially
 37 available nuclear fuel resources in the world shows that these resources are
 38 considerable and can be ~~considerably~~ increased with increasing explora-
 39 tion, the improvement of processing of low grade – large tonnage deposits
 40 (phosphates, black shales) – of refractory ore associated with peralkaline
 41 intrusions, the spreading of recycling spent U fuel and the development of
 42 new technologies for burning ^{238}U and ^{232}Th in new generations of
 43 nuclear power reactors.

Introduction

Uranium and thorium represent two major mineral resources for the production of energy. The use of U is already well developed whereas that of Th is still at the state of project. Moreover, until now, only a small fraction of the natural U, the isotope ^{235}U , is used in the reactors, leaving 99.3% of the natural uranium as ^{238}U unused. Also, only a small part of the nuclear material issued from nuclear fuel cycle is reprocessed to be used as a nuclear fuel. Therefore, a sustainable development of nuclear energy requires a wider development of existing technologies and the development of new ones to use more thoroughly the U and Th resources.

Uranium is enriched in the continental crust (1 ppm in average, Javoy 1999; 2.7 ppm in the upper crust) relatively to the primitive mantle (21 ppb) because of its incompatible behaviour during partial melting and fractional crystallization. Uranium deposits occur at nearly all stages of the geological cycle from surficial, sedimentary, diagenetic, metamorphic, igneous, to hydrothermal environments (Fig. 1). The about 1,200 U deposits listed in the new UDEPO database (OECD/NEA & IAEA 2009) have been grouped into 15 major types mainly based on their geological setting according to the classification developed by the IAEA–NEA in 1988–1989 and Dahlkamp (1993). However, in this chapter, we use a classification based on the geological, physical and chemical conditions controlling their

formation as proposed by Cuney (2009, 2010) (Table 1). The same type of classification has been developed here to present the Th deposits, but the variety of processes at their origin is much more limited.

~~Therefore,~~ the main aim of this contribution is to present a synthetic review of the world U and Th resources in the two first parts of the chapter. A third part is devoted to a summary of present and future programs devoted to the sustainable use of the U resources.

Uranium Resources

Three types of deposits: Olympic Dam, diagenetic-hydrothermal deposits and those related to meteoric water infiltration represent over 75% of identified world U resources. In the 2007 edition of the Red Book, published each 2 years by the IAEA, identified resources represent the sum of the reasonably assured resources for which grades and tonnages are estimated with the highest degree of confidence and of the inferred resources for which further exploration work is needed to confirm their estimation. In 2007, world identified resources recoverable at less than \$130US/kg U correspond to 5.469 Mt U (Table 2).

Very large low-grade resources (several millions t U) are also associated with phosphates (Morocco has about 70% of the resources of this type), with grades of 50–350 ppm U, and with black shales, the best example being the

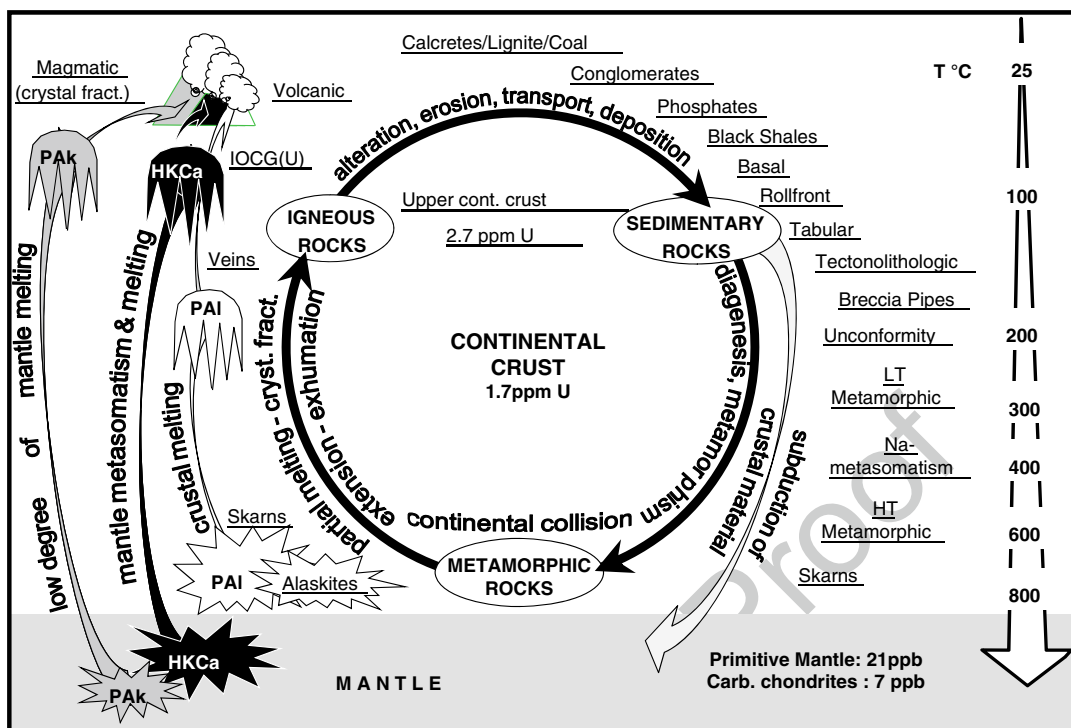


Fig. 1 Position of the major uranium deposit types along the geological cycle, the major uranium reservoirs of the Earth and the major uranium-rich magmatic associations: PAK peralkaline, HKCa high-K calc-alkaline, PAI peraluminous and alaskites (From Cuney 2009, modified)

Cambrian alum shales of southern Sweden. Including speculative (a resource that is expected to occur in geological provinces that may host U deposits according to the IAEA classification) and higher-cost resources, such as phosphates and black shales, the 2007 IAEA Red Book assesses the world global U resource at 11 Mt.

The different types of U deposits will be presented as far as possible from the highest to the lowest temperature fractionation processes, that is from magmatic processes to hydrothermal processes to sedimentary and surficial processes.

Magmatic Deposits

Related to Crystal Fractionation

Crystal fractionation is one of the major primary processes leading to U enrichment but is the most efficient in peralkaline magmatic systems. As a result of their peralkalinity and high temperature,

peralkaline melts have a very low degree of polymerization which permits high solubilities of the large, highly charged elements like U, Th, Zr, REE and Nb and thus causes their simultaneous and continuous enrichment until the most extreme stages of magmatic fractionation. Hence, deposits associated with peralkaline magmas are always hosted by the last and most fractionated magma batch at the roof or at the margin of the peralkaline plutonic complexes. When these melts crystallize, complex Th–Zr–REE–Nb silicates, phosphates and/or oxides are formed, and U is distributed among these mineral phases. These minerals are too refractory to allow for economic recovery of U. Only covaluation of the associated metals may allow future economic mining of such deposits.

The best example of this type of mineralization is the Kvanefjeld deposit (83,320 t U at 260 ppm U) in the Ilimaussaq plutonic complex in southern Greenland which is hosted by layered

Table 1 Genetic classification of the uranium deposits (From Cuneý 2010)

	Deposit type	Size	Grade%	Type example	Reference
M	Magmatic				
MCF	Crystal fractionation	Small to medium	0.04	Ilmaussaq	Sørensen (1974)
MPM	Partial melting	Large	0.01–0.05	Rössing (Namibia)	Berning et al. (1976)
H	Hydrothermal				
HV	Hydrothermal-volcanic	Small to very large	0.05–0.2	Strel'tsovskoye (Russia)	Chabiron et al. (2003)
HG	Hydrothermal-granitic	Small to large	0.1–0.6	Niederschema-Alberoda (Germany)	Golubev et al. (2000)
HD	Hydrothermal-diagenetic				
HDla	Intraformational redox				
HDlaTb	Tabular	Small to large	0.1–0.2	Grants (USA)	Hansley and Spirakis (1992)
HDlaTl	Tectonolithologic	Small to large	0.1–0.4	Arlit-Akouta (Niger)	Pagel (2005)
HDlaCb	Collapse breccia	Small	0.1–0.9	(USA)	Wenrich and Sutphin (2008)
HDBb	Basin/basement redox	Small to very large	0.2–20%	McArthur River (Canada)	McGill et al. (1993)
HDlf	Interformational redox	Small to medium	0.1–0.4	Oklo (Gabon)	Gauthier-Lafaye (1986)
HMp	Metamorphic-hydrothermal				
HMt	Metasomatic-hydrothermal				
HMiAm	Alkali-metasomatism	Small to large	0.1–0.25	Michurinka (Ukraine)	Scherbak and Bobrov (2005)
HMiSk	Skarns	Small	0.1	Mary Kathleen (Australia)	Maas et al. (1987)
E	Evapotranspiration	Small to large	0.014–0.1	Yeliree (Australia)	Carlisle et al. (1978)
S	Syn-sedimentary				
SMs	Mechanical sorting	Large	0.02–0.15	Witwatersrand (South Africa)	Frimmel et al. (2005)
SRT	Redox trapping				
SRTm	Marine (black shales)	Very large	0.005–0.03	Randstätt (Sweden)	Andersson et al. (1985)
SRTc	Continental (coal, lignite...)	Small to medium	0.001–0.05	Kazakhstan	IAEA (2005)
SCcr	Crystal–chemical/redox (phosphates)	Very large	0.005–0.03	Morocco, Florida	IAEA (2001)
M	Meteoric water infiltration				
MB	Basal-type	Small to large	0.01–0.1	Blizzard (Canada)	Boyle (1982)
MRf	Roll-front	Small to very large	0.01–0.2	Wyoming	Adams and Cramer (1985)
O	Others	Very large	0.01–0.04	Olympic Dam (Australia)	Hitzman and Valenta (2005)

Table 2 World uranium identified resources (reasonably assured + inferred) at less than 130 US\$/kg (IAEA 2007) and presumed additional potential

Country	Resource	Potential
Australia	1,243,000	High
Kazakhstan	817,300	High
Russian Federation	545,600	High
South Africa	435,100	Low
Canada	423,200	High
United States	339,000	Moderate
Brazil	278,400	Very high
Namibia	275,000	High
Niger	274,000	High
Ukraine	199,500	Moderate
Jordan	111,800	Moderate
Uzbekistan	111,000	Moderate
India	72,900	Moderate
China	67,900	Moderate
Mongolia	62,000	High
Denmark	32,300	Moderate
Algeria	19,500	High
Argentina	12,000	High
Central African Republic	12,000	Moderate
France	11,700	High
Malawi	11,600	
Spain	11,300	High
Sweden	10,000	Moderate
Somalia	7,600	
Turkey	7,300	
Portugal	7,200	Moderate
Germany	7,000	Moderate
Greece	7,000	
Romania	6,700	
Japan	6,600	Low
Vietnam	6,400	
Italy	6,100	Moderate
Gabon	5,800	High
Indonesia	5,800	
Slovenia	5,500	
Peru	2,900	Moderate
Congo Democratic Republic	2,700	Very high
Mexico	1,800	Moderate
Iran	1,600	
Chile	1,500	
Zimbabwe	1,400	
Finland	1,100	Moderate
Czech	700	Moderate
Total	5,468,800	

lujavrites, a highly fractionated quartz undersaturated peralkaline syenite. At Kvanefjeld, U is hosted mainly by steenstrupine, a complex U–Th–REE silicophosphate, disseminated in the lujavrites (Sørensen et al. 1974).

Magmatic fluids rich in fluorine are always involved in formation of U deposits related to extreme fractionation of peralkaline magmas because F and U are simultaneously enriched in highly fractionated melts (Linnen and Cuney 2005). Hence, some U and Th are fractionated from the silicate melt into F-rich magmatic fluids and transported over a few 100 m as at Bokan Mountain in Alaska, USA (Staatz 1978), or several kilometres from the intrusion in the Th veins of the Front Range, USA (Staatz et al. 1979). Also, some minor mineralization occurring in volcanic–plutonic environment can be related to such fluid/melt partitioning. Possible examples include the early Th–U–Zr–REE mineralization with Th-bearing uraninite in the Morro do Ferro deposit hosted by the Poços de Caldas peralkaline caldera in Brazil, the early U–Th–Mo mineralization in the Zoujiashan deposit hosted by rhyolitic lava and rhyodacites, in the western part of the Xiangshan caldera, China (Jiang et al. 2005), and the Rexpar U–Th–REE deposit in British Columbia, Canada (Morton et al. 1978). However, as the fluid/peralkaline melt partition coefficients of U are very low (Peiffert et al. 1996), the amount of U able to fractionate outside the intrusion is low, and related U deposits of this type are generally non-economic.

Extreme degree of crystal fractionation of highly potassic magmas may also lead to the formation of slightly peraluminous granites (Grosse 2007) or pegmatites (Lentz 1996) with a few to some hundreds ppm U, but typically, these bodies are too small to represent economic mineralization.

Related to Partial Melting

Partial melting in continental crust may also lead to the formation of U deposits. This type of deposit comprises low-grade disseminated uraninite concentrated in granitic pegmatoids occurring in migmatitic domains and represents the

other major type of deposit dominantly related to magmatic processes. The type example is the Rössing deposit in Namibia whose mineralization is hosted by granitic pegmatite sheets and small plutonic bodies, called alaskites or pegmatoids (Berning et al. 1976; Cuney 1980, 1982). They typically intrude into epicontinental sediments (arkoses, quartzites, black shales, marls, limestones), possibly associated with acidic volcanics metamorphosed to a high grade with evidence of local partial melting. This type of environment is generally enriched in U especially in arkoses and/or acidic volcanics and in organic matter- or phosphate-bearing lithologies. The Rössing U deposit in Namibia (246,500 t) is one of the lowest-grade (300 ppm) U deposits ever mined. Similar U mineralization is known in the vicinity of Rössing at Goanikontes, Husab, Valencia and Rössing South.

The large accumulation of alaskite dykes with relatively high U grade at Rössing results from the combination of the following parameters: (1) a U-rich source represented by intracontinental platform sediments and probably by the existence of synchronous felsic volcanism developed in rift structures; (2) a low degree of partial melting of the quartz-feldspar-rich part of the volcanosedimentary sequence that explains their weakly peraluminous character and their U enrichment; (3) structural control of alaskite emplacement linked to the late kinematic evolution of the Rössing Dome (Basson and Greenway 2004); (4) a chemical barrier represented by the Rössing formation marbles, stopping the rise of the alaskitic melts as the result of skarn-formation reactions with production of carbon dioxide shifting the solidus of the melts to a higher temperature and finally leading to their accumulation in the vicinity of the marble layers; (5) a reducing barrier represented by the graphite and sulphides from the Rössing formation, which has prevented the fractionation of U in magmatic fluids at this level, and the trapping of the U from magmatic fluids deriving from alaskites crystallized at deeper structural levels under oxidized conditions and (6) favourable climatic conditions allowed the oxidation of uraninite in the weathering zone and precipitation of uranophane in fractures enriching the upper part of the deposit.

Two hypothesis have been proposed for the genesis of the primary U mineralization in the pegmatoids: (1) extreme fractionation of a deeper seated granite body, as proposed for the Grenville pegmatites in Ontario (Lentz 1996) and for Rössing by Bowden et al. (1995), or (2) partial melting of U-rich meta-sediments or meta-volcanics, as proposed for Rössing and the Mont Laurier pegmatoids, Québec (Cuney 1982). The partial melting model for the origin of the mineralized leucocratic granite dykes of the Rössing type is supported by a series of features summarized by Cuney (2010).

Hydrothermal Deposits

Volcanic-Hydrothermal Systems

Uranium deposits associated to volcanic and volcanic-plutonic complexes correspond most typically to U veins and disseminations formed in geothermal systems developed shortly after the eruption of felsic volcanic rocks. The main U districts are hosted by caldera complexes, filled with alternating mafic and felsic volcanic rocks, and subordinate amounts of sedimentary layers. Highly fractionated felsic volcanic units generally represent the largest proportion of the volcanic succession. As the pyroclastic material can be transported in the atmosphere over several tens to hundreds of kilometres, this type of volcanism may represent an essential component for additional U to sedimentary basins located far away from these volcanoes. The pyroclastic rocks represent particularly favourable source rocks because they are relatively permeable, and a high proportion of the U is hosted by the glassy matrix from which it can be easily mobilized during devitrification.

The genesis of large deposits requires also the existence of a relatively shallow magmatic chamber (a few kilometres to about 5 km) that is active over several million years to provide the heat flux and the fracturing necessary to promote focused and protracted convective fluid circulations. As a consequence, the rocks within the caldera and underlying basement are deeply altered, and U is intensively mobilized from these rocks (Chabiron et al. 2003). The U ore bodies are mainly trapped

along basement structures reactivated after the caldera filling and may extend from the volcanic pile several hundreds of metres down into the basement, as at the Antei deposit in the Streltsovskoye caldera in Russia (Chabiron et al. 2003). They may also occur along the ring structures of the caldera as at McDermitt, USA (Castor and Henry 2000), at the margin of resurgent domes as at Xiangshan, China (Hu et al. 2009) or along sedimentary layers within the caldera as at the Dornot deposit in Mongolia (Petrov et al. 2003).

Peralkaline volcanic rocks represent by far the best source for U deposit related to volcanism. The Streltsovskoye caldera, (Transbaikalia, Russia), which hosts the largest U ore field of this type in the world (22 deposits, 250,000 t U at 0.20%), shares all the preceding favourable characteristics (Ishukova et al. 1991). The caldera is very large (140 km²), filled with a up to 1-km-thick pile of alkali basalts, trachydacites and liparitic tuffs with interlayered sedimentary horizons, and the magmatic activity lasted from 170 Ma to 142±7 Ma. The early phengite–illite alteration stage (133±5 Ma) and pitchblende deposition (133±4 Ma) (Chernyshev and Golubev 1996) immediately follow the last magmatic event.

The exceptional size of the resources at Streltsovskoye also results from the juxtaposition of four main U sources: (1) liparitic tuffs which represent 30–35 vol.% of the volcanic pile, (2) Variscan high-K calc-alkaline granitoids in the basement (Chabiron et al. 2003), (3) Ordovician U mineralization in the basement (Chernyshev and Golubev 1996) and (4) fluids expelled from the volcanic melts or from underlying magma chamber. This last parameter is however minor because the U fluid/peralkaline melt partition coefficient is strongly in favour of the melt (K_{DU} fluid/melt = 3·10⁻² to 4·10⁻², Peiffert et al. 1996).

A series of similar deposits are known in Asia: in the Dornot district in Mongolia, with similar ages to Streltsovka; the Permian–Jurassic Chatkalo-Kumarinski district and the Silurian–Devonian Karamazar district in Uzbekistan; the Betpakdalinskii district in the Balkhash Lake area and the Kokchetov area in Kazakhstan; the Tchouckotka region in eastern Siberia and the

Xiangshan Cretaceous caldera in China (Jiang et al. 2005). Similar but smaller U deposits, are also known in other parts of the world such as the ones hosted by the Tertiary McDermitt caldera in Nevada (Castor and Henry 2000).

High-K calc-alkaline meta-luminous volcanic rocks are a less favourable U source because a significant but variable portion of the U in these rocks tends to be trapped in accessory minerals (Leroy and George-Aniel 1992). Most deposits related to this type of volcanism have a relatively small size.

Highly peraluminous acidic volcanics, mineralized in U, are essentially known in the Macusani district, Peru. Pitchblende and autunite occur in sub-vertical to sub-horizontal fractures in the top tens of metres of Pliocene crystal-rich flows/tuffs. A resource of 10,000 t U has been estimated for the Chapi site and 30,000 t U to the whole Macusani district at an average grade of 0.1% U (IAEA 2009).

Granite-Hydrothermal Systems

Uranium deposits related to post-magmatic high-level hydrothermal systems associated with granites are dominantly associated with two mica peraluminous leucogranites. The largest U district of this type, from which about 300,000 t U have been extracted, is the mid-European Variscan U province, which extends for more than 2,000 km from Spain–Portugal to Bohemia, through Cornwall, Brittany, French Massif Central, Vosges and the Black Forest. The mineralization may occur within the granites (the so-called intragranitic deposits) as is the case for most deposits from the French Massif Central or within enclosing metamorphic rocks (the so-called peribatholithic deposits) as the deposits from the Erzgebirge. The mineralized veins extend over a length of a few metres to several hundreds of metres and occasionally up to 1 km. The thickness of the ore bodies is commonly 1–2 m but ranges from a few centimetres to 15 m, and their vertical extension varies between tens of metres to hundreds of metres. The grade ranges from a few hundreds ppm to several% U and averages 0.1–0.3% U. Local U enrichment occurs at the intersection with lamprophyre dykes.

Other districts with U mineralization related to peraluminous leucogranites include the Yenshanian belt (upper Jurassic to Cretaceous) in South-Eastern China and the Achala batholith in Central Argentina.

In the Variscan belt, primary U deposition occurred at the Stephanian–Permian transition (270 ± 15 Ma), 30–50 Ma after the emplacement of the granites (Holliger and Cathelineau 1986; Křibek et al. 2009), during a rifting event. This event results from the late Variscan collapse of the orogenic edifice, with the formation of numerous intracontinental Permian basins. Minor U occurrences have given slightly older ages at 425 and 330–340 Ma in Vendée (Cathelineau et al. 1990). In the Saint Sylvestre granite, which hosts the major uranium resources of the French Massif Central, the richest hydrothermal mineralization occurs where brittle fracturing was superimposed to late magmatic shear zones controlling the emplacement of the late generation of U-rich fine-grained leucogranites. Highly fractionated melts and fluids, enriched in U, expelled from these granite injections, were emplaced in the late magmatic shear zones. This phenomenon has enhanced the enrichment in magmatic-hydrothermal uraninite in the coarse-grained granites in the vicinity of the late fine-grained leucogranites (Cuney et al. 1990).

Most U deposits have vein-type morphology, but de-quartzified granites (episyenites) also represent a trap for many deposits in the French Massif Central (Leroy 1984; Cathelineau 1986). Episyenite formation is associated with meteoric fluid infiltration (Turpin et al. 1990) induced by the decompression resulting from a sudden increase in the rate of basement exhumation during late orogenic uplift at about 305 Ma (Scaillet et al. 1996). During their infiltration, the meteoric fluids (0.4 wt% NaCl) are heated up to 350–400°C. When the fluids moved back towards the surface, the decompression led to their boiling and then to their condensation at about $370^\circ\text{C} \pm 25^\circ\text{C}$ and 200 ± 50 bars which led to the dissolution of quartz (El Jarray et al. 1994). The vertical extension of episyenite bodies may reach at least 1 km as observed at the Bernardan deposit (6,610 t U, 0.56%) in Western Marche.

Then, the hydrothermal fluids responsible for the leaching of uraninite are low-salinity and low-temperature (160–180°C) aqueous solutions (Dubessy et al. 1987). Uranium deposition resulted from the mixing of an oxidized meteoric fluid able to leach uraninite from the enclosing leucogranites and of a connate “heavy” fluids with $\delta^{18}\text{O} = +8\text{‰}$ to $+15\text{‰}$ and $\delta\text{D} = -45\text{‰}$ to -30‰ . The connate fluid that probably derives from an overlying Permian basin (Turpin et al. 1990; Křibek et al. 2009) may have provided the reductants (hydrocarbons and/or H_2S) for U deposition. The $\delta^{13}\text{C}$ values of the carbonates of -17.6‰ indicate an organic origin for the carbon (Turpin et al. 1990).

Hydrothermal U deposits may also present different types of relations with highly fractionated high-K calc-alkaline granites, but they are less common and generally of smaller size. At Hotagen in Sweden, the deposits occur within a Palaeoproterozoic high-K calc-alkaline granite, but they were formed during a Caledonian tectonic-hydrothermal event. The Bois Noirs–Limouzat deposit in France (Cuney 1978), with 6,920 t U at grades of 0.27% U, is hosted within a high-K calc-alkaline granite, but drilling at depth has intersected uraninite-rich peraluminous leucogranites which probably represent the major U source for the system (Poty et al. 1986). The Příbram deposit in the Czech Republic, with 42,000 t U (Křibek et al. 1999), is hosted by Late Proterozoic and Cambrian weakly metamorphosed sediments, at the south-western margin of the high-K meta-luminous to slightly peraluminous calc-alkaline granites, granodiorites and monzonites of the Blatná suite which belongs to the Carboniferous Central Bohemian Pluton. A last but the major example of relation between highly potassic calc-alkaline magmatism and uranium deposit is the Olympic Dam deposit in Australia which is hosted by the highly fractionated Roxby Down granite. This deposit will be discussed in the last section dealing with uranium deposit types.

Some other U deposits related to hydrothermal systems located at high structural level do not appear to be associated to U-rich granites.

For example, for the Upper Cretaceous Schwartzwalder deposit, Colorado, USA (Wallace and Whelan 1986), (3,600 t U, 0.37%), the U source remains unknown.

Diagenetic-Hydrothermal Systems

Diagenetic-hydrothermal systems correspond to fluid circulations through porous fluvial, lacustrine, deltaic to near shore siliciclastic sediments, more rarely limestones during or after their burial. This leads to the formation of a large variety of epigenetic U deposit types. The diagenetic fluids are brines which may mix with infiltrated meteoric fluids. According to the location of the redox control within the basin and their depositional or structural environments, these deposits are subdivided into five subtypes.

Tabular Intraformational Redox Control Deposits

They are transitional with the syn-sedimentary deposits, because U may begin to precipitate shortly after sedimentation and burial, but more extensively during diagenesis. Ore bodies are conformable with the stratigraphy and form within coarse sandy layers intercalated between less permeable clay-rich horizons, generally at the margins of palaeochannels. Volcanic ashes within the sandstones commonly represent a major source of U and other elements (Mo, Zr). Uranium is generally leached under oxidizing and slightly acidic conditions, but interaction with volcanic ashes can make the solutions more alkaline. The fluids transporting U are generally low-temperature basinal brines. In the Grants region, USA, Hansley and Spirakis (1992) proposed that U was transported by brines expelled from evaporites.

Reduction of U in sandstone is controlled by the organic matter present as debris of fossil plants or layers of authigenic, or migrated organic material (humates), either with bacteria as a catalyst or through the production of biogenic hydrogen sulphide (Spirakis 1996). In sandstones, relatively poor in organic material, the reduction of U may be caused either by H₂S (biogenic and/or non-biogenic) produced from the interaction of oxidized groundwaters with pyrite or by H₂S

and/or hydrocarbons injected along structures from deep hydrocarbon reservoirs (Spirakis 1996). Major tabular deposits are those from the Grants region, Colorado, where over 240,000 t U at 0.09–0.21% have been mined. A few are known in Australia (Beverley, Honeymoon, Four Miles...), but many more have to be expected in this country with further exploration.

Tectonolithologic Intraformational Redox Control Deposits

The ore bodies are controlled both by the host lithology, permeable palaeochannels rich in reducing organic compounds as in the preceding deposit types, but together with a strong tectonic control. Typical examples are the deposits from the Arlit–Akouta area in Niger (Pagel et al. 2005). Two types of U sources can be considered: (1) the erosion of the U-rich volcanic and granitic complexes of the Air massif and (2) the acidic peralkaline volcanic tuffs dispersed in the different sedimentary formations from Devonian to Jurassic (Forbes et al. 1984).

In tectonolithologic deposits, mineralizing fluids are also diagenetic brines. For the Akouta deposit in Niger, temperatures of 85–175°C and salinities of 15–22 wt% NaCl have been estimated (Forbes 1989). The fluids were alkaline, as attested by the abundance of carbonate and analcime in the sediments, and oxidizing. The processes controlling ore deposition are similar to those described for tabular deposits and for some of the roll-front deposits. Uranium mineralization occurs in coarse-grained immature and permeable sandstones deposited in a fluvio-deltaic environment of the Guezouman and Tarat formations. At a more detailed scale, the mineralization is preferentially located in bottom-set layers and along basal fore-set layers of palaeochannels where the organic matter is preferentially accumulated and replaced by pyrite providing abundant reductants (Sanguinetti et al. 1982).

The Arlit–Akouta uranium district in Niger is one of the largest one with tectonolithologic deposits with about 115,000 t U already mined and more than 70,000 t U as identified resources at 0.2–0.4% U.

Diagenetic-Hydrothermal Karsts

They are generally called solution collapse breccia pipes. They are mainly known in the Grand Canyon region in Arizona, USA, but similar occurrences have been reported in China. In the Grand Canyon region, they form near-vertical, 30–175 m large, cylindrical pipes, located in flat-lying upper Palaeozoic to Triassic marine platform sediments (Wenrich and Titley 2009). Solution (karstification) of the Mississippian Redwall Limestone started mainly along and at intersections of fracture sets. Overlying strata have collapsed up to a distance of 1,000 m. Thousands of pipes are known but only about 100 of them are variably mineralized. Average ore grades vary from 0.4% to 1% U, and resources from some hundreds to 1,500 t U. Pitchblende associated with Cu-sulphide, arsenide and arsenic-sulphosalt minerals and locally bitumen occurs as disseminated replacements and minor fracture fillings.

The fluids in ore-related sphalerite, dolomite and calcite with homogenization temperatures of 80–173°C and salinities of 4–17 wt% equiv. NaCl were of probable diagenetic origin, derived from deeper part of the basin (Wenrich and Titley 2008). Temperatures, salinities, the Cu > Zn > Pb (± Ag, Co, Mo, Ni, V) sulphide paragenesis associated with the U ores, the ages of deposit formation and the presence of sulphur-rich bitumen are similar to those of Mississippi Valley-type (MVT) deposits. Two mineralization events have been dated at 260 and 200 Ma (Ludwig and Simmons 1992), a timing corresponding to a period of stability in the Pangea, that allowed many MVT deposits to form throughout the world.

In South China, Devonian–Carboniferous unmetamorphosed carbonate rocks host several deposits (Sanqilinyi, Sanbaqi and Saqisan), sharing many of the characteristics of the Arizona breccia pipes (Min et al. 2002). They occur in solution collapse breccias and solute on-fault breccias mineralized with pitchblende, coffinite and Fe, Cu, Pb, Zn and Ni sulphides. The matrix of the breccia is composed of organic matter, clays and limestone fragments. The deposits seem to result from the superimposition of an early

syn-palaeokarstic U mineralization associated with organic matter and a saline basinal brine percolation event at 110–251°C driven by a late Yanshanian tectonic event, enriching the U ore.

Basin/Basement Redox-Controlled Deposits

They are usually termed unconformity-related deposits because they are generally located in the vicinity of an unconformity between a metamorphic basement and an undeformed clastic sedimentary cover. The basement usually comprises Archaean granitic domes rimmed by U-rich and graphite-rich metamorphosed Palaeoproterozoic epicontinental sediments intruded by granitic bodies. The base of the basins consists of oxidized continental fluviatile, aeolian to marginal marine, highly mature, siliclastic sediments. The two main provinces hosting this type of deposit are the Athabasca Uranium Province, Saskatchewan, Canada and the East Alligator River Uranium Province, Northern Territory, Australia. Other U deposits which share some of the characteristics basin/basement redox-controlled deposits are those related to the Proterozoic basins of Thelon in Nunavut (Fuchs and Hilger 1989); Otish in Northern Québec (Gatzweiler 1987); Pasha Ladoga in Karelia, with the Karku deposit (Velichkin et al. 2005); and the metamorphosed Coolbro Sandstone in Australia, with the Kintyre deposit (Hanly 2005).

Possible U sources of unconformity-related deposits were the basement rocks and the sandstone cover. Archaean rocks underlying the Athabasca Basin are mainly composed of U-poor tonalites and cannot have represented a U source, but in the Northern Territory, high-K–Th–U Archaean granites do exist (Nanambu Complex). Palaeoproterozoic sediments which rim the Archaean domes in both provinces consist of epicontinental clastic to chemical deposits. Calc-silicates and meta-arkoses, as well as leucogranites and pegmatoids derived by partial melting of the Palaeoproterozoic meta-sediments, are enriched in uraninite and represent particularly easily leachable U sources (Sibbald et al. 1976; Annesley et al. 2003). Additional potential U sources are the Palaeoproterozoic U–Th-rich

high-K calc-alkaline granitoids. Also, late Hudsonian vein-type U deposits (e.g. Beaverlodge, Gunnar) demonstrate the ability of the Palaeoproterozoic basement to represent a favourable U source to form these deposits, but they may also themselves have contributed as U sources to the unconformity-related deposits.

Another alternative proposed by several authors is that the sandstone cover represents the main U source. However, the average U content of the regional sandstones is below 1 ppm, and 50–80% of this U is presently bound to zircon. Only the monazite destruction may have represented a significant U source, as in the Franceville basin, Gabon, with the extraction of about 75% of its U (Mathieu et al. 2001; Hecht and Cuney 2000). The average Th content of the sandstones being generally below 10 ppm, the amount of U deriving from monazite alteration, with a Th/U of about 20, was limited. Moreover, a significant part of the liberated U was trapped in altered zircons (U increases from a few hundred to several thousand ppm), but not leached out as proposed by Fayek and Kyser (1997), and in Fe–Ti oxides deriving from detrital Fe–Ti oxide alteration. Therefore, the strong U enrichment of the Palaeoproterozoic basement is preferred as the major source of U for the genesis of such large high-grade deposits.

Uranium solubility was favoured by the high fO_2 and chlorinity (up to 6 molal) of basal diagenetic brines. High fO_2 resulted from the lack of organic matter when the sandstones were deposited in continental environment during the lower Palaeoproterozoic. The pH, controlled by the kaolinite–illite–quartz paragenesis, was slightly acidic. Detrital feldspar was lacking or has been altered during diagenesis. Early diagenetic brines in detrital quartz overgrowths are Na rich and derive from evaporitic layers present in the upper parts of the basins, whereas the brines trapped later in pervasively silicified zones and drusy quartz, close to the mineralized zones, were enriched in Ca through their interaction with Ca-rich basement lithologies (Derome et al. 2003, 2005). Laser ablation ICP-MS analyses (Richard et al. 2010) reveal that the Ca-rich brines

are the richest in U with contents reaching several hundreds of ppm. Temperature and pressure close to the unconformity decrease from the early diagenetic (160–220°C, 1–1.25 kbar) to the ore stage (140–160°C, 0.6 kbar), (Derome 2003, 2005).

The oldest U mineralization age obtained so far is ca 1,590 Ma, from LA-ICP-MS U–Pb dating of uraninite and ^{40}Ar – ^{39}Ar dating of syn-ore illite, for both basement- and sandstone-hosted deposits (Alexandre et al 2009). This event and younger U–Pb ages also obtained on uraninite, interpreted as remobilization events, are attributed to several episodes of hydrothermal circulation resulting from far-field, continent-wide tectonic events. However, it is still uncertain if all the U has been deposited during a single event or if accretion of multiple stages of U deposition have occurred.

Most unconformity-type deposits are related to tectonic contraction, leading to reverse faulting along Hudsonian graphite–sulphide-bearing basement faults. If faulting is important to rejuvenate the permeability of the structures, the magnitude of the displacements is not always sufficient to create significant openings. Quartz dissolution represents another major way of creating a huge space permitting the deposition of massive U mineralization (Lorilleux et al. 2002).

To explain U reduction, as well as the source of Mg and B in the alteration envelopes and of the metals (Ni, Co, Cu, Zn, Au) in the polymetallic deposits, a basement-derived reduced fluid has been proposed by various authors. However, direct evidences for such a reduced fluid are still very weak.

In conclusion, if the degree of U and graphite enrichment of the basement and the intensity of quartz dissolution were some of the key factors explaining the genesis of the high grade – large-size unconformity-related – deposits, the extreme reactivity of the oxidized, acidic, highly saline, Ca–Na brines generated at the base of thick Proterozoic sandstone basins (free of organic matter and K-feldspar) able to scavenge U even from very refractory minerals seems to be the most important key factor.

Interformational Redox-Controlled Uranium Deposits

They are characterized by the location of the redox barrier to the upper part of an oxidized sandstone formation below an oil generating shale formation as exemplified by the deposits (Oklo, Mounana, Okelobondo, ...) of the Early Proterozoic Franceville Basin in Gabon (Gauthier-Lafaye 1986). The Francevillian series correspond to a 4–5-km-thick, unmetamorphosed, sedimentary sequence deposited at about 2.1 Ga. At the base of the basin, the FA formation (500–1,000 m thick) is mainly composed of conglomerates and fine- to coarse-grained, fluvial to deltaic sandstones (Weber 1968). The overlying FB formation consists mainly of organic matter-rich marine shales. All the U deposits of the Franceville basin are located in the upper part of the FA formation, immediately below the redox boundary represented by the FB black shales (Gauthier-Lafaye 1986). Uranium deposition has been dated by U–Pb discordia at 2.05 ± 0.03 Ga (Gancarz 1978). The ore forming fluids are very similar to those of unconformity-related deposits with 28.7 wt% NaCl to 30 wt% CaCl_2 eq. and trapped at 135–155°C and 1 kbar (Mathieu et al. 2000). Detrital monazites are also widely altered in the FA formation. The amount of U liberated during monazite alteration is here largely sufficient to account for the U in all the U deposits (27,635 t U at 0.38%) of the Franceville basin (Cuney and Mathieu 2000). Then, U transported by the diagenetic brines has been precipitated at the redox interface between the FA and FB formations.

Metamorphic Systems

After diagenesis, with increasing temperature and pressure, U deposits can also be formed during the circulation of metamorphic fluids in association with folding, faulting and/or thrusting of the rocks. The lowest grade of metamorphism associated with the most important release of fluids from the sediments is the most favourable for the formation of U deposits related to such processes. More specifically, during the metamorphism of epicontinental platform sediments, oxidized brines expelled from evaporitic layers, extremely

efficient for transporting U, may mix with hydrocarbons produced by black shales, for the precipitation of U. Uranium deposited by metamorphic fluids generally occur in veins. Typical examples are the Mistamisk U veins from Labrador, Canada (Kish and Cuney 1981), and some, if not all, U deposits of the Copper Belt, as exemplified by the Shinkolobwe deposit (25,500 t U, 0.40%) (Ngongo-Kashisha 1975; Audeoud 1982), in the Democratic Republic of Congo and deposits from Zambia (Meneghel 1979) such as the Kansanshi deposit (Křibek et al. 2005). They have all been formed during very-low-grade metamorphism at $350^\circ\text{C} \pm 50^\circ\text{C}$ of sediments deposited in epicontinental settings. ~~Highly saline oxidized brines deriving from evaporitic layers have transported U, and deposition has occurred by mixing with hydrocarbons derived from black shale layers (e.g. Kish and Cuney 1981).~~

At higher temperature, the metamorphic origin of the deposits is rarely well constrained. Many of them, if not all, are in fact metamorphosed deposits. For example, the Tiraun deposit in Switzerland considered as syn-metamorphic by von Pechmann and Bianconi (1982) corresponds in fact to a metamorphosed U mineralization. The Mary Kathleen skarn-hosted U deposit (10,176 t U at 0.11%), Australia, initially attributed to contact metamorphism (Cruikshank et al. 1980), is in fact temporally disconnected from the granite intrusions (1,740–1,740 Ma) and has been related to a later metamorphic event (at $1,550 \pm 15$ Ma). Conversely, the Lagoa Real U district (100,000 t U at 0.12%), Brazil, which genesis was related to the Brazilian metamorphic event (at about 550 Ma) by Lobato et al. (1983), is in fact much older, 1,450 Ma according to Turpin et al. (1988), or even older, at 1,870 Ma according to Chavès et al. (2007), and in fact represents a U deposit metamorphosed by the Brazilian event.

Metasomatic Systems

Na-Metasomatism-Related Deposits

Na-metasomatism is a widespread geological process that occurs in a large variety of conditions, but only some specific occurrences are associated with U ore genesis. Na-metasomatism

generally affects large volume of rocks, within which the mineralization occurs in a core of the alteration zones showing the most advanced stage of alteration. Na-metasomatism is ~~most commonly~~ developed in felsic rocks to form albitites, but it may ~~extend through granites and~~ meta-volcanic or meta-sedimentary rocks. In felsic rocks, K-feldspar and plagioclase are replaced by albite, quartz is dissolved and newly formed albite is deposited in the vugs left by quartz together with the deposition of U. In the largest mineralized districts of this type, the albitites form discontinuous zones extending over several tens of kilometres. Individual Na-metasomatic zones are normally several metres wide and several hundreds to several thousands of metres long. This alteration is associated with deep regional structures as best exemplified in the U district of Central Ukraine (Belevtsev and Koval 1968). Fluids associated with these processes derived from either or both a basinal brine or a magma as proposed for the Valhalla U deposit in Queensland, Australia, (Polito et al. 2007), or from the surface, as in the central Ukrainian U deposits (Cinelu 2008). Some authors consider that these deposits are related to metamorphic processes (Kushev 1972; Lobato et al 1983), others to post-granite emplacement hydrothermal circulation (Kazansky and Laverov 1978; Turpin et al. 1988). The geodynamic conditions and drivers responsible for the development of the largest U ore fields associated with Na-metasomatism are still poorly recognized.

The Michelin deposit (36,800 t U at 840 ppm) from Central Labrador, Canada, is hosted by deformed and recrystallized ash flow tuffs and porphyritic rhyolites with interbedded clastic sedimentary rocks and basalts belonging to the Palaeoproterozoic Aillik Group, but the major U concentration step is associated with typical Na- and Ca-metasomatism (Gandhi 1978).

Worldwide, it is remarkable that U mineralization associated with Na-metasomatism seems to occur mainly during one major period of Earth history, between 2.0 and 1.5 Ga with the central Ukraine district (180,000 t U) (Scherbak and Bobrov 2005), Kurupung (2,750 t U) in Guyana (Cinelu and Cuney 2006), Skuppesavon (690 t U

at 700 ppm) (Smellie and Laurikko 1984) and Pleutajok (4,000 t U at 0.10%) (Adamek and Wilson 1977) in Sweden, Morocco (Idir and Renard 2002), Liangshanguan (3,000 t U) in China (Jiarong and Zhutian 1988) and Lagoa Real (100,000 t U at 0.12%) in Brazil (Chavès et al. 2007). A far less important Na–U event is associated with the Pan-African–Brazilian orogenesis (500 ± 50 Ma) with deposits of: Espinharas (8,000 t U) (Ballhorn et al. 1981), Itataia, for the early hydrothermal phase affecting granite sheets (67,700 t U at 0.08%) (Netto 1983), both to the north-east of Brazil, and Kitongo (11,000 t U at 0.09%) in Cameroon (Vels and Fritsche 1988). The Coles Hill deposit in Virginia (45,000 t at 0.05%) in the USA is probably of Mesozoic age (Jerden and Sinha 1999).

Uranium deposits associated with Na-metasomatism represent a largely underexplored model. Vast domains of Palaeoproterozoic crust have not been evaluated for this type of deposit. Moreover, resource estimations from some districts like Lagoa Real in Brazil and Michelin in Canada remain underestimated because they have been evaluated by relatively shallow drilling (some hundreds of metres), whereas the Ukrainian district shows that such type of mineralization may extend down to 2 km or more.

Skarn-Related Deposits

They are associated to metasomatic processes generally occurring during contact or regional metamorphic events. Therefore, they can be also classified as metamorphic U deposits. The Mary Kathleen U–REE skarns in Australia are hosted in Palaeoproterozoic amphibolite-grade metamorphosed calc-silicate, mafic to intermediate igneous and sedimentary rocks. The sediments correspond to impure carbonates, sandstones and evaporates deposited in a shallow water shelf setting. A first phase of metamorphism and deformation (1,750–1,730 Ma) was accompanied by emplacement of granitic and mafic bodies and rhyolitic dykes. Skarns result from an extensive hydrothermal system by interaction between the volatile- and U–Th-rich high-K calc-alkaline Burstall Granite emplaced at 1,737 ± 15 Ma and

the enclosing calc-silicates and highly saline fluids derived from evaporates (Oliver et al. 1999).

A first phase of U and REE enrichment is presumed to have occurred in the skarns, at or near the present orebody (Maas et al. 1987). During the second phase (1,550–1,500 Ma), upper amphibolite facies conditions were reached (600–650°C, 3.5–4 kb) with a new phase of highly saline hydrothermal activity producing intense scapolitization in the sediments and the main phase of U–REE mineralization dated at $1,550 \pm 15$ Ma by Page (1983). Disseminated minute grains of uraninite enclosed in allanite or along veins are exclusively associated with the zones of retrogressed massive garnet $\pm$ diopside skarns (McKay and Mieztis 2001). Fluid inclusions in apatite recorded temperatures up to 500°C with 30–50% dissolved solids. The present U–REE mineralization (8,550 t U at 0.11%) at Mary Kathleen may correspond to a metamorphosed deposit with recrystallization of an older, granite-related U–REE mineralization, upgraded during a later metamorphic hydrothermal event.

The uranothorianite-bearing pyroxenites of Tranomaro, Madagascar, represent an extreme type of U deposit, hosted by skarns (Moine et al. 1985), but in fact, they correspond more to a Th deposit because the Th–U ratios higher than 1 and thus will be described in the Th resources section.

Syn-sedimentary U Deposits

Syn-sedimentary U deposits in marine environments are formed during sedimentation in shelf environments and essentially comprise U-rich black shales and phosphorites. These syngenetic U enrichments do not always reach a grade sufficient to make economically exploitable deposits at the present time, but they constitute potential resources for the future. They also represent an extremely favourable environment for the subsequent development of other types of U mineralization through additional concentration steps, for example partial melting or hydrothermal remobilization in a large variety of T–P–X condi-

tions. Three major types of syn-sedimentary U deposits can be distinguished according to the main mechanism controlling U deposition during sedimentation: (1) mechanical sorting, (2) redox trapping and (3) crystal-chemical and redox trapping.

Mechanical Sorting

This is the main process controlling the genesis of the quartz-pebble conglomerates (QPC) deposits. They represent the first U deposits formed on the Earth, ~~in an intracontinental setting~~. The earliest ones are hosted by the Dominion group in South Africa, deposited between $3,086 \pm 3$ Ma and $3,076 \pm 6$ Ma (Frimmel and Minter 2002); the latest ones are hosted by the Elliott Lake Group in Eastern Canada and were deposited between 2,496 and 2,215 Ma (Corfu and Andrews 1986). The two endmember models proposed for their genesis vary from a purely syngenetic origin, the placer model, with a detrital deposition of uraninite in fluvial to fluvio-deltaic environments (Frimmel et al. 2005), to an epigenetic origin with U precipitating from hydrothermal fluids (Barnicoat et al. 1997) or a combination of both in the modified placer theory (Pretorius 1961). The controversy is of crucial importance, the placer model being one of the major arguments for the existence of very low oxygen levels in the atmosphere prior to about 2.3 Ga. A series of features such as the high Th contents of the uraninites and their magmatic REE patterns strongly support a detrital origin of the primary uranium concentration (Cuney 2010). Later remobilization of the primary uraninite has ~~certainly~~ occurred, but is not significant for the ultimate origin of the metal accumulation. Historic production from this type of deposit is 246,000 t U, and identified resources reach 547,900 t U.

Redox Trapping

In shallow water marine environments, large amounts of U may accumulate adsorbed on organic materials and clay minerals in organic- and pyrite-rich black shales, also named oil shales. The largest deposits are the Cambro–Ordovician alum shales of the Ranstad area in

Sweden (Andersson et al. 1985) and the Chattanooga and the New Albany shales in the USA (Nash et al. 1981), but the Silurian graptolitic black shales of the Ronneburg-Gera deposits in Germany are the only deposits of this type which have been mined to any large extent because of their higher grades (169,230 t U at 850–1,700 ppm U) which are a result of a combination of hydrothermal and supergene enrichments (Lange and Freyhoff 1991). The Cambrian–Ordovician alum shales in southern Sweden are devoid of secondary enrichments. They represent U resources over 1 Mt U, and the Ranstad deposit alone contains ~254,000 t U at 170–250 ppm U. The alum shale has been deposited in shallow marine waters of the Iapetus Ocean. It contains up to 25 wt% organic carbon, and U and associated trace elements (Mo, V, Ni, Zn, Cu) are clearly syngenetic. The preferential U enrichment in the vicinity of the palaeoshores is interpreted to reflect a more vigorous bottom water circulation that promoted higher rates of mass transfer across the sediment/water interface relatively to the sediments deposited farther away. In the most enriched Upper Cambrian biozone (Peltura scarabaeoides Zone), the U enrichment is inversely correlated to the thickness of the zone, reflecting the low rate of detrital particle supply. The Kolm beds formed by resuspension of the sediments in an anoxic water column that favour U adsorption during diffusive exchanges between suspended particles and seawater may reach 1,000–8,000 ppm U (Schovsbo 2002).

In continental environments, coal, lignites, organic-rich bog peats, swamps, closed anoxic lakes, which may still be forming today, and also karst caverns represent other environments prone to concentrating surficial U accumulations generally in the order of a few tens of ppm (Morales et al. 1985). In such organic-rich environments, U can be deposited by adsorption on the organic material and/or by reduction of UO_2^{2+} by the anaerobic bacterial activity. Uraniferous lignite deposits in Kazakhstan and China contain from 20,000 to 50,000 t of U with U contents between 500 and 2,000 ppm. Several of these deposits

have been mined. China is presently testing U extraction from coal or lignite ash.

Crystal-Chemical and Redox Trapping

These are the main mechanisms of U fixation in the sedimentary phosphates. The sedimentary phosphates probably represent the largest (possibly up to 15–22 Mt U) low-grade U repository which may become a resource in a near future. It would be more sustainable to extract U during phosphoric acid fabrication rather than to spread fertilizers with 10–200 ppm U in the agricultural fields (Yamazaki and Geraldo 2003). Phosphorite deposits formed along shallow continental shelf from upwelling of nutrient-rich marine waters promoting intense development of living organisms onto a shallow continental shelf with restricted circulation. The organic matter and biologic activity has an important role in accumulation of U by oceanic phosphorites for its reduction (Baturin and Kochenov 2001). U^{4+} is a proxy for Ca^{2+} in the apatite structure, but a fraction of the U may also precipitate outside of the apatite structure together with other metals. The largest episode of phosphate deposition occurred during the late Cretaceous to Eocene (90–45 Ma) period, under the same palaeolatitude (8–15°N), along the southern margin of the Tethys Ocean. The phosphorite belt extends from Turkey to Morocco and beyond across the Atlantic to Colombia and Venezuela. The global Late Cretaceous sea-level rise, the circum-equatorial Tethyan oceanic circulation, associated with a northward Eckman offshore transport of surface waters arising from dominant easterly winds, have resulted in upwelling of nutrient-rich waters along the southern Tethys shelves and deposition of an organic and phosphate-rich sequence (Soudry et al. 2004). Morocco hosts a large part of the world resources of this type (6.9 Mt U, with average U contents of 50–150 ppm, IAEA 2001). However, most of the world production from phosphorites was extracted from Miocene–Pliocene phosphorites of Florida (17,150 t U) (Cathcart 1978) and in Kazakstan (40,000 t U). Small amounts of U have also been extracted from imported phosphates in Belgium (686 t U).

Meteoritic Water Infiltration

Basal-Type or Sealed Palaeovalleys Deposits

They are generally located in colluvium between a U-rich granitic basement and a basalt cover and are named palaeovalley or infiltration-type in Russian literature (e.g. Vitim deposits, Transbaikalia, Russia, Kondrat'eva et al. 2004). The basal-type U deposits are probably the equivalent of these deposits in the western countries. The colluvium is composed of poorly consolidated, highly permeable, fluvial to lacustrine, organic matter-bearing gravels and sands deposited in palaeovalleys incised in igneous and metamorphic rocks. It is capped by a low permeable cover consisting of plateau basalts or sediments. Uranium is leached from the granitic basement and precipitates by reaction with the organic matter during groundwater percolation in permeable sediments, between two aquitards: the basement and the basalt cover. The Blizzard deposit in Canada, with resources of 4,000 t U at 0.21% (Boyle 1982), the Tono deposits in Japan (5,000 t U at 500 ppm) and the Saint Pierre du Cantal deposit in the French Massif Central, which has produced 1,304 t U (Carré 1979), are typical examples of this type.

Roll-front deposits represent the best example of epigenetic U deposition at a redox interface (front). Host rocks are younger than Ordovician and were deposited in fluvial to lacustrine environments in intermountain basins, as in the Tertiary Powder River Basin in Wyoming (Adams and Cramer 1985), or in marine marginal plains, in channel, lagoonal and beach-bar settings on the marine marginal plains (Finch and Davis 1985). The source of U may be U-rich granites or volcanics external to the sediments and/or syn-sedimentary U deposited in reducing conditions or intercalated U-rich volcanic ashes. The reduced sandstone is buff, grey, grey-green or black coloured due to disseminated organic matter and/or pyrite and occurs down the hydrologic gradient relative to the oxidized sandstone. The reduction may be either of syn-sedimentary

origin, resulting from the maturation of detrital plant debris during diagenesis, or may be epigenetic, induced by the infiltration of hydrocarbons or H₂S migrated from deep oil reservoirs along faults (South Texas, Goldhaber et al. 1978; Kazakhstan, Aubakirov 1998; Ordos basin, China, Cai et al. 2007). The migration of hydrocarbons in the Ordos basin, China, is directly evidenced by the presence of oil/gas inclusions in the calcite cement and healed fractures in quartz grains. Bacterial sulphate reduction may be involved in some roll-front deposits (Dongsheng district, north of the Ordos basin, China, Cai et al. 2007) as pyrite aggregates intimately intergrown with coffinite have large variations in $\delta^{34}\text{S}$ values ($-34\text{‰} < \delta^{34}\text{S} < +18\text{‰}$) typical of bacterial reduction. In most proposed models, U is transported by oxidized low-temperature meteoric waters infiltrated through permeable sandstones confined between two aquitards corresponding to mudstone. The reduced sandstone is oxidized and takes a pink-red colour due to hematite, or a yellow-orange colour due to limonite, or even may become white grey when iron has been totally leached out. Uranium deposition is controlled by the interplay of the permeability of the sediments, the distribution of reducing components and for some of them by bacterial activity. In some other occurrences, interbedded mafic volcanics may also play a role in the reduction processes. The resulting orebodies exhibit C-shapes in cross section and are sinuous along the roll-front interface. In the Inkai deposit, Kazakhstan, they may extend laterally up to more than 100 km. Uranium ore minerals are typically pitchblende or/and coffinite. Resources associated with this type of deposit are very important and reach over 1 Mt U for Kazakhstan.

Evapotranspiration

Calcretes

These deposits are known from Tertiary to present time, in surficial continental environments. Most commonly, they are hosted by surficial

1211 sediments deposited in fluvial to lacustrine/
1212 playa systems, which have not been subjected to
1213 significant burial and may be cemented by a
1214 variety of minerals: calcite, gypsum, dolomite,
1215 ferric oxide, strontianite or halite and uranyl
1216 minerals. The cement results of the fluctuation
1217 of the groundwater level and of evapotranspira-
1218 tion in arid to semi-arid climatic conditions. The
1219 economically important calcrete are referred to
1220 as valley calcretes by Carlisle et al. (1978), but
1221 the ore bodies are hosted in fact by highly imma-
1222 ture, porous, fluvial valley-fill sediments.

1223 The U source is most commonly U-rich gran-
1224 ites or acidic volcanics which are weathered in
1225 large catchment areas, and the associated V is
1226 generally derived from mafic rocks or shales.
1227 Uranium is leached and transported by slightly
1228 alkaline, oxidizing surface waters or shallow
1229 groundwaters and carried as uranyl carbonate
1230 complexes. During downflow migration, water
1231 alkalinity and salinity increase due to progressive
1232 evaporation. In valley calcrete deposits, basement
1233 highs along the valley represent barriers to the
1234 groundwater flow, directing it towards the surface,
1235 where evaporation sharply increases, inducing
1236 CO₂ degassing, and the breakdown of the uranyl
1237 carbonates. The predominance of vanadates (car-
1238 notite and tyuyamunite) in these deposits is due to
1239 their solubility, two orders of magnitude lower
1240 than that of other uranyl minerals, in the pH range
1241 5–8.5 (Langmuir 1978). Mann and Deutscher
1242 (1978) propose that V transported as V⁴⁺ com-
1243 plexes in slightly reduced groundwater is oxidized
1244 to V⁵⁺ by mixing with highly oxidized groundwa-
1245 ter transporting U in uranyl carbonates, thus
1246 resulting in carnotite precipitation. Increasing K⁺,
1247 V⁵⁺ and U⁶⁺ activities in the solution during evap-
1248 oration of upwelling groundwaters also helps for
1249 carnotite deposition.

1250 Calcrete deposits are known in Australia,
1251 Namibia, South Africa, Mauritania, Somalia,
1252 Jordania, USA (called caliches), Argentina and
1253 China. The largest ones are the Langer Heinrich
1254 (63,520 t U at 510 ppm) and Trekkopje (42,360 t
1255 U at 100 ppm) deposits in Namibia and those of
1256 Yeelirrie (44,520 t U at 1,270 ppm), Lake
1257 Maitland (9,190 t U at 260 ppm) and Lake Way
1258 (3,900 t U at 460 ppm) in Australia.

Other Types

1259 *Uranium mineralization associated with IOCG*
1260 *deposits*, mainly represented by the Olympic
1261 Dam iron oxide Cu–Au (U–Ag–REE) deposit
1262 (IOCG deposit) in South Australia, are classified
1263 in this category because too little information is
1264 available about the U mineralization process and
1265 the mechanism of U deposition within the deposit,
1266 from studies of the author, does not seem to result
1267 from a single process. Mineralization occurs in a
1268 zoned hematite–breccia complex hosted by the
1269 Roxby Downs Granite, one of the most fraction-
1270 ated high-K calc-alkaline granite of the Hiltaba
1271 suite, and dated at 1,588 ± 4 Ma (Creaser 1996).
1272 The breccia complex extends approximately over
1273 5–7 km along a NW–SE direction and over more
1274 than 1 km at depth. Granite emplacement is con-
1275 temporaneous with the extrusion of the Gawler
1276 Range Volcanics (Reynolds 2000). Dating indi-
1277 cates that magmatic activity, brecciation and
1278 Cu–Au mineralization are synchronous (Johnson
1279 and Cross 1995). The Olympic Dam ore genesis
1280 is related to the unmixing of a hot, high-saline
1281 fluid from a granitic magma which then mixes
1282 with oxidized meteoritic fluids (Hitzman et al.
1283 1992). The high Cl–S ratios of the fluids com-
1284 pared to other hydrothermal systems are the rea-
1285 son for very low enrichments in Pb and Zn,
1286 elements weakly soluble in S-poor fluids.

1287 Compared to other IOCG deposits such as
1288 those of the Conclurry district in Queensland,
1289 Olympic Dam is entirely hosted within U–Th-
1290 rich high-K calc-alkaline granites and volcanics.
1291 In the mineralized breccias, U minerals are repre-
1292 sented both by finely dispersed euhedral uranin-
1293 ite crystals, typical of a high-temperature
1294 mineralization, and by much more abundant
1295 botryoidal pitchblende, coffinite and U–Ti oxides
1296 in veins corresponding to lower temperature
1297 deposition. Hitzman and Valenta (2005) proposed
1298 that leaching of U from the wall rocks by the
1299 hydrothermal fluids produced the enrichment in
1300 the IOCG deposits. Uranium enrichment in the
1301 ore is 10–40 times larger than in unaltered host
1302 rocks. The only available age determined on
1303 pitchblende at 1,400 Ma, is from an unpublished
1304 report of Trueman et al. (1988). This means either
1305

that pitchblende have been re-equilibrated during a later hydrothermal event with radiogenic Pb loss, or has been deposited 190 Ma after the formation of the diatreme. The last interpretation would mean that the main stage of U deposition may be much younger than the IOCG system. Therefore, a more detailed study of the U mineralization process is clearly needed for IOCG deposits and especially in the Olympic Dam deposit, by far the largest U deposit of the world, with resources of 1.9 Mt U at 340 ppm, but U is produced as a by-product of Cu, Au and Ag ores.

A series of other deposits, such as those located in limestone, marbles or related to K-metasomatism need further research to be classified according to the present genetic scheme. The Tumallapalle deposit hosted by metamorphosed stromatolitic dolomitic limestone is being mined in India in the Proterozoic Cuddapah basin in Andhra Pradesh state; mineralization has been dated by Pb–Pb isotopes at $1,756 \pm 29$ Ma (Zachariah et al. 1999). The non-metamorphosed equivalent of this type of mineralization is possibly represented by the Mesozoic Todlito lacustrine limestone, New Mexico, USA (Gabelman and Boyer 1988). The U mineralization seems to be epigenetic and is controlled primarily by permeable zones developed during folding and secondarily by joints.

The Itataia deposit hosted in graphitic marbles and alaskitic dykes also remains quite unique (Netto 1983). The first ore stage, occurring in the alaskites, shares the same characteristics as Na-metasomatism-related deposits, but the vugs left by quartz dissolution are filled with xenomorphic zircon aggregates, coffinite, sulphides, organic matter and idiomorphic apatite. The main ore stage corresponds to a hydrothermal karst developed in the marbles and filled with massive pink U-bearing colophane.

The Elkon deposit, located in the Sakha Republic of eastern Asian Russia, is also an unusual type of U deposit with vein stockworks associated with K-metasomatism and gold mineralization (Kazanskii 2004 and references therein). Total resources of the Elkon district are estimated in excess of 324,000 t U, at an average grade of 0.1–0.15% U, and with gold values ranging from less than 1 ppm to several ppm (wise-uranium.org). Host rocks are Archean to Palaeoproterozoic

high-grade metamorphic rocks. The mineralization is controlled by NW–SE striking and steeply SW dipping faults reactivated during the Mesozoic and by pyrite–carbonate–potassium feldspar altered rocks. Three main stages of alteration separated by brecciation episodes have been recognized: (1) pyrite (Au, Ag)–ankerite–orthoclase, (2) pyrite(Au, Ag)–dolomite–orthoclase and (3) calcite–adularia, all associated with de-quartzification and Na loss. The only primary U mineral is brannerite; Boitsov and Pilipenko (1998) distinguish three U ore varieties: gold–brannerite, gold–uraninite and brannerite–silver–gold mineralization. Temperatures of the U mineralization were 160°C and 250°C according to fluid inclusion temperatures. U–Pb isotopic dating gives ages of 135–130 Ma for the primary brannerite which correlates with the emplacement of Early Cretaceous monzonite and nepheline syenite intrusions (Boitsov and Pilipenko 1998).

Unconventional Resources

According to the IAEA, unconventional resources represent resources from which uranium can only be recovered as a minor by-product, such as U associated with phosphorites, non-ferrous ores, carbonatites, black shales, lignite and seawater. However, this definition may evolve with the uranium prices and technological improvements, and some of these resources, like uranium from black shales or from phosphorites, may become a major resource in the future.

Other significant non-conventional resources which have to be considered are the following:

- Several projects are being developed in the world (many in South Africa and also in the Czech Republic, Kyrgyzstan and Tajikistan) for reprocessing the tailings produced during previous uranium or other metal extraction. For example, the company Rand Uranium, created by Harmony Gold and USA-backed Pamodzi Resource Fund, is currently estimating the feasibility of reprocessing tailings for Au and U extraction in the Randfontein/Westonaria region, Witwatersrand, South Africa.
- About 1,100 t U have been already recovered from lignite ash from 1964 to 1967 produced in

1401 North Dakota, USA. Recently, an agreement 1444
 1402 has been signed in 2007 between Sparton and 1445
 1403 the Xiaolongtang Guodian Power Company of 1446
 1404 Yunnan, China, to test the extraction of U from 1447
 1405 coal ash produced by the burning of lignite coal. 1448
 1406 This coal has a high ash content (20–30%) and 1449
 1407 an average U content of 65 ppm (20–315 ppm). 1450
 1408 With an average U content of 125 ppm, annual 1451
 1409 coal ash produced from three power stations 1452
 1410 contains about 150 t U. Assuming a U recovery 1453
 1411 rate of 70%, 105 t U/year could be produced. 1454
 1412 – U may also be extracted from monazite recov- 1455
 1413 ered from sand placers if REE and Th produc- 1456
 1414 tion from this resource restart in the future. 1457
 1415 Monazite from sand placers typically contains 1458
 1416 several thousands ppm U. 1459
 1417 – U has been recovered from porphyry copper 1460
 1418 operations from ores from the USA and Chile 1461
 1419 with very-low-grade U contents (tens of ppm). 1462
 1420 It is probable that several presently mined ore 1463
 1421 deposits contain significant levels of U which 1464
 1422 may have not been checked to avoid additional 1465
 1423 regulations specific for radioactive materials. 1466
 1424 Recently, the Talvivaara Ni–Zn mine, with 1467
 1425 15–20 ppm in the ore, announced ([www.tal-](http://www.talvivaara.com) 1468
 1426 [vivaara.com](http://www.talvivaara.com)) a production of about 350 t U/ 1469
 1427 year from the leach solution with 25 mg/l U. 1470
 1428 – Some tens of tons of U are produced each year 1471
 1429 from water treatment processes associated 1472
 1430 with the management of former U mines and 1473
 1431 tailings. For example, about 38 t of U has been 1474
 1432 produced in 2007 at the Königstein mine in 1475
 1433 Germany from cleaning of mine water ([www.](http://www.world-nuclear.org) 1476
 1434 [world-nuclear.org](http://www.world-nuclear.org)). 1477

1435 Thorium Resources

1436 Introduction

1437 The average abundance of Th in the Earth's crust
 1438 is about 5.6 ppm, but Th is enriched in the upper
 1439 crust with 10.5 ppm. At high temperatures,
 1440 Th commonly has the same behaviour as U and is
 1441 deposited together with rare earth elements (REE)
 1442 in a great variety of minerals. The most important
 1443 Th minerals are monazite $[(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4]$

with a few hundreds of ppm up to 26.4% Th), ura- 1444
 nothorite $[(\text{Th}, \text{U})(\text{SiO}_4)]$ with up to 38% UO_2 1445
 and thorianite $[\text{ThO}_2]$ which forms a continuous 1446
 solid solution with uraninite $[\text{UO}_2]$. Other miner- 1447
 als that contain smaller amounts of Th are allanite 1448
 $[(\text{Ce}, \text{Ca}, \text{Y}, \text{Th}, \text{U})_2(\text{Al}, \text{Fe}, \text{Mg})_3(\text{SiO}_4)_3(\text{OH})]$ 1449
 with up to 4.35% Th), bastnäsite $[(\text{Ce}, \text{Th}, \text{La}, \text{Y},$ 1450
 $\text{Ca})(\text{CO}_3)\text{F}]$ with up to 41% Th), betafite–euxen- 1451
 ite–pyrochlore $[(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6]$, 1452
 brockite $[(\text{Ca}, \text{Th}, \text{Ce})\text{PO}_4 \cdot \text{H}_2\text{O}]$, xenotime 1453
 $[(\text{Y}, \text{U}, \text{Th})\text{PO}_4]$ with up to 2.2% Th), fluorapatite 1454
 $[\text{Ca}_5(\text{PO}_4)_3\text{F}]$ and zircon $[\text{ZrSiO}_4]$. Thorogummite 1455
 is a product of the alteration of thorite caused by 1456
 hydration induced by its metamictization. Many 1457
 of the Th-bearing minerals are remarkably resis- 1458
 tant to weathering because ThO_2 has a very low 1459
 solubility at low temperature; therefore, Th tends 1460
 to become enriched in the oxidized zones of most 1461
 Th deposits. Its solubility strongly increases with 1462
 decreasing pH. At a pH of 3, Th solubility reaches 1463
 100 ppm as a sulphate complex. For example, Th 1464
 is deposited in acid hot spring concretions in 1465
 Th-rich quaternary alkali basalts in Italy. At low 1466
 temperature, Th is strongly adsorbed on limonite 1467
 and clay minerals. At high temperature, Th solu- 1468
 bility is enhanced primarily as an F-complex, but 1469
 the Cl , PO_4 and CO_2 anions may also markedly 1470
 increase its solubility. In addition, there are a 1471
 number of hydroxide, silicate and phosphate 1472
 complexes (Langmuir and Herman 1980). 1473
 Thorium occurs in a large variety of deposit 1474
 types: 1475
 1. Placer deposits which corresponds to sands 1476
 enriched in heavy minerals 1477
 2. Carbonatites (e.g. Fen in southern Norway) 1478
 3. Alkaline and peralkaline igneous complexes 1479
 (e.g. Ilimaussaq in Greenland) 1480
 4. Pegmatites (e.g. pegmatoids from anatectic 1481
 domains as in the Mont Laurier district, 1482
 Canada) 1483
 5. Thorium-bearing veins and lodes (e.g. the 1484
 Lehmi Pass veins in the USA) 1485
 6. Quartz-pebble conglomerates (e.g. Witwa- 1486
 tersrand and Blind River–Elliot Lake 1487
 deposits) 1488
 7. Skarns and hornfels deposits (e.g. the 1489
 Mary Kathleen deposit, Tranomaro district, 1490
 Madagascar) 1491

The main source of the world's Th until recently was the monazite. Monazite is recovered as a by-product of processing heavy-mineral sands mainly for the extraction of ilmenite, rutile, leucoxene and zircon. Thorium itself is a by-product of refining monazite for its REE content. However, future production will probably come from bastnaesite in the carbonatites and from thorite in the Th veins.

Early use of Th mainly resulted from the very high melting point of ThO_2 (3,300°C). In non-energy applications, Th was used as chemical catalyst, light bulb elements, lantern mantles, arc-light lamps, welding electrodes and heat-resistant ceramics. The production reached about 1,000 t in the 1970s and has decreased thereafter. A continuous oversupply of Th on the market was caused by the production of REE from monazite. Increased costs related to increasing regulatory constraints have progressively limited monazite commercial value, and non-radioactive substitutes have been developed (Hedrick 2008). For example, between 1980 and 1995, 165,000 t of monazite was mined in Western Australia, and most of the production was exported to France for extraction of REEs, but the monazite plant in France has closed because its operators were unable to obtain a permit for a disposal site for Th and its decay products. The total amount of Th which has been produced worldwide until 1987 is estimated at 39,000 t (IAEA 1987): 17,000 t in the USA, 8,000 t in Australia, 6,000 t in China, 4,000 t in India, 2,000 t in Germany and 2,000 t in France as purified Th nitrate. Some quantities have been also produced in Canada, Malaysia, Brazil, Turkey and the former USSR. The production of Th is presently of some hundred tonnes per year (IAEA 2002).

World Resources

It is generally believed that Th resources should be three to four times larger than the U resources because the Clarke concentration of Th is three to four times larger than that of U. However, such a statement does not take into account the differences of chemical properties between U and Th. Uranium has two valence states, U^{4+} and U^{6+} , and

is very soluble under the oxidized state, as UO_2^{2+} . Thorium has only one valence state, Th^{4+} , and has a low solubility at low to intermediate temperature. This property has several major consequences: (1) Th minerals can be concentrated physically in placer-type deposits as resistates, (2) most other Th deposit types are formed in magmatic and high-temperature hydrothermal environments, and (3) metallurgical extraction of Th from ores requires more costly processes than for U.

Most Th resource estimations correspond to potential resources because specific exploration and comprehensive resource estimation of Th deposits have never been really undertaken. For example, in China, a substantial amount of Th is produced annually as a by-product of the huge REE production at Bayan Obo, in Inner Mongolia, but the only available resource estimation dates back to 1984. The estimates of the Th resources mainly date from exploration made in the 1950s–1980s for U and thus are uncertain. Hence, detailed investigations of the resources as well as ore processing tests should be performed before it can be decided whether the Th resources can be defined as an economical asset. Thorium resources are found in a variety of countries and are compiled in Table 3.

Thorium resources are dominantly associated with peralkaline magmatic complexes: first in carbonatites, then in vein-type occurrences generally deriving from magmatic fluids expelled from carbonatites and in peralkaline rock complexes (Table 4, Fig. 2). Placer-type deposits with monazite represents one quarter of the world resources.

Thorium as a Nuclear Fuel

More than 99.99% of natural Th is ^{232}Th , the rest are ^{230}Th and ^{228}Th . Although not fissile itself, ^{232}Th is fertile and absorbs slow neutrons to produce ^{233}U , which is fissile. The main factors generating interest in Th as a potential fuel in nuclear reactors with respect to U result from the fact that (1) the Th fuel cycle produces much less Pu and other transuranic elements and thus may present less problems in waste disposal; (2) highly radioactive actinides are “burnt” because the Th fuel

Table 3 World thorium resources by country

Country	Global resource	Identified (10 ³ t Th)	Prognosticated (10 ³ t Th)
Australia ^a	489	13	476
USA ^b	432	440	274
China ^c	–	–	380
Turkey	880	344	400–500
India	319	319	–
Brazil	1,306	221	329–700
Venezuela	–	300	–
Norway	180	132	132
Egypt	295	100	280
Russia		75	–
Greenland		54	32
Canada	173	44	128
South Africa	115	18	130
Malaysia ^b		–	4.5
CIS ^d	1,650	–	–
Others	388	33	81
Total	6,227	2,053	2,655–3,126

Sources: IAEA (2006)

Identified Resources (*RAR* reasonably assured resources + *EAR-1* estimated additional resources) are estimated at a cost of USD 80/kg

^ahttp://www.australianminesatlas.gov.au/aimr/commodity/thorium_09.jsp, taking into account an arbitrary 10% loss during the mining and processing of Th from an initial estimate of 543,700 t Th

^bUSGS commodities evaluation 2010

^cWorld Mining. Annual review. 1984

^dUSGS has deleted in 2010 the resources for Norway in its report because of the poor evaluation of the occurrences

^eCIS = Commonwealth of Independent States. Among the other countries having Th resources mainly as placer deposits are Madagascar, Liberia, Burma, Thailand, Indonesia, Sri Lanka and Bangladesh.

Data from many countries of the world are lacking, and many of the figures are based on assumptions.

USGS data are reported in ThO₂ whereas all others are given in Th with the same numbers!

Table 4 Thorium resources (in 1,000 t Th) classified according to major deposit types (IAEA-NEA 2007)

Deposit	Resource	%.
Carbonatite	1,900	31.26
Placer	1,500	24.68
Vein-type	1,300	21.39
Alkaline rocks	1,120	18.43
Other	258	4.24
Total	6,078	100.00

Including prognosticated resources, the total reaches over 6 Mt Th. The differences between with the estimations of Table 3 result from the different costs and degrees of geological assurance used

water U reactors; (5) virtually all of the Th is potentially useable in a reactor, compared with the 0.72% ²³⁵U of natural U and (vi) ²³³U is a better fuel than ²³⁵U and ²³⁹Pu because of its higher neutron yield per neutron absorbed. So, theoretically, one unit mass of natural Th could produce about 40 times more energy than the same amount of natural U (i.e. U²³⁸ + U²³⁵). 1970s data indicated that a 1,000 MWe Th fuel reactor requires an initial loading of ~40 t Th and ~10 t of highly enriched U (~90% U²³⁵) and annual reloading of ~10 t Th. Compared to the present needs of 67,000 t of natural U for the 435 U-fuelled reactors, 500 Th-fuelled 1,000-MWe reactors would have an annual demand of about 5,000 t of Th only. Hence, the 3-Mt world-identified Th resources would be enough to last 500 Th-fuelled reactors 600 years.

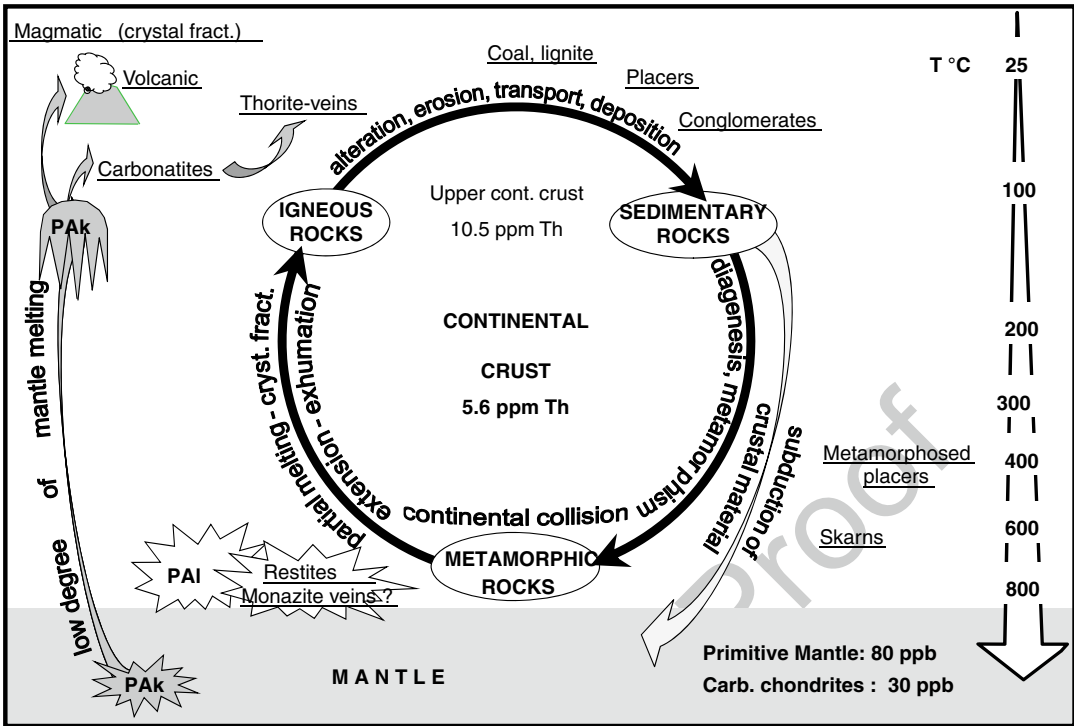


Fig. 2 Position of the major thorium deposit types along the geological cycle, the major thorium reservoirs of the Earth and the major magmatic associations associated with Th deposits. *PAk* peralkaline, *HKCa* high-K calc-alkaline, *PAI* peraluminous (Cuney)

[AU8]

1606 Only a few commercial-scale Th-fuelled
1607 nuclear reactors have been developed in Germany
1608 and the USA in the 1970s–1980s but shut down
1609 in late 1980s. Presently, the Moscow’s Kurchatov
1610 Institute is developing a Th–Pu fuel for feeding
1611 existing Russian Vodo-Vodyanoi Energetichesky
1612 (VVER)-1,000 reactors, partly to burn up stocks
1613 of Pu, in a joint program with the US company
1614 Thorium Power and US government funding.
1615 Fissile ²³⁹Pu fuel is placed in the centre of the
1616 reactor and the Th around it ([http://www.world-](http://www.world-nuclear.org/info/info.html)
1617 [nuclear.org/info/info.html](http://www.world-nuclear.org/info/info.html), May 2007). India is
1618 also building a 470-MWe fast breeder reactor
1619 that will use a Th-fuelled blanket with anticipated
1620 completion in 2010. India is also currently testing
1621 components for a 300-MWe technology demonstrator
1622 Th-fuelled reactor for completion towards
1623 2020. The development of a full scale Th-fuelled
1624 commercial Th reactor in India is scheduled
1625 for 2030.

Thorium Deposits

1626
1627 During partial melting and fractional crystalliza-
1628 tion in the mantle, Th has a strongly incompatible
1629 behaviour similar to that of U and other highly
1630 charged and/or large ionic radius elements (U,
1631 REE, Zr, Nb, ...). This behaviour is particularly
1632 enhanced in peralkaline magmas because of their
1633 high degree of depolymerization resulting from
1634 the high temperature of these melts and their
1635 excess in alkalis with respect to the quantity of
1636 alumina necessary to make the feldspars (Peiffert
1637 et al. 1996; Cuney 2009). The excess of alkalis
1638 appears as feldspathoids, sodic-pyroxenes and
1639 amphiboles and other alkali-rich phases. Hence,
1640 Th, U, REE, Zr and Nb are enriched together in
1641 peralkaline silicate melts, and the initial Th–U
1642 chondritic ratio of 3–4 tends to be preserved
1643 (Cuney and Kyser 2008). Thus, in ore deposits
1644 resulting from the fractional crystallization of

peralkaline magmas, Th will tend to be three to four times more abundant than U. Like for U resources in this type of magmatism, Th is bound to refractory minerals together with the REE, Zr and/or Nb. As a consequence of these properties, a large part of Th deposits are directly or indirectly related to peralkaline magmatism: (1) carbonatites which generally represents the last phase of peralkaline complexes, (2) magmatic fluids mainly deriving from carbonatites leading to Th deposition in metasomatized rocks (fenites) or in veins associated or not with U, REE, Zr and Nb and (3) quartz saturated or undersaturated acidic plutonic, pegmatitic or volcanic rocks (Fig. 2).

Deposits Related to Crystal Fractionation

Peralkaline igneous rocks generally originate from low degree of partial melting of the mantle followed by more or less extensive fractional crystallization. The U-, Th-, REE-, Zr- and Nb-mineralized bodies represent always the most fractionated parts of plutonic complexes (Cuney and Kyser 2008). Peralkaline complexes are known all over the world (Fitton and Upton 1987; Woolley 1987, 2001; Kogarko et al. 1995). ~~The Illimaussaq complex in southern Greenland and the Lovozero and Khibini alkaline massifs in the Kola Peninsula USSR, the caldera of Poços de Caldas in Brazil and the alkaline syenite body at Pilanesberg, South Africa, are among the best known.~~ They are typically anorogenic, zoned or layered, enriched in Na or K. They contain an extremely large variety of Th–U-bearing minerals.

Acidic Plutonic, Pegmatitic or Volcanic Rocks

Some granites, pegmatites and syenites may be strongly enriched in Th and associated elements. ~~They are generally high level post-orogenic intrusions.~~ They represent a large reserve of Th and U for the future. The Bokan Mountain peralkaline granite in the USA and the silica undersaturated Illimaussaq peralkaline complex in Greenland, already described as a U resources in the preceding section, represent also two to three times larger Th resources than U resources, the average chondritic ratio being essentially preserved during fractionation. Hence, the U resources of

Illimaussaq being estimated at 85,000 t U and using an average Th–U ratio of 3 for the deposit, a resource of 255,000 t Th is obtained.

The Lovozero massif in Russia's Kola Peninsula, emplaced during Upper Devonian at the same time as the Khibiny massif, is one of the world's largest peralkaline complexes, with an area of 650 km². It is unique regarding the abundance and diversity of Th mineralization (Ermolaeva et al. 2007). In the peralkaline pegmatites and veins of Lovozero, Th has segregated into complex but specific Th minerals such as umbozerite Na₃Sr₄Th(Mn,Zn,Fe,Mg)(Si₈O₂₄)(OH), Ti–Th silicates Na_{0–7}Sr_{0–1}ThTi_{1–2}Si₈O_{22–23}(OH).nH₂O and Na–Th silicates (Na,K)₄Th₃[Si₈(O,OH)₂₄].nH₂O, thorite, steenstrupine–thorosteensrupine series members and Th phosphate (Th,Na,K,Ca,Mg,U,Sr,Ba)[(P,Si,AlO₄),nH₂O].

The Thor Lake Be, Y, REE, Nb, Ta, Zr and Ga deposits in the Great Slave Lake district, Canada, are related to the nearly circular (16 by 33 km) Blatchford Lake peralkaline complex (Davidson 1982). The Blatchford Lake complex consists of a suite of gabbro, quartz syenite and granite, intruded by the hypersolvus reibeckite Grace Lake Granite and then by the hypersolvus reibeckite Thor Lake Syenite. The Thor Lake Syenite has been dated by U–Pb in zircon at 2,094 ± 10 Ma, respectively (Bowring et al. 1984). Principal radioactive minerals are zircon and bastnaesite with minor REE-rich apatite and monazite. Felsic dykes within the Grace Lake Granite and Thor Lake Syenite are one order of magnitude richer in U and Th than the host rocks. Most mineralized zones occur within the western part of the Thor Lake Syenite. The deposits are related to albitite or greisens. Accessory minerals include zircon, uranothorite, allanite, magnetite, hematite, columbite, pyrochlore, carbonates, bastnaesite and lanthanite. U occurs in an east–west trending pegmatite dyke complex that can be traced over a strike length of 2.5 km and widths of up to 400 m. An indicated resource of 4.06 Mt at 183 ppm Th (743 t Th) and an inferred resource of 122.3 Mt ore at 173 ppm Th (21,158 t Th) have been estimated from the data published by www.avalonraremetals.com (March 2009) taking the lowest cut off at 1.6% REEO.

The Sæteråsen trachyte (Permian Oslo graben, Norway) has high concentrations of Zr, Nb, Y, REE and Th (490 ppm) in euxenite, pyrochlore, chevkinite, fergusonite and apatite (Ihlen 1983). Mineral separation performed in 1980 showed, however, that the trachyte was difficult to exploit with respect to these metals as it is very fine-grained. A preliminary estimate gives 8 Mt of ore at 490 ppm Th.

In the Høgtuva Palaeoproterozoic granitic orthogneiss occurring in basement windows of the Caledonides in Norway, another potential resource for Be, Zr, REE, U and Th has been identified. The resource has been drilled for Be and contains 0.5 Mt of rocks with 500 ppm Th (Lindahl 2007).

The Brockman Zr, Hf, Nb, Ta, Y, REE, Ga and Be deposit in Western Australia is hosted in the “Niobium Tuff,” a fluorite-bearing rhyolitic volcanoclastic unit of the Halls Creek Group (Taylor et al. 1995). Up to 371 ppm Th has been reported by Ranstead (1994), but no resource evaluation is available.

Carbonatites

With 1.9 Mt Th, more than 31% of the world Th resources are concentrated in carbonatites. Carbonatite occurrences have been reviewed in North and South America by Woolley (1987), in the former USSR by Kogarko et al. (1995) and in Africa by Woolley (2001). Carbonatites generally contain some tens of ppm Th; however, some may reach several hundreds of ppm, such as the carbonatites from the Gardar Province in Greenland contain with up to 843 ppm Th (Upton and Emeleus 1987). An extremely large variety of Th minerals can be present: pyrochlore, monazite, apatite, perovskite, titanite, zircon and baddeleyite and also less frequently thorianite, thorite, betafite, cerite, bastnäsite, xenotime, allanite and aeschynite. However, in the present market conditions, carbonatites do not represent a commercial source of Th. Carbonatite-related deposits can be subdivided into deposits generated by magmatic and/or magmatic-hydrothermal processes and those enriched by supergene processes.

Magmatic carbonatite-related deposit is best represented by the *Araxá carbonatite*, in Brazil, a Cretaceous ring complex of approximately

4.5 km in diameter, which not only represent the largest Nb deposit of the world (495,000 t at 2.5% Nb₂O₅), but probably also the largest Th deposit. Thorium resources have been estimated to more than 1,200,000 t ThO₂ mainly hosted by pyrochlore in the Barreiro deposit with additional resource in the Área Zero deposit (30,000 t Th, IAEA 2002). The magmatic incompatible element enrichment has been strongly enhanced by ~~lateritic weathering~~ by carbonate dissolution.

The Mountain Pass deposit in California/USA is associated with a peralkaline intrusive complex composed of eight 100/2,000-m-long plugs of alkaline intrusions (shonkinites, syenites and carbonatites) and about 200 dykes of carbonatite, emplaced at 1.4 Ga. The Sulphide Queen carbonatite, which represents the main intrusion of this type in the complex, is tabular. The reserves were estimated at 29 Mt at 8.9% REO, mostly hosted by bastnaesite, the second in importance after Bayan Obo. The Th resource of ~~mountain pass~~ is not known, but the bastnasite has relatively low Th (about 100 ppm), but thorite has been also described. The carbonatite is likely derived from an enriched mantle source (Castor 2008).

The Late Cretaceous Poços de Caldas intrusion in Brazil is one of the largest peralkaline complexes of the world, about 28 km in diameter, emplaced between 78 and 76 Ma (Schorsch and Shea 1992). Similar to Ilimaussaq, it is composed of a silica-undersaturated highly potassic igneous suite. The igneous complex forms a nearly perfect circular ring structure of caldera type. ~~About 1,000 t U has been mined from the Cercado deposit.~~ A Th–REE mineralization exists within the caldera at Morro do Ferro, with about 30,000 t of Th and 100 t of U, as uranotorite and fluorcarbonates. The deposit results from the weathering in lateritic conditions of a carbonatite body (Waber 1992).

The Fen Complex in Telemark (600 Ma), Norway, mainly consists of søvite (calcite carbonatite), rauhaugite (dolomite carbonatite), rødberg (hematite–calcite–carbonatite) and fenite (alkali-metasomatized granitic gneiss). The highest concentrations of Th are found in the iron-rich rocks rauhaugite and rødberg, with concentrations ranging from 0.4 to 0.13 wt% Th. The US

Geological Survey has estimated reserves of about 170,000 t Th and resources of 150,000 t Th. However, the scientific basis for these old estimates is somewhat unclear, and they have not been confirmed by the Norwegian Geological Survey. Moreover, separation of very fine-grained ore minerals is a great challenge for processing the ore. Thus, the Fen carbonatite rather represents a chemical reserve.

The peralkaline Palabora intrusive complex was emplaced at about 2030 ± 18 Ma in north-eastern Transvaal, South Africa (Eriksson 1984). In the central part of the complex, phoscorite and carbonatite form the Loolekop pipe (1.4 by 0.8 km). This pipe has been intruded by a dyke-like banded carbonatite. The main U- and Th-bearing mineral is uranothorianite, $(U, Th)O_2$, which is recovered as a heavy mineral together with baddeleyite and processed for U production (Verwoerd 1986). ~~The uranothorianite contains more Th than U.~~ With an average grade of 0.01% Th, the carbonatite should contain about 10,500 t Th for every 100 m of depth (Verwoerd 1986).

The Bayan Obo deposit in Inner Mongolia, China, is a giant polymetallic REE–Fe–Nb ore deposit of hydrothermal origin which hosts 70% of the world's REE resources (Yuan et al. 1992; Chao et al. 1992). It is located on the northern edge of the North China craton, near the suture of the Caledonian subduction of the Mongolian plate beneath the craton. It is hosted in marble and quartzite that were metamorphosed prior to mineralization. Replacement textures provide evidence for the epigenetic, hydrothermal and metasomatic origin of the ore deposit. Hydrothermal activity evidences range from 1.26 Ga to beyond 343 Ma. Monazite and bastnaesite U–Pb ages indicate that the episodes of REE mineralization lasted about 150 Ma (555–395 Ma). The most abundant REE minerals at Bayan Obo are monazite, bastnäsite and huanghoite $[Ba(Ce, La, Nd)(CO_3)_2F]$. The main Th minerals include thorianite and thorite. Thorium also occurs as isomorphic substitution in the REE–Nb minerals, REE–fluorocarbonate minerals and aeschynite-type minerals (Luo et al. 2010). However, the Th content and a recent evaluation of the resources of this deposit are

lacking. The monazites and bastnaesites of Bayan Obo ores are typically very low in U (<5 ppm) but have up to 7,000 ppm Th. Pb and Nd isotopes from Bayan Obo ore and gangue minerals indicate a crustal origin for the REEs (Wang et al. 1994). Chao et al. (1995) propose that the REEs and associated elements were scavenged from the underlying crust by acidic hydrothermal solutions activated by Caledonian subduction.

Several carbonatite occurrences in Australia, such as the Mount Weld, Cummins Range and Yangibana carbonatite complexes, are also considered as potential Th resources. The mineralization results from primary magmatic enrichment of the incompatible elements further upgraded by supergene alteration in the case of the Mount Weld and Cummins Range occurrences. The 2.0 Ga Mount Weld carbonatite complex is a large, high-grade Y, Nb, Ta, P, Zr, Ti and REE resource (Duncan and Willett 1990; Lottermoser 1990) where the REE are contained in secondary monazite relatively poor in Th. The typical Th content of the deposit is about 600 ppm (Mernagh and Mieztis 2008). In the Cummins Range carbonatite complex, the main Th minerals are monazite, pyrochlore, bastnäsite, aeschynite, baddeleyite, pandaite and thorianite (Andrew 1990; Richards 1985). About 500 ppm Th has been measured in the top 48 m of weathered zone in one drill hole (Richards 1985). The Yangibana ferrocarbonatite–magnetite–REE-bearing dykes in the Gascoyne Province of Western Australia occur as lenses and pods from 2 to 25 m in width and traceable for up to 25 km (Pearson et al. 1996). They are typically the last stage of a peralkaline complex fractionation enriched in REEs, fluorite and U–Th. Grab sample values vary from 1,062 to 5,230 ppm Th. Th is mainly hosted by monazite and bastnäsite.

Deposits Related to Partial Melting

During partial melting of the continental crust of peraluminous material, at low temperature, the produced magmas are strongly polymerized, and this will severely limit the dissolution of large and highly charged elements (U, Th, LREE, Zr)

in the silicate melts (Peiffert et al. 1996; Montel 1993). Therefore, the most abundant large and highly charged elements (Th, LREE, Zr) will be already saturated during partial melting and enter into the structure of accessory minerals (monazite, zircon, uranothorite). These accessory minerals will concentrate into the restitic material. Generally, these accumulations are of limited size and essentially correspond to centimetres to metres long biotitic selvages of migmatites in high-grade metamorphic domains. Thorium concentrations may reach several tens to hundreds of ppm. During the extraction of a silicate melt, the accessory minerals may be transported as a suspension through channelways essentially concordant with the local metamorphic foliation on variable distances. Then, they may locally form larger accumulations in veins, concordant or discordant with the local metamorphic foliation when the most mobile fraction of the silicate melts depleted in these elements escapes towards higher structural levels along tectonic structures.

Such occurrences are known in many high-grade metamorphic domains such as the Mont Laurier pegmatoidic veins of the Grenville belt in Canada (Cuney 1982), the Th- and U-bearing leucocratic granitic rock and pegmatite–aplite dykes from the Bancroft area of Ontario, in the Namib desert of Namibia, in the Charlebois Lake area of northern Saskatchewan and on the north shore of the St. Lawrence River in Québec (Cuney and Kyser 2008). Similar occurrences occur at Crockers Well in South Australia where thorianbrannerite occurs in sodic granitic and felsic gneisses (Ashley 1984).

Deposits Related to Metasomatic Systems

Metasomatic Th deposits occur in marbles in high-grade metamorphic domains generally at the contact with granitic intrusions but sometime with no visible intrusion at least at the level of observation and may result from magmatic or metamorphic fluid infiltration.

The uranothorite-bearing pyroxenites of Tranomaro, South–East Madagascar, represent

an example of a Th and U deposit hosted by skarns (Moine et al. 1985). A metasomatic zonation may be developed between granite injections and marbles, dominantly controlled by a bimetasomatic exchange of Ca and Si between the two lithologies, but the granites are not always outcropping. The main mineralization is associated with skarns composed of non- or poorly mineralized meionite-bearing endoskarns and highly mineralized Al-diopside–spinel–corundum exoskarns. Uranothorianite is the main ore mineral. A later episode of mineralization, of minor importance, corresponds to fluorophlogopite–fluoropargasite–uranothorianite–REE-rich hibonite veins. Fluid circulation responsible for metasomatism and U–Th mineralization is synchronous with granulitic metamorphism from 850°C to 800°C and 5–3 kbar. Although CO₂ was a major fluid in the metasomatic reactions, fluorine has played a major role in the complexing and simultaneous transport of Th, U, REE and Zr in the skarns (Moine et al. 1998). Most of the Th–U ratios of the mineralized rocks are between 2 and 3, close to the average crustal ratio and thus indicate a simultaneous enrichment in U and Th. It is proposed that the fluids involved in the metasomatic reactions and Th–U–REE–Zr mineralization are derived from the oversaturation of the granitic melts injected in the Tranomaro metamorphic series and from the devolatilization reactions occurring at depth during granulitic metamorphism (Boulvais et al. 1998). From 1955 to 1968, the French Atomic Energy Commission (CEA) and private companies have produced 1,030 t of U and 3,218 t of Th, thus corresponding to an ore with an average Th–U ratio of about 3.

The Mary Kathleen deposit is hosted in the Corolla Palaeoproterozoic formation close to the contact with the foliated, coarse-grained Th–U-rich Burstall Granite. The Corolla formation (1,780–1,760 Ma) is composed of metamorphosed evaporates, calc-silicate rocks, marble, meta-pelites, meta-psammities and minor metavolcanics. To its western margin, the Burstall Granite is cut by a network of microgranite and rhyolite. Two main phases of hydrothermal activity and associated metasomatism were recognized.

Phase 1 (1,750 and 1,730 Ma) corresponds to the emplacement of granitic and mafic bodies and the formation of large garnet/pyroxene skarns with minor U and REE ($\pm$ Th) mineralization (Holcombe et al. 1992). During phase 2 (1,550–1,500 Ma), upper amphibolite facies was reached with intense scapolitization of the Corolla formation (skarns 2) together with U, REE and Th mineralization (Oliver et al 1999). The hydrothermal fluids involved in the two phases were highly saline and are assumed to be derived from the evaporitic Corolla formation sediments (Oliver et al. 1999). The mineralization consists essentially of allanite and uraninite is disseminated throughout the allanite zones. Mary Kathleen is considered to be a skarn-hosted metamorphic–metasomatic-hydrothermal deposit. The global resource within the orebody has been estimated at 10,200 t U at 0.11% U, with 3.0% REOs and 220 ppm Th. Hence, the resource of the Mary Kathleen deposit can be estimated at about 2,040 t Th.

Deposits Related to High-Temperature Hydrothermalism

Uranothorite Veins

These deposits are widely distributed throughout the world but are relatively rare. They are localized at shallow crustal levels, in shear zones, faults, breccia zones and diatremes in meta-sedimentary and meta-volcanic rocks, and generally associated with carbonatites, but such rocks have not always been identified. Narrow fenitized (alkali-metasomatized) wall-rock selvages may occur adjacent to veins and dykes. The main Th-bearing minerals in the deposits are thorite, thorogummite, monazite and brockite. They are frequently associated with various REE minerals (allanite, bastnäsite, xenotime, cenosite, florencite and synchysite). Quartz, hematite and/or magnetite, feldspar, micas, carbonates, barite, apatite, fluorite and rutile are the common gangue minerals. Some deposits show transitional features between the primary magmatic concentrations disseminated within the most fractionated

part of peralkaline magmas or carbonatite and vein systems such as at Eskisehir in Turkey, at Batan Obo in China and at Mountain Pass in California, USA.

The Nolans Bore deposit in the Northern Territory, Australia, has world-class characteristics, in terms of size and grade of REE, P, U and Th. It occurs as veins and lodes, localized in shear zones, fractures, stockworks, breccia zones and in two zones over a strike length of about 2 km. Four styles of REE mineralization have been recognized (http://www.arafuraresources.com.au/nol_geo.html): (1) massive fluorapatite dykes with 4–6% REE, (2) high-grade REE ore with 10–20% REE found in cheralitic apatite-poor rocks, (3) calc-silicate-hosted apatite–allanite–epidote REE mineralization and (4) zones of low-grade REE mineralization in gneisses (Hussey 2003). The average Th content of Nolans Bore fluorapatite is 0.23% Th (0.07–0.59%) (Hussey 2003). According to Mernagh and Mieziitis (2009), this high Th content suggests that the Nolans Bore deposit is not related to a carbonatite, or to fluids derived from them, but is more likely to hydrothermal fluids associated with an NYF-type pegmatite.

The Lemhi Pass District, Idaho and Montana, is characterized by quartz–thorite–hematite veins, shears and brecciated zones and monazite–thorite–apatite-bearing shears and replacements with biotite and alkali feldspar. Allanite and monazite are locally abundant, and brockite and xenotime may also occur. They are typically fine-grained and coloured in pink to brown as a result of the abundant hematite and thorite. Within the Lemhi Pass district, Staatz (1979) mapped 219 Th–REE veins. The veins range from 1 m to over 1,325 m in length and from a few centimetres to 12 m in width. The Last Chance vein (1,325 m long and 3–8 m wide) represents the largest individual Th resource in the district. The ten largest veins, with an average grade of 0.43% ThO₂, represent 95% of the district's identified Th resources.

Mineralization has not initially been linked to any specific intrusives in the district. However, the possible presence of an underlying buried

peralkaline complex possibly associated with carbonatites is indicated by the occurrence of: (1) carbonate minerals in many of the veins, (2) one breccia pipe with a calcite matrix adjacent to a mafic dyke, (3) a few carbonate-bearing mafic dykes and (4) a syenite and an ultramafic sill of possible carbonatitic affiliation (Gillerman 2008). A direct relation of Th deposits characterized by the iron oxides, apatite, REE and F association with alkaline intrusive or carbonatite complexes is observed in the Powderhorn district in Colorado (Van Gosen and Lowers 2007). Numerous other Th vein occurrences exist in the USA: Wet Mountains district in Colorado, Capitan Mountain and Laughlin Peak in New Mexico and Bokan Mountain district in Alaska.

In the Eskisehir-Sivrihisar district, in Turkey, the Kizilcaören F–Ba–Th–REE deposit is mainly hosted by anchimetamorphic sediments and rarely trachytic tuffs and breccia pipes adjacent to alkaline porphyritic trachyte and phonolite. Five breccia pipes occur in the area. Two different phase of carbonatite injection during late Oligocene have been distinguished: a first one occurring as dykes up to 1.5 m in width and a second one occurring as dykes ranging in size 1–10 cm cutting the breccia pipes and veins. Fracturing, brecciation and mineralization are associated with the carbonatite intrusions. The mineralization infills radial circular and funnel-shaped fractures and breccia pipes. During the first stage, predating the brecciation event, fluorite and barite are mainly deposited. The second stage corresponds to Th-rich bastnaesite with minor fluocerite, brockite, florencite and monazite deposition after the brecciation. The deposit has been interpreted as formed by the upwelling of carbonatitic magmatic fluids guided by circular, radial and funnel-shaped fractures. Temperatures of 550–300°C and 300–190°C have been obtained for the first and second stage, from fluid inclusion studies. Reserves are of 380,000 t of ore at 0.2% ThO₂ and 3% REE (Stumpfl and Kirikoglu 1985). Additional Th reserves also occur at Kuluncak, Hekimhan and Malatya (Gültekin et al. 2003), and total resources may reach 880,000 t Th.

Monazite Veins

The Mesoproterozoic Steenkampskraal monazite vein in South Africa is the largest of a number of vein-type monazite–apatite–chalcopyrite–magnetite deposits occurring in the Namaqualand high-grade metamorphic complex in South Africa (Andreoli et al. 1994), a totally different setting than the thorite veins always emplaced at shallow crustal levels. The vein intrudes the Roodewal Suite composed of charnockites, tonalites and enderbites. The deposit is tabular in shape with a thickness varying from 30 to 90 cm and has been traced down dip at least to 450 m. The monazite lode itself is dark grey to brown, is fine-grained and massive and has sharp contact with the wall rock. The ore body contains monazite, quartz, apatite and magnetite with small amounts of zircon, pyrite, chalcopyrite, galena and ilmenite. The monazite display high ThO₂ contents (8–8.8 wt%) and gives a U–Pb age of 1,180±40 Ma. At an average grade of 17% REEOs and 2.5% ThO₂, Steenkampskraal is the highest grade REE deposit in the world. From the age relationships and the existence of orthopyroxene, Andreoli et al. (1994) propose that the monazite veins of the Steenkampskraal district formed in granulite facies (800–860°C, 5–6 kbar). An origin by protracted fractionation of a rare metal-enriched magma, yielding anorthositic cumulates and P-rich immiscible liquids, is proposed for the deposit by Andreoli et al. (1994).

Syn-sedimentary Deposits

Because of its resistance to weathering and its high specific weight, monazite tends to accumulate as heavy mineral layers with other high-density minerals such as ilmenite, rutile, xenotime, zircon, etc. Water currents or waves may concentrate heavy mineral grains in a river bar (alluvial placers) or on a beach (coastal placers), respectively. Most of the heavy mineral sand deposits in the world are concentrated by the action of the waves, but they may also result from sorting in river valleys or deltas (alluvial or stream placers), or from aeolian sorting (aeolian

placers) as extensive dune systems, as at the North Stradbroke Island in Queensland, Australia. Most heavy mineral sand concentrations occur onshore, but offshore deposits are also known. Most of the deposits are recent, but fossil more or less consolidated or even metamorphosed placers do also exist.

Necessary conditions for an efficient fractionation of heavy minerals include: (1) low rates of clastic sediment supply and long periods of weathering and abrasion of the source area to create a mature heavy mineral suite, (2) an energetic swell wave climate driving large sand fluxes onshore and along shore and (3) changing sea levels, especially marine transgressions that have the effect of moving heavy minerals from the shelf onto the present coast. Additional factors which may also play a role in the formation of economic heavy mineral deposits include: (1) episodic fluctuations in storminess, (2) alternation of steep headlands and relatively flat embayments in coast and shelf morphologies, (3) diverse depositional environments with contrasting sediment budgets (e.g. sand shelf bodies and barriers) and (4) subtle tectonic effects that promote reworking of the sands (Roy 1999). For getting placers with high Th resources, the degree of enrichment of the source area in monazite is certainly a necessary additional condition, as observed especially in India (Kerala) and in Sri Lanka.

Monazite placers are reported all over the world: Australia, India, Bangladesh, Sri Lanka, Burma, Malaysia, Thailand, Indonesia, China, Brazil, Madagascar, Egypt, Liberia and the USA (Jayaram 1987).

Coastal Placers

In India, coastal placers are best developed along the beaches of the south-west coast of India, in Kerala and south-western Tamil Nadu (Jayaram 1987). They are essentially beach or barrier deposits with development of dunes produced by aeolian action which is prominent during the dry months. The beach sands of the Chavara bar (Kollam, Kerala) contain 0.5–1% monazite at 9.0% ThO₂. In Manavalakurichi, south-western

Tamil Nadu, the monazite content may reach 3–4% at 9–10% ThO₂. On the east coast of India, monazite concentrations consist of extensive dunes fringing the coast in the Andhra Pradesh state and the eastern part of the Tamil Nadu and the Orissa state. At Cuttak and Ganjam in the Orissa state, the thickness of the placer is about 30 cm with a monazite content of 2.5%. The higher percentage of monazite in this area is attributed to the high density of intrusion of the pegmatites and leptynites in the hinterland. Elsewhere in India, monazite sand deposits occur in other parts of Andhra Pradesh. Monazite content of placers rarely exceeds 3%, and the maximum Th concentration is about 3,000 ppm in the sediment, with an average concentration of 60 ppm.

In Sri Lanka, relatively rich deposits occur along the N and N-W coast. Alluvial deposits also occur in the lower valley of Kaleganga in the Ratnapura district. The largest placer deposit (12,000 t monazite) near Pulmoddai is 3-km long and 50-m wide and contains 3 Mt of sand at 0.4% monazite.

In Southern China, monazite placers occur between Chianhua Hsien in south-western Hunan and Kung Chen Hsien in north-eastern Kwangsi and extensive deposits in the Kwangtung province.

In Australia, shoreline deposits are located on the east coast, northern NSW and southern Queensland and south-west WA (Mernagh and Mieztis 2009). About 165,000 t of monazite was produced from placers and exported from 1980 to 1995. About 159,500 t was produced from deposits in Western Australia and the remaining 5,500 t from New South Wales and Queensland. Most available resources in shoreline deposits in Australia are mined out; remaining resources are in national parks and built-up areas. Presently, monazite which is no more extracted is dispersed back through the original host sand to avoid the concentration of radioactivity. Hence, it becomes no more economic to recover the dispersed monazite for its REE and Th content from these sands. In order to estimate Australia's Th resources in the heavy mineral sand deposits, Geosciences

Australia has used a value of 7% Th from limited historic data on the Th content in monazite. Sircombe (1997) gave a median value of 6.7% Th and a mean of 7.2% Th from the analysis of 250 monazite grains. The maximum Th value in this suite of monazites was 27%, but 95% of the grains had less than 14.4%.
In Brazil, monazite occurs associated with ilmenite and zircon in coastal placers along the eastern and south-eastern Atlantic coast. *In the USA*, the Florida beach placers are estimated to contain 0.3–1% monazite.

Dunes

Monazite placer deposits associated with the formation of dunes have been reported in India and in Australia. Near Manavalakurchi, in India, at the mouth of the Vailiyar river, monazite placers are formed by aeolian action on the beaches, especially during the dry season. They contain 3.3% monazite with 9–10% ThO₂. In Australia, dune placers occur in Queensland with resources of about 25,000 t Th. Most of them are located in national parks or conservation areas, except the North Stradbroke mine, and their monazite content is generally low, only 0.2–0.3% of the heavy mineral fraction.

Offshore Placers

Offshore placers are known in India and Australia but should exist in other countries. In India, they occur 600 m off from the Neendakara–Kayankulam bar over a length of 22 km with 0.05% monazite at 9.5% ThO₂. In Australia, they occur off the southern Queensland and northern New South Wales coast.

Stream Placers

In stream placers, heavy minerals are concentrated in sand and gravel by the action of rivers. They occur along well-defined channels or benches. In the Cooljarloo region, Western Australia high-grade sections 40 m thick with 4.4% heavy mineral concentrations exist. In the USA, they are known from southern Virginia to central North Carolina. These deposits were formed at the intersection of shorelines and major

palaeorivers, during multiple transgressive/regressive events from Cretaceous to Tertiary time.

Fossil Placers

They are known in sandstones, conglomerates and arkoses from the Proterozoic to the late Tertiary. Some of these placers may contain up to several thousands ppm Th, but most have less than 100 ppm. In Australia, the Murray Basin is a major fossil monazite placer in New South Wales (with a resource of about 27,000 t Th), Victoria and South Australia with variable monazite content (Mernagh and Mieztis 2009). In Western Victoria, the placers were formed in an offshore environment with monazite contents of 1–1.5% and are relatively large (232,000 t Th). Other fossil shoreline deposits are in the Eneabba and Cooljarloo areas north of Perth, in the Yoganup area south of Perth, in south-west Western Australia and in the Eucla Basin in South Australia and Western Australia.

Metamorphosed Placers

Metamorphosed placers are known from low-grade to high-grade domains. Examples are the low-grade metamorphosed extensive Ordovician–Silurian quartzites of the Despenaperros zone in Spain (Alia 1956) or the high-grade Palaeozoic monazite, sillimanite, staurolite and kyanite schists, gneisses and migmatites in the Piedmont of the eastern USA (Twenhofel and Buck 1956).

Coal, Lignite

Th adsorption on organic matter, clay minerals and Fe-oxides increases with increasing pH (Syed 1999). Th⁴⁺ is strongly absorbed on carbonaceous materials (coal, lignite, petroleum, bitumen and thucolite). However, most peat bogs have low Th contents (~10 ppm), but Th content may increase two- to tenfold in the vicinity of Th-rich rocks (Boyle 1982). Some US coal may contain up to 100 ppm Th (Facer 1979). Hence, Th extraction from ash from coal and lignite power plants has been considered. For example, 13 t of Th per year are produced in a typical 1,000 MWe coal power plant in the form of ash. One pound of Th contains the energy equivalent of 5,000 t of coal

(Ragheb and Tsoukalas 2010). Hence, extraction of Th from coal would yield 31 times the energy equivalent of the coal. It is interesting to note that in the USA alone, the ashes accumulated only for the year 1981 from 154 coal-fired power plants of 1,000 MW contain 801 t of U and 1,971 t of Th, assuming U and Th concentrations of 1.3 and 3.2 ppm, respectively, in the coal (Gabbard 1993).

Towards a Sustainable Use

In the present generation of nuclear reactors (second- or third generation), only ^{235}U is burned, which represents 0.72% of the natural U (1/140). In fact, even less than that is really used because part of ^{235}U remains in depleted U after the enrichment process (0.25–0.30% ^{235}U), and a significant proportion of ^{235}U remain in the spent nuclear fuel (0.8–1% ^{235}U). The fraction of ^{235}U which is burned (3–4%) in the nuclear reactors produces a series of highly radioactive nuclides which represent the high-level wastes. Besides, about 1% of ^{238}U is transformed to ^{239}Pu (50%) and ^{241}Pu (15%) by neutron capture during the nuclear reactions. Only ^{239}Pu is fissile. About 70 t Pu contained in used fuel is removed each year in the world when refuelling reactors. A large part of the information summarized here comes from the website of the World Nuclear Organization (www.world-nuclear.org) and from OECD/NEA (2007).

During the enrichment process, every tonne of natural U gives about 130 kg of enriched fuel with 3.5% ^{235}U . This means that the production of 1 t of enriched U requires about 7.7 t natural U, and thus about 6.7 t of depleted U is produced. Therefore, huge amounts and variable types of nuclear materials are produced along the U nuclear fuel cycle (Table 5). Many processes have been developed for a sustainable use of these different types of nuclear materials: depleted U, spent fuel, Pu and even high-level nuclear wastes. Moreover, since the signature of the non-proliferation treaty between Russia and the USA (known as the Megatons to Megawatts program), a program has been set up to convert highly enriched

Table 5 Inventory of recyclable materials (www.world-nuclear.org)

	Quantity (t)	Natural U equivalent (t)
Plutonium from reprocessed fuel	320	60,000
Uranium from reprocessed fuel	45,000	50,000
Military plutonium	70	15,000
Military highly enriched uranium	230	70,000
Depleted uranium tails	1.6·10 ⁶	–

U (HEU) from nuclear weapons into fuel for electricity production.

Depleted Uranium

Uranium enrichment leaves depleted U tails with 0.2–0.3% ^{235}U . Depleted U tails are either stored as UF_6 or de-converted back to U oxide, especially in France. Every year, over 50,000 t of depleted U is produced in the USA, Europe and Russia. The world stock in 2009 is about 1.6 Mt. With the decrease of the activities for military enrichment, a lot of enrichment capacity remains unused, particularly in Russia. Consequently, an agreement has been signed in 1995 (which should cease in 2010) between Tenex (Russia) and Areva and Tenex and Urenco for re-enrichment of part of the depleted U tails. The tails resulting from that secondary re-enrichment, with only about 0.10% ^{235}U , are now owned by Tenex.

During de-conversion of depleted U, UF_6 is reacted with hydrogen at 700°C to yield HF which represents a by-product for sale and U-oxide powder which is packed for storage. About 300,000 t of depleted uranium was de-converted by the beginning of 2007. The main de-conversion plant is run by Areva NC at Tricastin, France. Another plant operating at Zelenogorsk in Russia has been developed based on the French technology. The construction of another plant is planned in the USA (New Mexico). The resulting depleted U oxide is either considered as a waste or as a long-term strategic

2457 resource which can be used in the fast neutron
2458 reactors of the fourth generation.

2459 Spent Fuel

2460 In some countries (e.g. France, UK, Japan), spent
2461 fuel is reprocessed to separate highly radioactive
2462 nuclides to recover its U and Pu, which represent
2463 about 95% of the volume of the spent fuel, and
2464 thus to reduce by about 20 times the final volume
2465 of high-level wastes.

2466 Pu ~~can be easily~~ recycled by mixing it with
2467 depleted U to produce a mixed-oxide fuel (MOX)
2468 which can be used in conventional nuclear power
2469 stations. MOX fuel with of about 7% Pu is equiv-
2470 alent to U-oxide fuel enriched to about 4.5% ^{235}U .
2471 If weapons-grade Pu is used (over 93% ^{239}Pu),
2472 only about 5% Pu is needed; 260 t weapons-grade
2473 Pu exists in the world. If all this Pu was used in
2474 MOX fuel, it would be equivalent to a little over
2475 one year's world U production. A single recycle
2476 of Pu in the MOX fuel increases the energy
2477 derived from natural U by some 12%, and if the
2478 U is also recycled, this reaches about 22% (based
2479 on light water reactor fuel with burn-up of 45
2480 GWD/tU). In 2006, about 180 t of MOX fuel was
2481 loaded into over 30 reactors (mostly PWR) in
2482 Europe, providing about 2% of the nuclear fuel.
2483 So far, about 2,000 t of MOX fuel has been loaded
2484 into power reactors.

2485 The U recovered from reprocessing used
2486 nuclear fuel is called reprocessed uranium
2487 (RepU). The re-use of RepU is not straightfor-
2488 ward, essentially because two new U isotopes
2489 ^{232}U and ^{236}U are formed by or following neutron
2490 captures. ^{232}U is essentially a decay product of
2491 ^{236}Pu , and its abundance increases with storage
2492 time in spent fuel, peaking at about 10 years. As
2493 both isotopes decay much more rapidly than ^{235}U
2494 and ^{238}U , they are much more radioactive, and
2495 especially ^{232}U . Strong shielding is required to
2496 handle such material. Also, ^{236}U is a strong neu-
2497 tron absorber which slows down the chain reac-
2498 tion that entails the use of higher enrichment
2499 levels of ^{235}U of the new fuel to compensate for
2500 stronger neutron adsorption. Moreover, during
2501 the re-enrichment process for production of the
2502 new fuel, the lighter isotopes ^{232}U and ^{236}U tend to

be further enriched. This problem limits the used
of RepU. This process has been mainly used in
UK, where 16,000 t of RepU from Magnox reac-
tors has been converted to about 1,650 t of
enriched fuel, but this recycling was stopped in
1996 due to economic factors. Much smaller
quantities have been converted, in France and
Japan. Some RepU from Swiss, Germany and
Russia is presently re-enriched by blending with
military highly enriched U.

2513 Military Uranium

2514 Since 1987, the USA and countries of the former
2515 USSR have signed a series of disarmament trea-
2516 ties to reduce the nuclear arsenals by about 80%.
2517 The 2,000-t HEU existing in US and Russian
2518 weapons and other military stockpiles are equiva-
2519 lent to about 12 years of world mine production.
2520 The contract signed between the US Enrichment
2521 Corporation (now USEC Inc) and Russia's
2522 Technabexport (Tenex) in 1994 permits USEC to
2523 purchase a minimum of 500 t of weapons-grade
2524 HEU (equivalent to around 20,000 bombs) over
2525 20 years to 2013, at a rate of up to 30 t/year from
2526 1999. HEU which contains at least 20% ^{235}U and
2527 usually about 90% can be diluted with depleted
2528 U, natural U or partially enriched U. This weap-
2529 ons-grade material is diluted by a factor of about
2530 25:1 with depleted U, or 29:1 with depleted U
2531 that has been enriched slightly (to 1.5% ^{235}U) to
2532 minimize levels of radiogenic ^{234}U deriving from
2533 the natural decay of ^{238}U . In Russia, HEU is
2534 diluted to 15,259 t U enriched at 4.4% ^{235}U , using
2535 depleted U tails re-enriched at 1.5% ^{235}U . This
2536 quantity of diluted HEU is equivalent to about
2537 137,000 t of natural U. Presently, dilution of HEU
2538 stockpiles is equivalent to 9,000 t U production
2539 from mines each year, and meets about 13% of
2540 annual world reactor requirements.

2541 Conclusions

2542 Uranium deposits are known in nearly all part of
2543 the geological cycle from high-temperature, mag-
2544 matic, hydrothermal or metasomatic processes to

low-temperature hydrothermal or sedimentary processes (Fig. 1). Identified U resources can satisfy U needs at the present rate of consumption for about 80 years. According to the number of new reactors which will be connected to the grid during the next years, this estimate may decrease. However, increased exploration efforts particularly in strongly underexplored countries as in Africa and South America (Table 2) may counterbalance this evolution. The main problem for satisfying the U needs will more probably result from the difficulty of opening new uranium mines due to technical, regulatory, financial, environmental and political problems. Besides, increasing burn-up and thermal efficiency in existing and new reactors, reducing the amount of ^{235}U in the depleted U, may reduce the demand and recycling of nuclear material resulting from the industrial and military U cycle (depleted U, Pu, spent fuel) and will continue to represent an additional significant source of fuel (MOX, RepU) for the nuclear power stations. In a relatively near future (2030?), reactors of the fourth generation should be able to burn most of the ^{238}U , which may increase the duration of the U resources by a factor of at least 60, i.e. about 5,000 years at the present rate of consumption.

Thorium represents an additional radioactive fuel source which should be used in conventional or specific reactors in a near future. Thorium resources occur in a large variety of geologic environments, but are essentially associated either with highly fractionated peralkaline magmatism (especially with carbonatites) and associated magmatic fluids, or placer-type concentrations. Thorium contained in the ash derived from the burning of coal may represent an additional significant resource in the future if efficient extraction processes are developed. However, the present knowledge of the Th resources in the world is relatively poor because of inadequate exploration efforts arising out of insignificant demand. In a near future, with the possible development of Th-fuelled reactors and the urgent needs of renewed REE resources, in response to the recent policy of China concerning restrictions on REE exports, Th could be first obtained as a by-product of the REE–Th-bearing minerals, the

REE covering most of the extraction costs. Then, with further development of Th reactors in the future, other ore minerals with higher Th contents, such as thorite, would be more likely sources.

Uranium and thorium cannot be considered as renewable resources, because at each nuclear cycle, part of these elements are burnt out to produce energy, but as additional resources are created during each fuel cycle, U and Th can be considered as highly sustainable resources.

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Author Queries

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Queries	Details Required	Author's Response
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AU4	References Wenrich and Titley (2008), Derome (2003, 2005), Mernagh and Mieizitis (2008), Sørensen (1974), Pagel (2005), Wenrich and Sutphin (2008), IAEA (2005) have not been provided in the reference list. Please provide.	
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