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Classification of Uranium Deposits

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A listing of the recognized types of uranium mineralization shows nineteen determinable types out of which only six can be classified as of economic significance at present: Oligomictic quartz pebble conglomerates, sandstone types, calcretes, intra-intrusive types, hydrothermal veins, veinlike types. The different types can be genetically related to prevalent geological environments, i.e. 1. the primary uranium occurrences formed by endogenic processes, 2. the secondary derived from the primary by subsequent exogenic processes, 3. the tertiary occurrences are assumed to be formed by endogenic metamorphic processes, however, little is known about the behaviour of the uranium during the metamorphosis and thereby the metallogenesis of this tertiary uranium generation is still vague. A metallotectonic-geochronologic correlation of the uranium deposits shows that a distinct affinity of the uranium exists to certain geologic epochs: to the Upper Archean - Lower Proterozoic, to the Hercynian and in a less established stage: to the Upper Proterozoic.

Various classifications of uranium deposits have been published in the past. Maucher (1962) listed the more important ones in his uranium book. Comprehensive studies were also published by Roubault (1958) and Heinrich (1958), and more recently by Ruzicka (1971) and Ziegler (1974).

During the last ten years several new types of uranium deposits have been discovered: the veinlike -, intraintrusive - and calcrete types. In the same period, especially after the 1965-70 uranium exploration boom, much new data on uranium deposits became available. Thus, an up to date review and reclassification of the types of deposits of economic significance at present seems justified. However, the study had to be restricted to deposits of the Western World. Information of uranium deposits in the Eastern Block countries is too sparsely and incomplete to be incorporated in this paper.

A general classification of recognized types of uranium mineralization by the time stratigraphic relationship of host rock to ore emplacement is set out in Figure 1.

This classification shows 19 types of which only six have economic significance (Dahlkamp 1974, 1975). They are, in random order:

- Oligomictic quartz pebble conglomerates
- Sandstone types
- Calcretes
- Intra-intrusive type
- Hydrothermal veins
- Veinlike types

At the time of writing there are two additional viable proposition types which may be mentioned, and these exist only due to the present prosperous circumstances. These are the contact-metasomatic uranium deposit Mary Kathleen

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Mode of origin	Host rock	Example	
Sedimentary	CONGLOMERATES	Elliot Lake (Canada)	1
		Witwatersrand (S. A.)	2
	Blackshales	Ranstad (Sweden)	1
	Phosphates	Florida (USA)	1 + 2
		Cabinda (Angola)	1 + 2
	Acid tuffs	Wyoming (USA)	1
		Cotaje (Bolivien)	1
Intrusive — Intraintrusive	Peralkaline Syenites	Ilimaussaq (Greenland)	1 + 2
	Carbonatites	Phalaborwa (S. A.)	2
	ALASKITES	Rössing (SW-Africa)	1
	Pegmatitic Alkali-Granites	Ross Adams (USA)	1
	Granites	Bingham (USA) (Cu-Porphyry)	2
Intrusive	Pegmatites	Bancroft (Canada)	1
	HYDROTHERMAL VEINS	Schwartzwalder (USA)	1
Metamorphic	Phyllites	Forstau (Austria)	1
	Schists	Portugal	1
Contact-metasomatic	Calc-Silicates	Mary Kathleen (Australia)	1
Supergene	VEINLIKE TYPES	Alligator River (Australia)	1
		Rabbit Lake (Canada)	1
	SANDSTONES	Western USA	1
		Arlit (Niger)	1
	CALCRETE	Yeelirrie (Australia)	1
	Lignites	N-S Dakota (USA)	1
	Phosphates	Bakouma (ZAR)	1 + 2
	Karst	Bighorn/Wyo. (USA)	1

Capital letters: economic deposits
Small letters : subeconomic deposits
------------ : 1977 in production
1: main-product
2: by-product

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Fig. 1. Classification of Uranium Occurrences I

in Australia and the pegmatitic uranium deposit Madawaska in Bancroft, Canada.

For the sake of completeness, mentioning should be made of various polymetallic deposits from which uranium is extracted as a byproduct.

The different types of deposits can be genetically related to prevalent geological processes, as depicted in Figure 2. These are:

1. the primary, magmatogenic uranium occurrences formed by endogenic processe

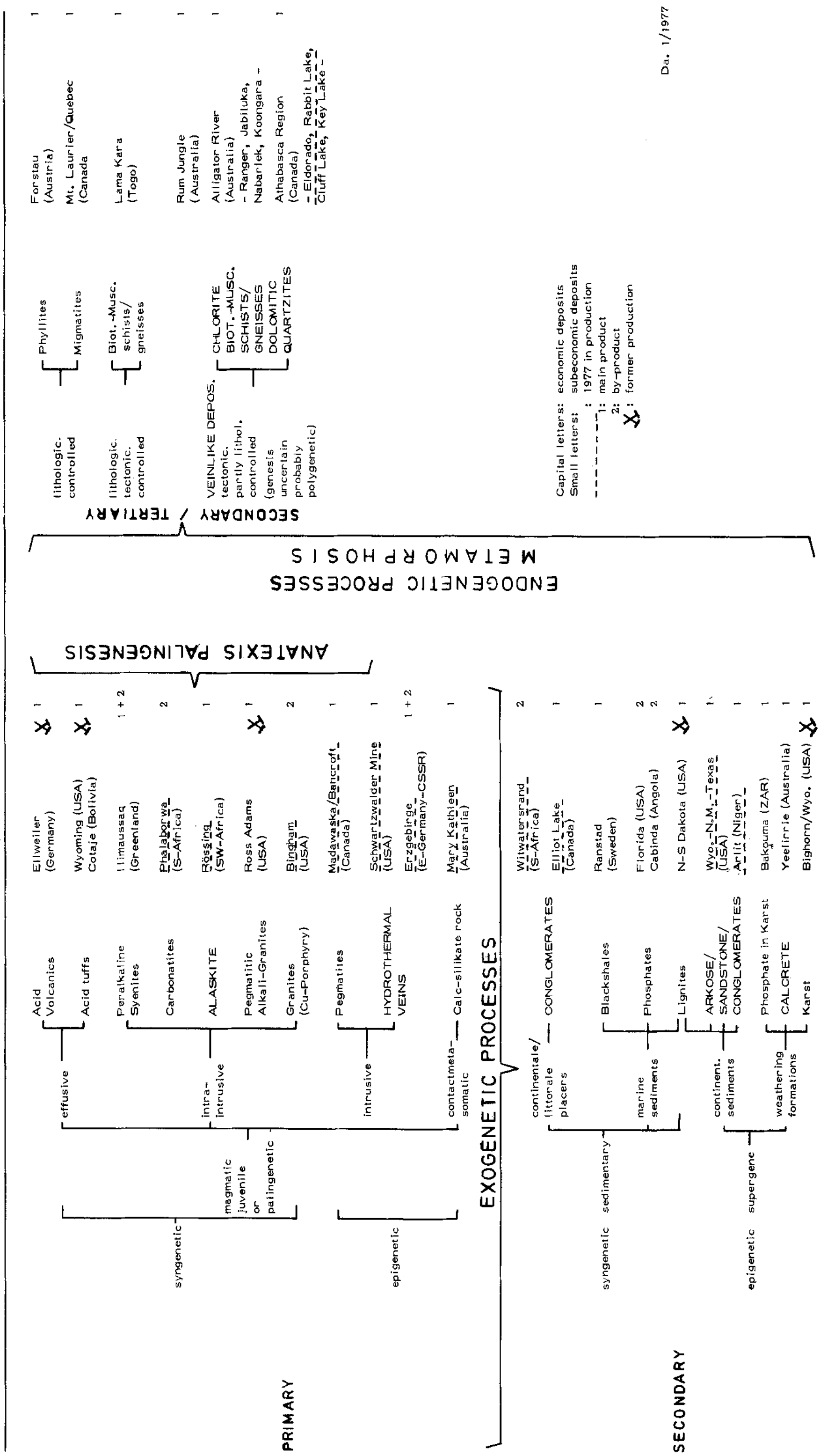

Fig. 2. Classification of Uranium Occurrences II

2. the secondary uranium occurrences which were formed by subsequent exogenic processes from the primary types.

3. the tertiary generation which was formed by endogenic metamorphic processes from the primary as well as from the secondary uranium occurrences.

This cycle closes if by anatexis or palingenesis the secondary and tertiary types are retransformed into the primary type. Figure 3 represents the interrelationship between source and host rocks of uranium deposits, in the form of a schematic geological profile.

The genesis and the problems of the deposits in the various inferred metallogenic processes may be summarized as follows:

1. PRIMARY OCCURRENCES:

The origin of the uranium in the primary occurrences is reasonably well established as either, juvenile magmatic, prevailing in the early Precambrian, or palingenetic/anatectic, prevailing in younger times.

2. SECONDARY OCCURRENCES:

They owe their existence to exogenic processes. In upper Archean-lowest Proterozoic times when non-oxidizing conditions prevailed (Ramdohr, 1955) mechanical weathering and sedimentation formed placer deposits with detrital uranium, whereas after the change to an oxidizing atmosphere which occurred at the latest during the middle of the Lower Proterozoic (approx. 2200 M. A.) (Schidlowski et al., 1974; Fiebiger, 1976), chemical liberation of uranium lead to subsequent mineralization in a suitable lithochemical environment.

Dependant on climatic and transport conditions uranium was either:

a) transported into the sea and concentrated in organic ooze (sapropels, black shales), and in marine phosphates or

b) concentrated into terrestric sediments in intracratonic and intramontane basins, occasionally in littoral clastic sediments, and in weathering crusts. This was the mode of origin of the sandstone and calcrete types of deposits and, according to some authors (Knipping, 1974), even the veinlike types such as Rabbit Lake.

3. TERTIARY OCCURRENCES

The metallogenesis of the tertiary U-mineralization is still quite vague. Very little is known about the behaviour of U during metamorphism.

In comparing rock units of different grades or facies of metamorphism the following might be observed:

A) In phyllites such as those from Forstau, Austria, the ore controls are clearly lithologic. Based on all apparent indications, the introduction of uranium was exogenic into the lagoonal sediments (Petrascheck et al 1974, 1977). Syngenetic or epigenetic introduction has not yet been established.

B) In biotite-muscovite schists or gneisses of the amphibolite facies, e. g. in the U-occurrences in Togo, the ore is structurally and lithologically controlled. The origin of the uranium in this geologic environment can be explained either as
a) of truly magmatic origin, or
b) as the result of remobilization and redeposition from earlier sediments.

C) The veinlike deposits of the Athabasca Basin in Canada, and in the Northern Territory of Australia, contain relatively high and partly abnormally high accumulations of uranium in mylonitized carbonatic rocks and chlorite-muscovite-biotite schists and gneisses. In the Key Lake orebodies in Saskatchewan, Canada, these host rocks were derived from biotite-cordierite-sillimanite gneisses and amphibolites of the Abucuma facies (Dahlkamp & Tan 1977), and at Cluff Lake from rocks of the upper amphibolite facies which derived by retro-

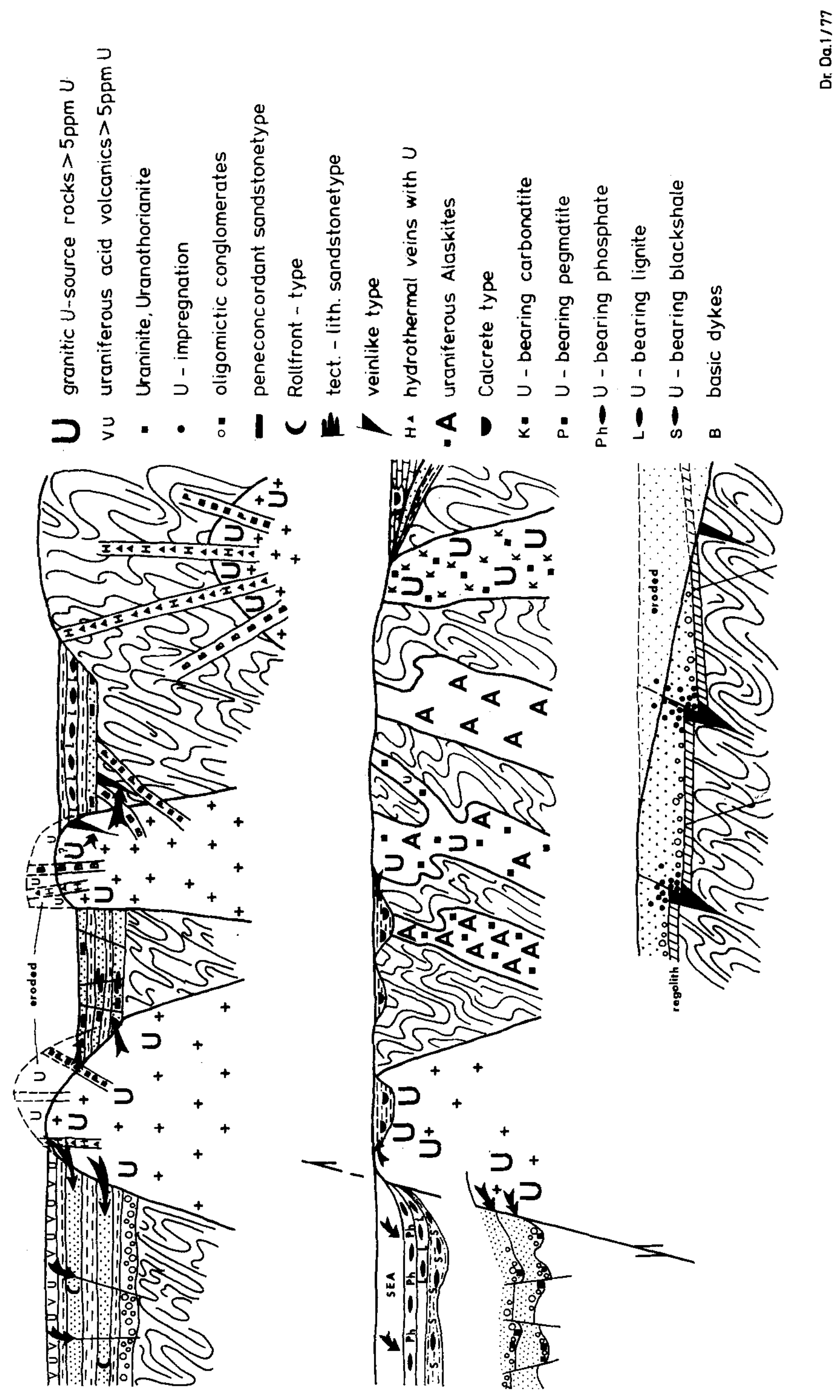

Fig. 3. Diagram of Occurrence and Formation of U-Deposits

grade metamorphism from rocks of the granulite facies (Herring 1975, Pagel 1975). The host rock of the Alligator River deposits, Northern Territory, Australia belong also to the amphibolite facies with retrograde alterations within the ore zones.

The genesis of this veinlike type of deposits is still not understood. A polygenetic evolution seems to be the most plausible hypothesis with the open question what role metamorphism has plaid. (see also chapter "Veinlike Deposits")

The veinlike deposits of the Massif Central in France are similar in appearance, but here the orebodies prevail in a specific granitic facies as the host rock (Moreau et al. 1966; Gangloff 1970).

Characteristics of the types of economic deposits

As shown in Figure 1 six main categories of economic uranium deposits exist which are now described in more detail.

Conglomerate Type (Fig. 4)

(Griffith 1967; Anhaeusser 1969; Bowie 1970, 1977; Robertson 1974)

The uranium host rock is an oligomictic conglomerate consisting of quartz pebbles in a quartzitic matrix rich in pyrite. The dominant ore minerals are uraninite, brannerite and locally uranothorite. The uranium minerals commonly occur in well-winnowed quartz pebble conglomerate lithofacies developed within depressions, possibly paleo-channels, upon the Archean basement surface. Other factors affecting uranium localisation and concentration in addition to proximity to major unconformities, are the packing density of the quartz pebbles and the abundance of pyrite.

Although there are numerous occurrences of uraniferous oligomictic conclomerates in Precambrian Shields, only Lower Proterozoic/uppermost Archean strata, older than 2200 million years, contain significant uranium concentrations. Geographically, only two districts are known presently which are being exploited economically.

a) Blind River - Elliot Lake, Ontario, Canada. (Little 1970, 1974; Robertson 1974)

b) Witwatersrand - Orange Free State, South Africa. (Liebenberg 1955; Schidlowski 1966; Hiemstra 1968; Whiteside 1970)

a) The economy of the Blind River - Elliot Lake district is based upon uranium only. The average grade of the ore is about 0.15 % uranium.

Thicknesses of the ore interval vary between 1.5 and 10 m; the lateral widths and lengths of the individual ore bodies are in the range of 100 to 1000m.

b) In the Witwatersrand - Orange Free State district uranium is produced as a byproduct in gold mining. Average contents in this case are around 0.025 % uranium.

The thicknesses of the mineralized lenses vary between several centimetres and several metres. The widths reach several hundred metres and the lengths several thousand metres. Ores have been mined to depths approaching 3,000 metres.

The genesis of the uranium deposits is debatable, but most geologists believe in Ramdohr's (1955, 1959) opinion that uranium was transported as heavy minerals and deposited syngenetically with the enclosing lithofacies. To permit this process a non-oxidizing or low oxygen atmosphere is required, an environment which no longer exists on earth.

Sandstone Type

(Bigotte & Obelianne 1968; Gangloff 1970; Stipanicic 1970; Dodson 1972; Grutt 1972; Adler 1974; Barthel 1974; Breger 1974; Harshman 1974; Belluco & Rodriguez 1977; Pfiffelmann 1975)

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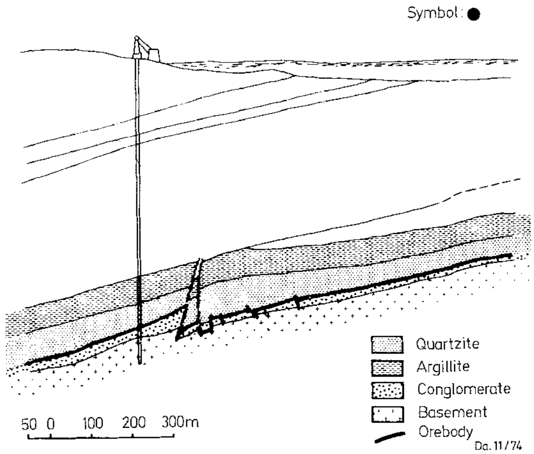

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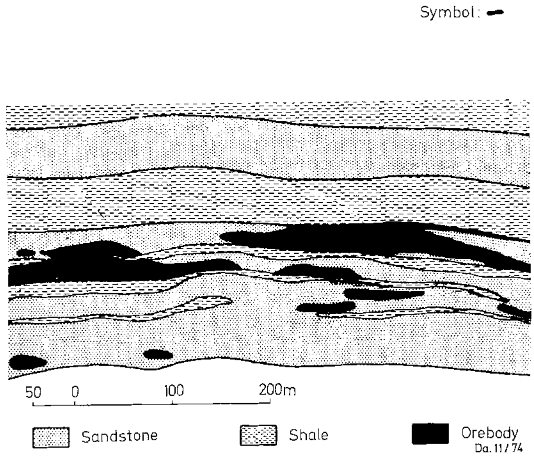

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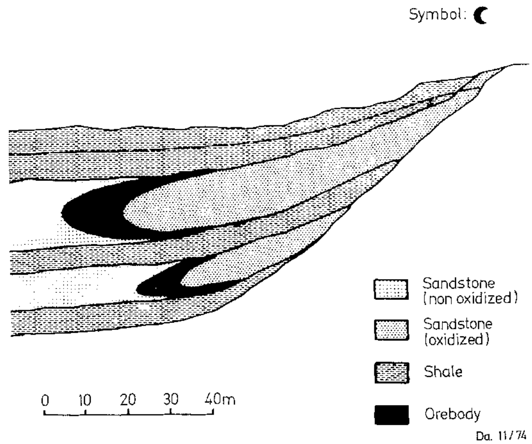

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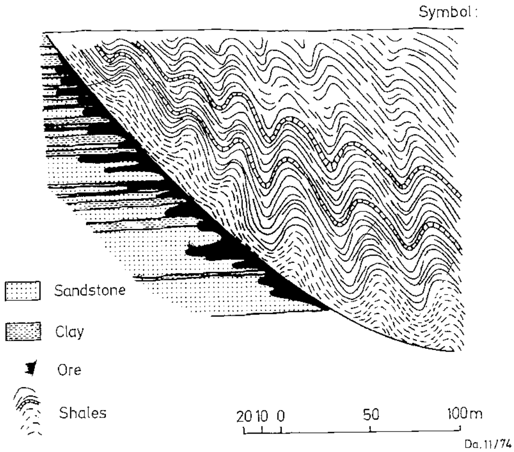


Fig. 4. Conglomerate Type (idealized, after Griffith (1967)

Fig. 5. Sandstone-Type/Peneconcordant (idealized, after Grutt Jr. 1972, Clary et al. 1963

Fig. 6. Sandstone-Type/Roll-Front (idealized)

Fig. 7. Sandstone Type/Tecto-Lithologic (idealized,after Gangloff 1970)

This category is divided into three subgroups
- Peneconcordant Deposits
- Roll-type Deposits
- Tecto-lithologic Deposits

Peneconcordant Deposits (Fig. 5)

Peneconcordant deposits are epigenetic, controlled by lithology. They are flat-lying or gently dipping bodies essentially parallel with the enclosing strata. Ore deposits are best developed in cross-stratified, medium-to-coarse grained arkoses and sandstones. The depositional environments of the host rock are mainly fluviatile - stream channels, flood plains and fluvialcoalesced alluvial fans - but may also be of a deltaic or lagoonal character.

The proximity of these deposits to unconformities is remarkable. This type of deposit is characterized by its significant pyrite content, the presence of vegetal organic material and of amorphous organic substances, and by vanadium concentrations which can often be mined economically exclusive of the uranium.

The dominant ore minerals occurring in the reduced zone are pitchblende and coffinite, to some extent associated with vanadium oxide minerals (montroseite etc.). Within the oxidized zone the important uranium minerals are carnotite, tyuyamunite or francevillite, all of which are uranyl vanadates. Accessory elements are Mo, Se, Cu and others.

Stratigraphically, this type of uranium deposit is found mainly in the Tertiary, Jurassic, Triassic and Carboniferous periods. The main ore districts are the Colorado Plateau, where vanadium is being produced along with uranium, and the Paguate-Grants-Churchrock District, New Mexico, United States; the Agades Region in Niger; the sub-Andean zone of Argentina; the Lake Frome embayment in South Australia.

Average uranium contents vary between 0.15 and 0.4 %. In plan the ore bodies show amoeba-shaped to lenticular oblong contours. The lateral extension is several tens to several thousands of metres. Thicknesses vary between 1 and 5 metres and can be up to a maximum of 15 metres.

Roll-Type Deposits (Fig. 6)

The lithology and provenance of the host rock for roll-type deposits are similar to those of peneconcordant deposits. The ore bodies are epigenetic and controlled by lithology and chemohydrology.

Uranium mineralization follows the contact between oxidized and non-oxidized sandstone. This boundary is regarded as the furthest downdip or outer penetration front of oxidizing ground water. A characteristic is the interbedding of the mineralized permeable layers in impermeable horizons (clay-, siltstones etc.). The dip of the strata is generally less than 5° (unless post-ore tectonics have caused tilting as in the Shirley Basin/Wyo.).

The ore bodies transect the stratification of the host rock and are thus discordant with the strata. In cross section, the form of the ore bodies resembles a crescent. The plan view of the deposits is like that of an irregularly laid pipe.

Main ore minerals are pitchblende and coffinite. In addition, selenium as ferroselite, $FeSe_2$ (as native Se in the protore), is enriched on the convex side of the roll front. Molybdenum (jordisite, MoS_2) and calcite are enriched on the concave side of the roll front. In addition, arsenic, phosphorus and copper seem to occur coincidentally with uranium.

Stratigraphically, roll-type deposits occur chiefly in the Tertiary strata (Paleocene, Eocene in Wyoming; Eocene, Miocene and Pliocene in Texas), but they also occur in the Uravan Mineral Belt, Utah and Colorado, in strata of the Jurassic period.

The main district of these deposits are the intracratonic sedimentary basins of Wyoming (Powder River, Shirley, Gas Hills) and the Texas Gulf Coast.

Average uranium contents vary between 0.1 and 0,5 %. The dimensions of the ore fronts in the apex zones are up to 15 metres (average: few tens of cm - 10 m); the widths between a few centimetres and several hundred metres; and the strike lengths extend up to several kilometres.

Tecto-Lithologic Deposits (Fig. 7)

The deposits are tectonically-lithologically controlled epigenetic deposits (called stack-deposits in USA) which occur in rocks of the same type as the peneconcordant and roll-type deposits.

One characteristic of stack deposits is the uranium concentration in or along permeable fault zones with linguiform impregnation of the adjacent clastic sediments.

Main ore minerals in the reduced zone are pitchblende with subordinate coffinite. In the oxidized zone uranyl vanadates are present.

Stratigraphically, this type of occurrence is found in the Triassic and Jurassic periods as well as in the Lower to Middle Proterozoic.

Main deposits are found in the Franceville Basin of Gabon and at Ambrosia Lake/Grants District, New Mexico, U.S.A.

The average uranium contents vary between 0.1 and 0.4 % at thicknesses ranging between a few tens of centimetres and 10 metres and lateral dimensions of 100 metres and more.

Besides the above listed uranium districts, minor mostly subeconomic occurrences of sandstone type mineralisation are found e. g. in the Permian of Europe (Matos Dias & Soares de Andrade 1970; Gangloff 1970; Mittempergher 1970, 1974; Barthel 1974; Herbosch 1974; Lukacs & Florjancic 1974; Petrascheck et al. 1974, 1977), Miocene of Japan (Hayashi 1970, Katayama et al. 1974), Miocene-Pliocene of Pakistan (Moghal 1974; Basham & Rice 1974), Karoo formation of South Africa (v. Backstroem 1974), Proterozoic sediments in NW-Canada (Morton 1974).

Veinlike Deposits

(Gangloff 1970; Dodson 1972; Knipping 1974; Ryan 1974; Anthony 1975; Eupene et al. 1975; Foy & Pederson 1975; Rowntree & Mosher 1975; Hoeve & Sibbald 1976; Tapaninen 1976; Dahlkamp & Tan 1977)

Veinlike deposits are characterized by pitchblende mineralization in massive ore veins (Nabarlek/Aust.) or bodies (Key Lake, Cluff Lake D/Canada) and as impregnations in shear zones in metasedimentary/crystalline rocks (Ranger/Australia, Rabbit Lake/Canada, Massif Central/France). The mineralization is mostly mono-mineralic, rarely polymetallic.

The main ore mineral is predominantly but not always colloidal, thorium-free pitchblende. Occasionally crystalline uranium oxide minerals are developed (Key Lake, Cluff Lake D). In oxidation zones, secondary products (uranium hydroxides and uranium silicates) may occur. The gangue, if present, consists of quartz and carbonate and occasionally hematite.

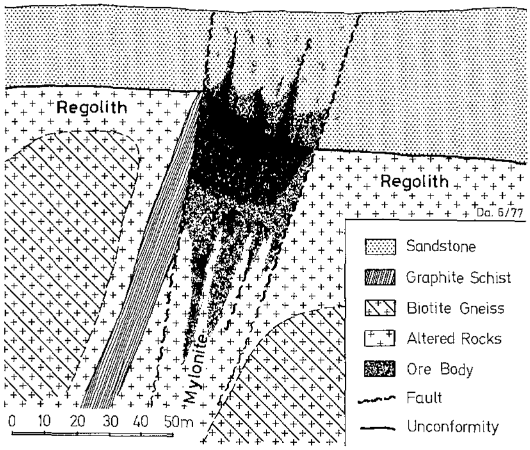
Veinlike uranium deposits are restricted to two geological epochs: The majority, including the Canadian and Australian occurrences, are present in rocks of Lower Proterozoic age. The remaining deposits, situated in France, Portugal and Spain, occur in Hercynian (Upper Carboniferous to Lower Permian) mobile belts.

The average uranium contents vary between 0.2 and 0.35 %, but may reach grades as high as a few percent, as at Nabarlek, Key Lake, Cluff Lake D. Thicknesses range between a few centimetres to about 100 m with lengths of up to a few hundred metres, more rarely to more than 1000 m. One characteristic phenomenon is the depth, which rarely exceeds 150 m.

Concerning the genesis of the veinlike type of deposits some geologists (Knipping 1974) interpret them as supergene. Analyses of fluid inclusions, however, (according to Poty et al. 1974) point to a formation temperature of 340-350°C for the deposits of the Massif Central, and to about 200°C (Little 1974) or 160°C (Pagel 1975) for Rabbit Lake/Saskatchewan.

At first glance, the most plausible genetic explanation would involve metamorphic events, causing remobilization and accumulation of the uranium from primary occurrences or from uraniferous sediments.

Age dates from the Beaverlodge deposits in Saskatchewan, Canada, support the validity of this theory for this region.



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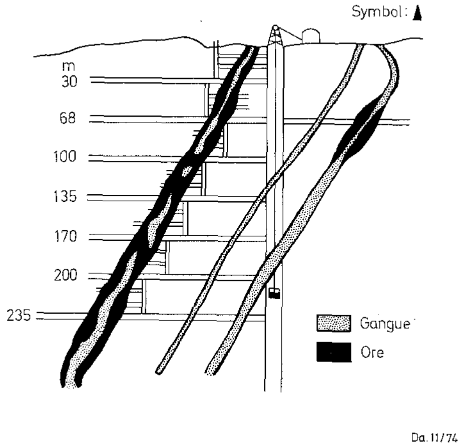

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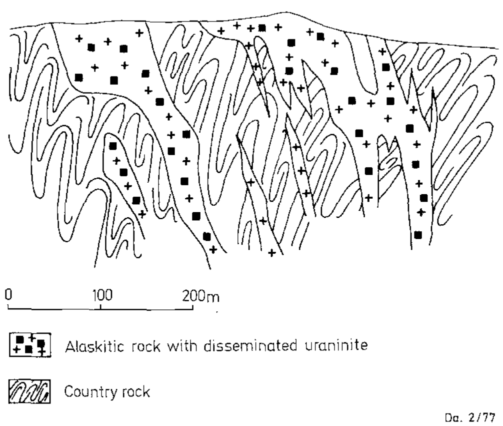

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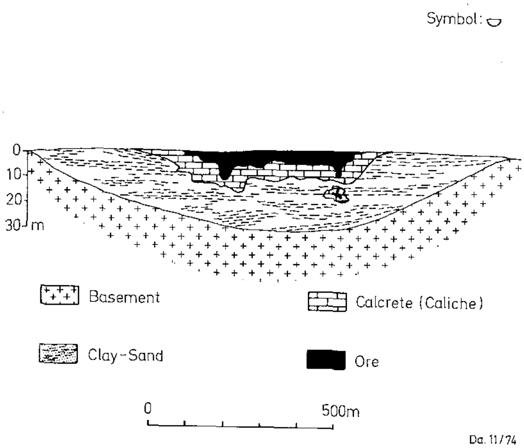

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Fig. 8. Veinlike Type (idealized)

Fig. 9. Hydrothermal Veins (idealized, after Roubault 1958)

Fig. 10. Intraintrusive Type (idealized)

Fig. 11. Calcrete-Type (idealized)

The oldest pitchblende-generation is dated at approximately 1780 m.y. (Koeppel 1968) which is more or less concurrent with the Hudsonian Orogeny. The exact petrographic- and depth-related sample location, however, is uncertain; it may have been at depth (-1000 m in the Fay Mine) or from an open pit (Bolger, Gunnar).

This Hudsonian age is in strong contrast to the age of all other veinlike deposits in the Athabasca region, namely Rabbit Lake (Knipping 1974), Cluff Lake (Tapaninen 1976) and Key Lake (Dahlkamp & Tan 1977). In all of these deposits the oldest uranium generation is established as 1100 m.y. This age coincides with another uranium date from Beaverlodge.

The younger ages differ by 700 m.y. from the Hudsonian orogeny (ab. 1780 m.y.) which metamorphosed the Aphebian sediments. No indications of post-Hudsonian metamorphism are evident in this region. Only dolerite dykes of 1180 m.y. (Sibbald & Munday 1976) approach the younger ages.

In the Cluff Lake (Tapaninen 1976) as well as in the Key Lake orebodies (Dahlkamp 1977), low formation temperatures are indicated. At Key Lake the occurrence of the kaolinite and chlorite gangue implies a hydrous phase. The low temperatures are supported by the presence of bravoite and alpha-U_3O_7.

Similar conditions exist in the deposits of the Alligator River region, N. T. /Australia (Dodson 1974; Hills & Thakur 1975; Hills 1975). Few and not well established age datings of 1880 m. y. for Koongarra and 1700 m. y. for Ranger exist, which are concordant with the orogeny (1700 - 1800 m. y.) of the Koolpin formation (S. Alligator River) and the Koolpin equivalent formation in the East Alligator river region and the Golden Dyke formation at Rum Jungle. Most pitchblende ages are around 900 m. y. and no metamorphic event can be attributed to this age.

Based on some indications - further research is in progress - a preliminary hypothesis of the genesis of the veinlike uranium deposits as discovered in Lower Proterozoic metasediments in Canada and Australia may consider the following evolution:

1. During the middle to upper Lower Proterozoic uranium was transported synsedimentary into marine or lagoonal basins located around or in between Archean highlands.

2. The Hudsonian or time equivalent orogenies may have caused - but not necessarily had to - a further concentration of uranium in strata-concordant seams or lenses (conceivable e. g. for the peneconcordant "veins" in the deep sections of the Fay Mine - Beaverlodge - Canada and the mineralizations beneath the Ranger No. 3 orebody (400 m deep), N. R. -Australia.

3. Middle Proterozoic weathering perhaps connected with lateritisation - i. e. processes similar to the biorhexistasy as described by Erhart (1967) - decayed and regolithized the paleosurface of the Hudsonian metasediments and Archean cores to a depth of several tens of metres. Uranium and other elements were mobilised by these processes.

4. A theoretical conclusion would be: the mobile elements migrated into tectonic traps and precipitated where they encountered adequte agents for precipitation (reductants such as ferrous (Fe^{++}) minerals, argillaceous, graphitic and chloritic zones, changes of permeability, pH, Eh etc.). (In this context see also Knipping 1974, Dodson et al. 1974, Barbier 1974).

Unfortunately two important phenomena apparently contradict, a metallogenesis as simple as that described above; at least for the Athabasca region.

a) fluid inclusions (Little 1974, Pagel 1975) point in places to formation temperatures of up to 200°C i. e. much too high for purely supergene emplacement;

b) age datings of the Athabasca formation (Raemaeker 1976) gave 1350 m. y., thus predating the oldest generations of uranium oxides of 1100 m. y. ; this means that the period of regolithisation must have ended at least 150 m. y. earlier than the oldest uranium ages.
However, the discrepancy may be resolved by the following hypothesis:

5. Following the formation of ore deposits as described under 3 and 4, the Athabasca Formation was deposited and its thickness of several 1000 m affected the underlying mineralization in two ways:

a) diagenetic processes with hydrous phases and temperatures (as deduced from fluid inclusions, minerals etc.) mobilized and redeposited more or less in situ the uranium, thereby causing a destruction of the original radiogenic equilibrium and simultaneously forming a new "primary" generation of uranium oxide with a rejuvenated age of about 1100 m. y.

b) The covering sediments protected the orebodies against further weathering and leaching.

6. Successive episodic uplifting resulted in erosion of the overlying cover formations and consequently changed the static equilibrium. Limited redistribution of the uranium within the ore deposits occurred. New generations of mineralization (sooty pitchblende) originated.

Alternatively the whole weathering cycle of points 3 and 4 could be disregarded and the metallogenesis could be based on diagenetic processes solely. However, to substantiate this hypothesis the following conditions have to be proven:

a) diagenetic processes must be capable of mobilizing uranium, and especially nickel (Key Lake), and also additional elements (Cluff Lake) and transporting these along distances of up to several kilometres in order to form the huge metal concentrations of up to several tens of thousands of tons of uranium, and also nickel as at Key Lake.

b) The tectonic host zones and migration channels which are open and permeable at surface must remain so under the pressure of up to several 1000 m of cover.

Hydrothermal Vein Deposits (Fig. 9)

(Furnival 1939; Kirchheimer 1952, 1963; Derriks & Vaes 1956; Derriks & Oosterbosch 1958; Roubault 1959; Griffith 1967; Heyse 1971; Ruzicka 1971; Little 1974; Rich & Barabas 1976)

Unlike the supergene veinlike deposits, real veins in the classical sense are regarded as of magmatic hydrothermal origin. A distinction is made between

a) polymetallic parageneses with Co, Ni, Bi, Ag, or Ni, Co and Cu. (In a katathermal origin, uranium occurs as isometric uraninite, partly thorium-bearing).

b) monometallic lodes of pitchblende.

The gangue is quartz, calcite/carbonate and occasionally fluorite and baryte.

Geochronologically, these hydrothermal lodes can be classified as Variscian (Upper Carboniferous to Lower Permian); (Schwarzwald/Germany, Erzgebirge/Germany-CSSR, Massif Central/France), Upper Proterozoic (Shinkolobwe/Zaire, Port Radium/Canada), and Laramide (Schwartzwalder Mine/USA).

Contents vary between 0.1 and 1% of uranium and higher, plus the accessory elements that can be mined and extracted as by-products.

Thicknesses of the mineralized veins vary between centimetres and metres, the length being in the range of several tens to hundreds of metres. The extension in depth, contrary to the supergene veinlike deposits, may be 1000 m and more (Pribram, CSSR). The mineralization, however, is strongly intermittent. The uranium mineralized sections occupied only 12% of the vein extensions at Pribram and 8% at Jachymov (CSSR).

For completeness, the uranium-molybdenum paragenesis should be mentioned. In the Western world there are no economic deposits of this type of mineral association, but they are known to exist in the Soviet Union (Kasanskij et al. 1976) and Roumania.

In India the presently exploited deposit of Jaduguda (average U content of 0.06%, Bhola 1958) may be attributed to this hydrothermal type of deposit.

Intra-intrusive Type (Fig. 10)

(Mackevett 1958; v. Backstroem 1970, 1974; Bowie 1970, 1977; Andrade Ramos & Fraenkel 1974; Armstrong 1974; Berning et al. 1976; Moreau 1977)

The intra-intrusive type is represented by only one economic deposit at Roessing, South West Africa. Here, the uranium mineralization occurs in an intrusive alaskite.

Primary uranium minerals are uraninite and, to a lesser extent, betafite. They occur disseminated in the alaskite. Secondary uranium minerals predominate in the weathering profile. However, independent of the nature of the ore minerals, the total uranium content remains almost constant.

The deposit has been dated as Upper Proterozoic.

The average ore grade varies between 0.03 and 0.04 % U_3O_8. The ore body has a diameter of 700 m and has been tested to a depth of 500 m.

To the intra-intrusive type belong also: Carbonatites, quartz-monzonites, e. g. granites, from which uranium is recovered as a by-product e. g. at Palabora, South Africa and Bingham, U. S. A., and also ultimately the pegmatitic alkali granites of the worked deposit Ross Adams/Bokan Mtn. - Alaska.

Calcrete Type (Fig. 11)

(v. Backstroem 1974; Cameron 1976; Haycraft 1976)

In arid climatic regions uranium is concentrated in irregular lenticular forms within flat channels cut into Archean granitic basement rocks. The depressions are filled with clay and sand and calcrete (= caliche). The uranium occurs as uranyl vanadate (carnotite, tyuyamunite).

The only economic deposit of this type, Yeelirrie, is located in Western Australia. The average uranium content is 0.1 to 0.2 %.

The mineralization is situated close to the surface, a condition enhancing the economics of the deposit. Dimensions are a thickness of 8 m, a lateral width of 500 m and a length of 6000 m. Similar occurrences are known in Namibia/South West Africa.

Potential Types of Deposits for Future Resources

Potential sources and reserves of uranium are:

- black shales (Kolm/Sweden, Chattanooga-shale/USA., Korea, Cuba)

- phosphates (Morocco, Angola, Florida/USA)

- lignites (Dakota/USA)

They all have low uranium concentrations only in the order of 10 to a few 100 ppm, but the reserves in some cases are extensive. A common problem to these deposits is the difficult and costly extractive metallurgy. Another difficulty is the environmental impact: most of the deposits could be mined only in large open pit operations.

In addition, uraniferous pegmatites such as those formerly mined in the Bancroft District in Canada or in Madagascar may again become exploitable if uranium prices continue to rise at a rate faster than the costs of mining and milling. Additional to these examples are migmatitic types as known from Mont Laurier, Quebec.

Another category comprises occurrences which may be attributed to the intra-intrusive type. They include uranium-bearing carbonatites (similar to Palabora/South Africa), quartz monzonites (Charlebois/Canada), adamellite (Crockers Well/Australia), lujavrite (Ilimaussaq-Kvanefjeld/Greenland), foyaite (Pocos de Caldas, Brazil) and certain pegmatitic differentiates. They contain uranothorite, uranothorianite and complex ore minerals composed of titanium, tantalum, niobium, thorium and uranium which are difficult to process and have low uranium contents (between 0.01 and 0.1 %). Uraninite is rare.

For completeness, brines and salt lakes shall be mentioned. They contain uranium up to several 100 ppb, as in the Searle Lake, California. Also, seawater with a content of 2.0 ppb U is regarded as potential source.

Grades and Reserves

Figure 12 presents a summary of grades and contents and Figure 13 shows a

TYPE OF DEPOSIT	SYMBOL	AVERAGE U-GRADE in %	TOTAL U-POTENTIAL (MINED + RESERVE) ≤ $ 15 p.lb.		MINED AS	
			Individual Deposit in t U	Uranium District up to max. t U	Main Product	Secondary Product
CONGLOMERATE-TYPE	●	0,025-0,15	15000-100000	200000	1. U 2. Au	- U
SANDSTONE-TYPE	(— ≢	0,2	5000-25000	150000	U	Cu, V, Mo, Se
VEINLIKE TYPE	▼	0,2-2	10000-250000	450000	U	Ni
HYDROTHERMAL VEINS	▲	0,1-1	100-25000	50000	1. U 2. Co, Ni, Ag, Bi	U
INTRAINTRUSIVE TYPE	◆	0,04	10000 ≥ 100000	100000	1. U 2. Cu	U
CALCRETE-TYPE	◡	0,1-0,2	40000	40000	U	V.
BLACK SHALE + PHOSPHORITE-TYPE	▬	0,02-0,08	10000-70000	300000	1. U 2. P	U

Fig. 12. Uranium Grade and Potential of Types of Deposits

cumulation of the total reserves of the different types of deposits. The two figures illustrate the dominance and economic significance of the different categories.

Metallotectonic-Geochronologic Correlation of Uranium Deposits

In order to complete the classification the remarkable geochronologic-stratigraphic correlation of uranium deposits has to be considered (Dahlkamp 1977).

The presentation in Figure 14 outlines the association of uranium deposits with certain geologic epochs. (For epigenetic deposits the age of the host rock, not the age of ore formation, is used). This relationship is documented on a selective metallotectonic map (Fig. 15), where most of the deposits occur in the Precambrian, especially in the Lower Proterozoic, in the Hercynian, and in cover sediments surrounding these basements (Ziegler 1974, Bowie 1977, Dahlkamp 1977).

By plotting the symbols of the different types of deposits into a diagram (Fig. 16) which comprises geochronology, host rock, and also the petrographic-stratigraphic setting of the deposits, it becomes obvious that the uranium deposits show a direct or indirect affinity to:

a) the uppermost Archean - Lower Proterozoic

b) Hercynian - Upper Carboniferous to Lower Permian

c) in a less established stage: to the Upper Proterozoic

In addition to these facts, epigenetic deposits in sandstones and calcretes occur in remarkable spatial proximity to granitic complexes of the above ages.

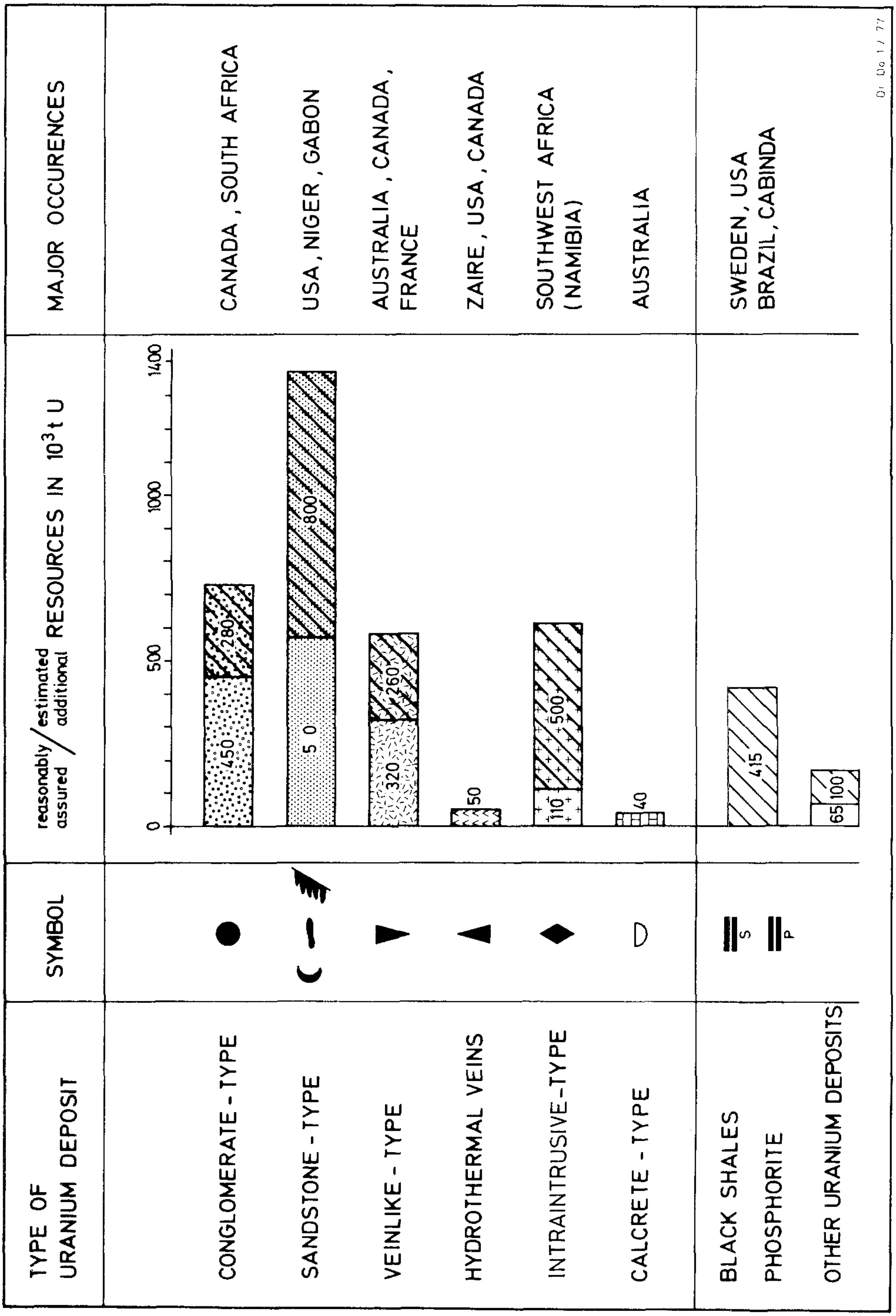

Fig. 13. Free World Uranium Resources by Type of Deposit

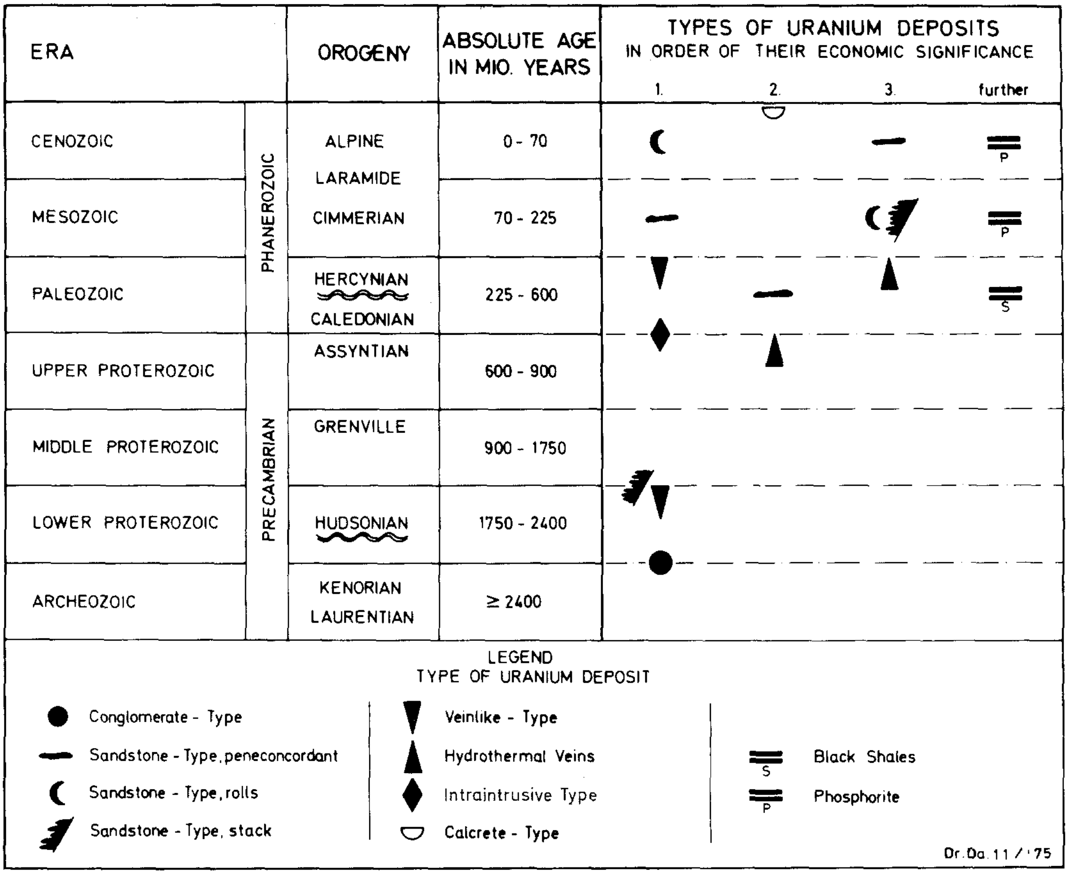

Fig. 14. Geochronologic Distribution of Types of Uranium Deposits

EXPLANATION OF NUMBER INDEX TO FIG. 15

No.	Name of Uranium Deposit	Country
	CONGLOMERATE TYPE	
1	Elliot Lake District	CAN.
2	Witwatersrand	S.A.
	SANDSTONE TYPE	
3	Wyoming District	USA
4	New Mexico District	USA
5	remaining Colorado Plateau	USA
6	Gulf Coast District	USA
7	Malargue, Sierra Pintata	ARG.
8	Salta	ARG.
9	Arlit	NIGER
10	Mounana, Oklo	GABUN
11	Ningyô Tôge, Tônô	JAPAN
12	Zirowski Vhr	YUG.
13	Lake Frome Basin	AUS.
14	Westmoreland District	AUS.
	VEINLIKE TYPE	
15	Beaverlodge District	CAN.

No.	Name of Uranium Deposit	Country
16	Rabbit Lake	CAN.
17	Cluff Lake	CAN.
18	Key Lake	CAN.
19	Rum Jungle	AUS.
20	Alligator Rivers District Jabiluka, Koongarra, Ranger, Nabarlek	AUS.
21	Central Massive	FRANCE
22	Vendée	FRANCE
23	Iberian Meseta	SPAIN/PORT.
	HYDROTHERMAL VEINS	
24	Port Radium	CAN.
25	Shinkolobwe	ZAIRE
26	Schwartzwalder Mine, Colo.	USA
27	Spokane District, Washington Sunshine Mine Midnite Mine	USA

No.	Name of Uranium Deposit	Country
28	Sonora, Durango, Chihuahua Prov.	MEX.
29	Poços de Caldas	BRAS.
	Agostinho	
	Cercado	
30	Singhbum District	INDIA
31	Hoggar	ALGERIA
	INTRAINTRUSIVE TYPE	
32	Rössing	S.W.A.
33	Phalaborwa	S.A.
	CALCRETE TYPE	
34	Yeelirrie	AUS.
	OTHER TYPES	
35	Bakouma (U-Phosphate)	Z.A.R.
36	Ranstad (Black Shales)	SWED.
37	Mary Kathleen (pyrometasomatic)	AUS.

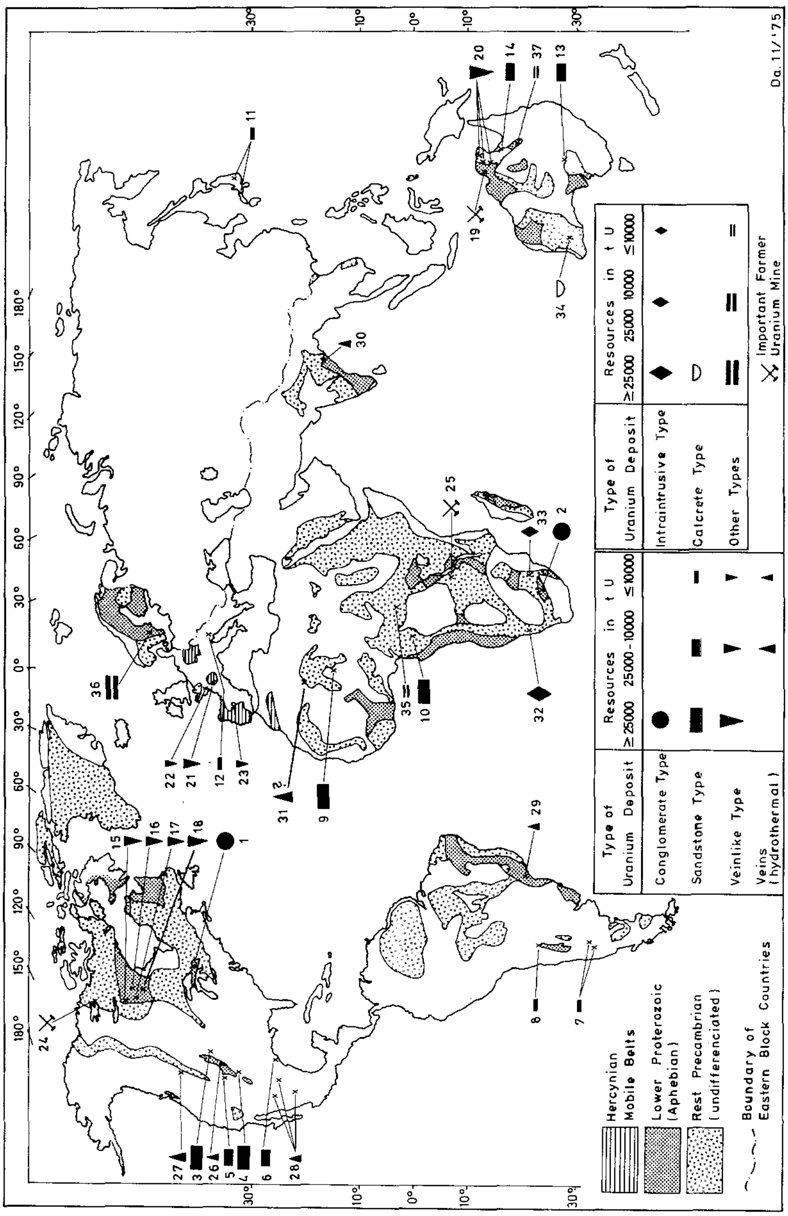

Fig. 15. Metallotectonic Distribution of Uranium Deposits of the Western World

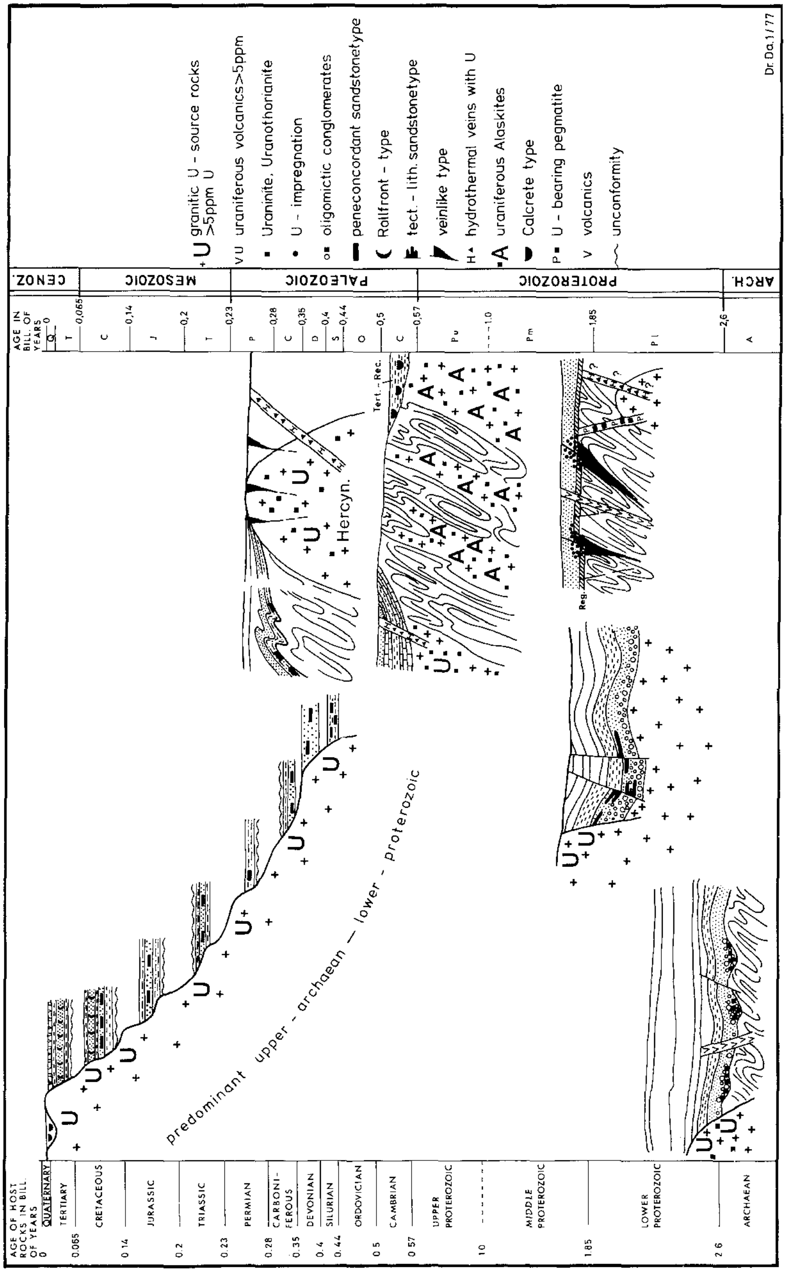

Fig. 16. Geochronologic-Stratigraphic Distribution of U-Host Rocks and Types of U-Deposits

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