PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Mode of Occurrence and Distribution of Uranium Deposits

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Phil. Trans. R. Soc. Lond. A 1979 **291**, 289-300
doi: 10.1098/rsta.1979.0027

Phil. Trans. R. Soc. Lond. A. **291**, 289–300 (1979)
Printed in Great Britain

The mode of occurrence and distribution of uranium deposits

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Uranium deposits occur in association with igneous, sedimentary and metamorphic rocks. The bulk of low-cost reserves, however, occurs in Precambrian rocks or in Phanerozoic sediments immediately overlying the basement. In basement rocks, as well as in more recent rocks, major uranium deposits are spatially associated with leucogranites. In Phanerozoic sediments, close to the basement uranium is enriched in continental clastic formations under reducing conditions. Favourable lithologies are alternating horizons of clay and sandstone containing carbonaceous matter.

Metamorphic developments are associated with zones of crustal thickening with a world-wide era of concentration at around 1900–1700 Ma ago. Uranium is also enriched in more recent metamorphosed clastic sediments.

Deposits directly associated with igneous rocks tend to occur in unsaturated facies rich in volatiles.

Granitic and alaskitic pegmatites also carry economic amounts of uranium. The most important secondary deposits of recent origin are those occurring in carbonate- or sulphate-cemented sediments.

Introduction

Uraninite, or the less well crystallized variant, pitchblende, was first identified from a vein deposit at Joachinstal, Bohemia, in 1727. It was later recovered from similar deposits in Bohemia, Saxony and Cornwall. Before the end of the last century uraninite was known to occur in pegmatites mainly at localities in Norway and the U.S.A.; and also by that time carnotite had been recognized in sandstones in Colorado and Utah. In the early 1920s a fourth type of uranium occurrence, that of uraninite in quartz-pebble conglomerates, was reported from the Witwatersrand, South Africa. Thus, by the outbreak of World War II the main modes of occurrence of low-cost uranium, with the exception of uranium in calcretes, had been recognized. Soon after the war the major provinces of Colorado–Wyoming; Witwatersrand; Northern Territory, Australia; South Australia; and northern Saskatchewan were known to contain considerable amounts of uranium. The reserves in these provinces today total more than 60% of the world (excluding Communist countries) tonnage. The most important new provinces discovered since 1950 have been the Blind River–Elliot Lake field of Ontario; Agadès basin, Niger; and Rössing, South West Africa (figure 1).

It is convenient to classify known uranium deposits as vein-type, uranium in sandstones, uranium in conglomerates, and other uranium deposits.

Vein-type deposits

No uranium vein deposit more than 2000 Ma old is known either in Archaean† nuclei or in younger rocks. The earliest that uranium is known to have been mobilized and concentrated

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† Nomenclature used: Precambrian: Upper Proterozoic 1200–600 Ma; Middle Proterozoic, 1800–1200 Ma; Lower Proterozoic 2400–1800 Ma; Archaean older than 2400 Ma.

in veins appears to have been associated with a major orogenic event between 1900 and 1700 Ma ago when there was also widespread regional metamorphism and granite formation. For example, in Northern Territory, Australia (figure 2), the first period of mineralization is dated at around 1800 Ma; in the Arjeplog–Arvidsjaur region of Sweden at 1740 Ma; in the Beaverlodge district of northern Saskatchewan (figure 3) at 1780 Ma; and in the Franceville basin, Gabon, at 1740 Ma. At many localities there is evidence of repeat mineralization: for example, at Beaverlodge this took place at 1100, 270 and 100 Ma. In the Alligator Rivers province successive ages are tentatively established as 1880, 1700, 900 and 500 Ma (Dodson *et al.* 1974). Another Precambrian example is provided by Rabbit Lake, northern Saskatchewan, where the initial mineralization was at 1075 Ma, with later introduction or remobilization as recent as a few hundred million years ago (Knipping 1974).

Figure 1. Major uranium deposits and provinces (non-Communist countries): 1, Beaverlodge; 2, Cluff Lake; 3, Wollaston belt; 4, Elliot Lake/Agnew Lake; 5, Bancroft; 6, Makkovik; 7, Ilímaussaq; 8, Spokane; 9, Wyoming basins; 10, Uravan; 11, Grants; 12, Texas; 13, Poços de Caldos; 14, Figueira; 15, Salta; 16, Malargue; 17, Ranstad; 18, Massif Central; 19, Salamanca; 20, Urgeiriça; 21, Hoggar; 22, Agadès; 23, Bakouma; 24, Mounana; 25, Shinkolobwe; 26, Rössing; 27, Witwatersrand; 28, Singhbhum; 29, Alligator Rivers; 30, Westmoreland; 31, Mary Kathleen; 32, Yeelirrie; 33, Frome/Yarramba.

Younger vein deposits developed in Upper Proterozoic times are Shinkolobwe, Swambo and Kalongwe, in the Zambesi–Damaran mobile belt to the northwest of the Kaapvaal and Rhodesian cratons, and are dated at 620 Ma.

The most recent deposits of economic significance are associated with the Hercynian and Alpine orogenies as for example in Europe where ages of mineralization range from 300 to 50 Ma. Associated granites are about the same age or older as in Cornwall where the granite batholith is dated at 290 Ma whereas ages for uranium mineralization are 290, 225 and 50 Ma (Darnley *et al.* 1965).

A fairly typical example of a uranium vein deposit in Lower Proterozoic sediments is that of Koongarra in the Alligator Rivers region 225 km southeast of Darwin. The mineralization, which is essentially of pitchblende, occurs above a reverse-faulted contact with the Kombolgie Formation (Middle Proterozoic). Quartz-chlorite schists are host to the bulk of the mineralization. In breccia zones, fragments are cemented by quartz-chlorite and dark green chlorite rock with an appreciable development of haematite. Graphitic chlorite schists also occur in the sedimentary sequence, but the ore tends to form beneath this horizon. The controls for mineralization appear to have been physico-chemical with uranium precipitating from carbonate-rich solutions. The first phase of mineralization is closely associated in time with renewal of activity in the Archaean complexes of Nanambu and Rum Jungle at about 1800 to 1700 Ma

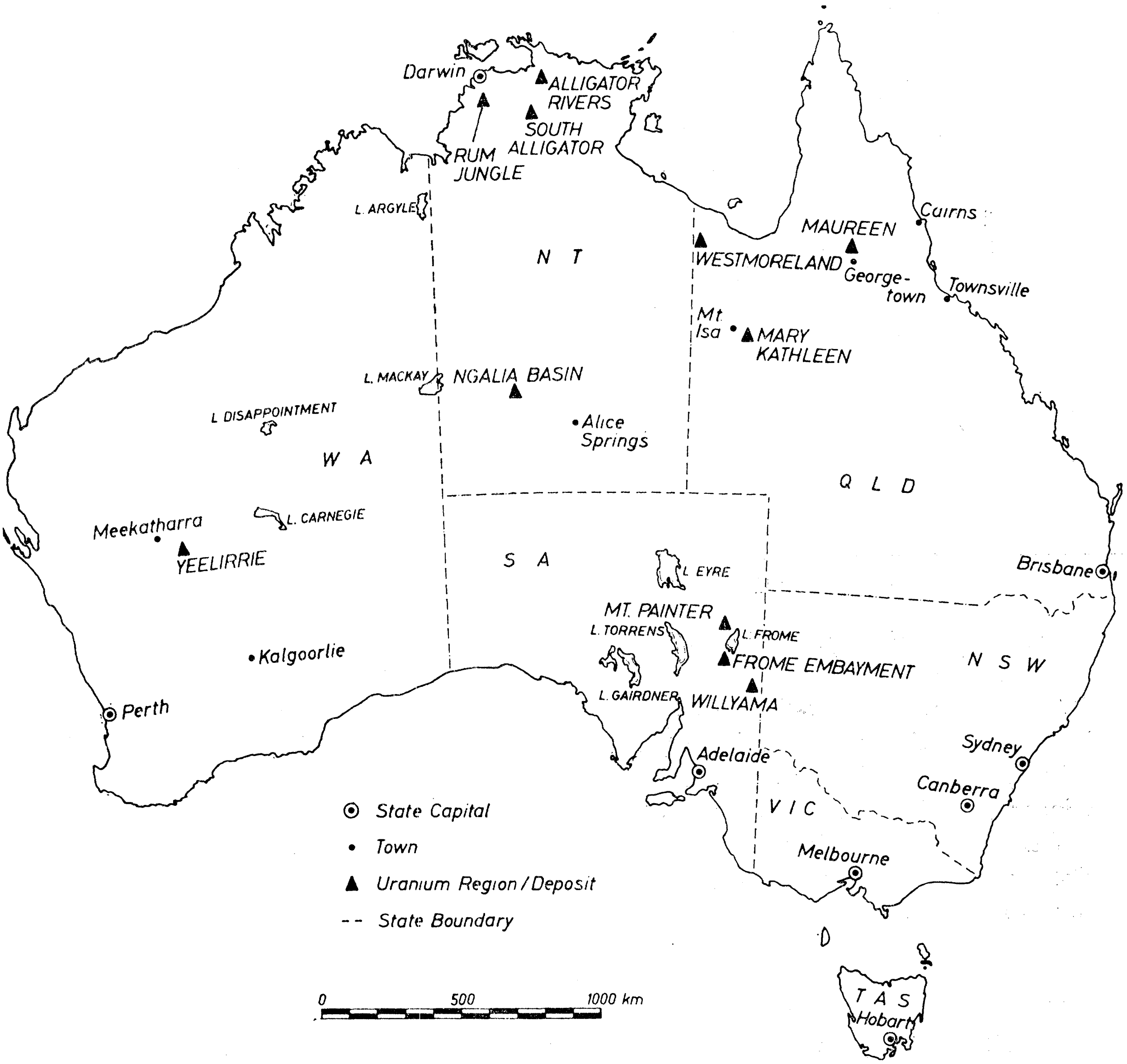

FIGURE 2. Locality map of Australian uranium deposits. After Ryan (1977).

ago and the emplacement or formation of granitic masses in the region. Relatively low-grade regional metamorphism (amphibolite facies) and orogenic quiescence since Middle Proterozoic times seems to have been an important feature in mineralization being preserved in more or less its original form in the whole of the Alligator Rivers region.

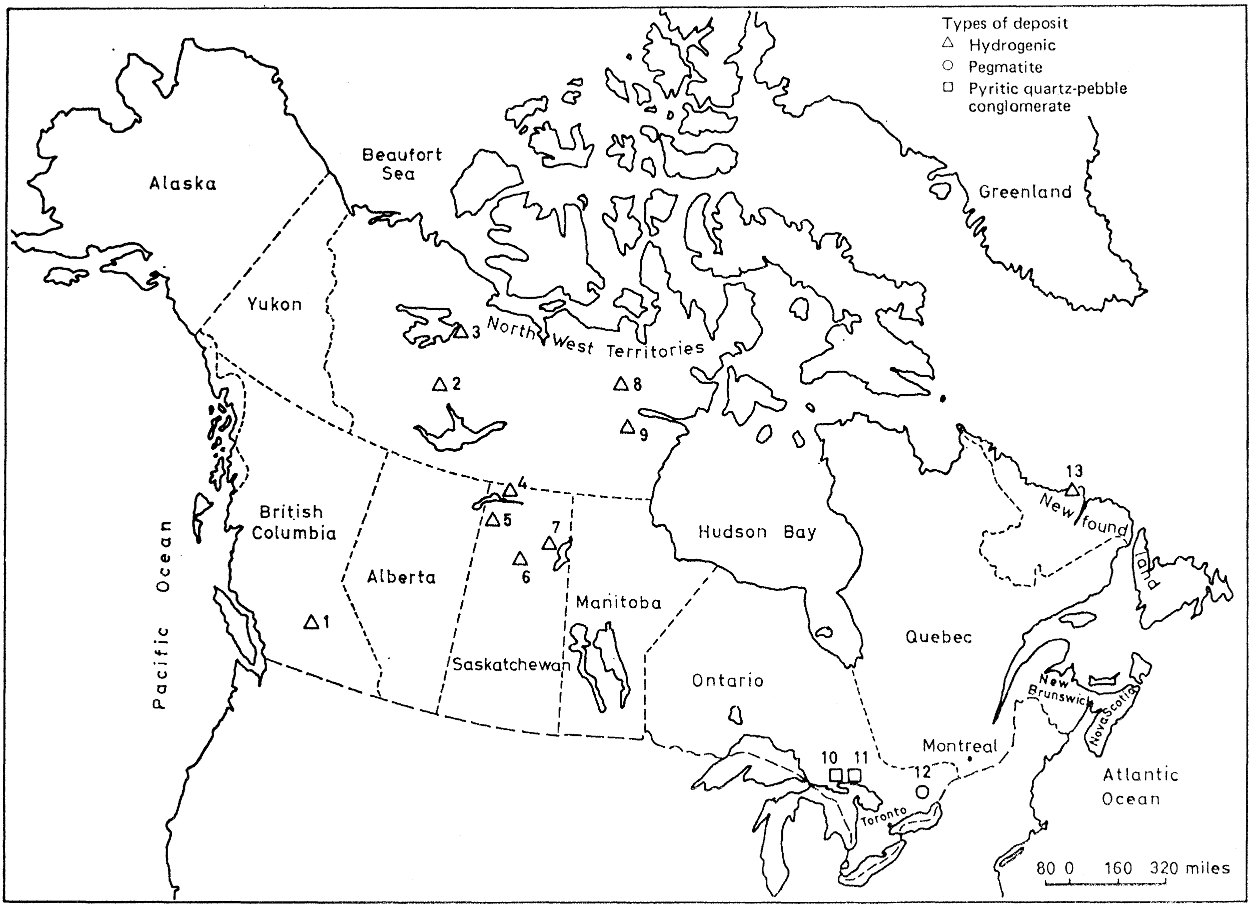

Figure 3. Past and potential producers of uranium in Canada. After McMillan (1977).

Phanerozoic vein deposits, for example those of France, tend to be associated with leucogranites, especially 'two-mica granites' with relatively high uranium contents (10–20 parts U/10^6) and low Th : U ratios. Veins tend to be near vertical and commonly occur in regions invaded by basic dykes and with structural zones with abundant chloritic rock. The main primary uranium minerals are pitchblende and coffinite which are associated with relatively minor copper, iron and lead sulphides.

Well known deposits in other parts of the world are Urgeiriça, Portugal; Schwartzwalder, Colorado; Sunshine and Midnite, Spokane. Together, vein deposits compose nearly 20% of total world reserves.

URANIUM IN SANDSTONES

Uranium deposits in sandstones are among the best documented of all types of mineral deposit. They are also the most important as a source of uranium as they contain about 34% of known reserves. The bulk of uranium in sandstones occurs in the Colorado–Wyoming province of the U.S.A. in sediments ranging from Triassic to Eocene in age. Major deposits are classified into two main types – peneconcordant and roll – on the basis of their morphological characteristics. Like deposits in Precambrian sediments, they are commonly associated with unconformities, troughs and ancient stream channels. They are confined essentially to fluviatile quartzose sandstones and mudstones and vary enormously in size from small pockets to large volumes of mineralized sediment thousands of square metres in lateral extent and thirty or more metres thick. The most favourable host rock seems to be an impure medium- to coarse-grained quartz sandstone containing clay minerals, volcanic ash and plant remains. Carbonaceous matter, however, is not always an important localizing factor. A reducing environment resulting from the presence of detrital pyrite, introduced humic substances, or hydrogen sulphide, can be equally effective at precipitating uranium from ground waters. Roll deposits have probably formed in a number of ways, but essentially they appear to have resulted from the downward migration of oxygenated water into a reducing environment. A clear-cut redox front, however, is not always recognizable (Adler 1974). The roll deposits in the Gulf Coast area of Texas appear to have resulted from the introduction of hydrogen sulphide from underlying gas and oil deposits (Adler 1974). A feature of sandstone-type deposits in the U.S.A. is that they are relatively shallow, extending from surface to a depth of 200 m, though some are as deep as 700 m. Grades are generally greater than 0.1% with the uranium contained mainly in pitchblende and coffinite.

Other significant deposits in sandstones are those of Niger where several occurrences are present in Carboniferous and younger sediments on the western margin of the Aïr Massif of Precambrian age. At Arlit, where a major deposit occurs, the sediments are deltaic, fluviatile to lacustrine in nature with abundant carbonaceous matter and pyrite. The richest pockets of mineralization, mainly of pitchblende and coffinite, appear to have been concentrated in traps created by the response of the sediments to tectonic movements. Uranium reserves in the Agadès basin could well prove to be of the order of 200000 t, making the region one of the most significant discovered since World War II.

Somewhat similar deposits occur in the Frome Embayment province of South Australia where a relatively thin deposit of Phanerozoic rocks immediately overlies the Precambrian basement. Deposits exhibiting features similar to those of the Colorado–Wyoming province are currently being investigated. It would appear, however, that the environments differ in respect of the absence of tuffaceous sediments in the Frome Embayment. Uranium deposits also occur in sandstones at Figueira (Brazil), Sierra Pintada (Argentina) Nagalia basin (Australia), Ningyo-Toge and Kurayoshi (Japan), Val Rendena (Italy), Zirovski Vhr (Yugoslavia) and Forstau (Austria).

URANIUM IN CONGLOMERATES

Uranium in conglomerates constitutes about 17% of world uranium reserves. The grade tends to be somewhat lower than in vein or sandstone-type deposits thought it is about 0.1% U_3O_8 in the Blind River–Elliot Lake area. In the Witwatersrand it averages between 200 and 300 parts $U_3O_8/10^6$ which means that uranium recovery is generally possible only as a by-product of gold.

Two main systems in the Witwatersrand basin are uranium bearing: the Dominion Reef System and the overlying Witwatersrand System. In the former, a typical placer assemblage of heavy minerals occurs, particularly in the Klerksdorp area. The main uranium mineral, thorian uraninite, is associated with brannerite, uranothorite, columbotantalite, monazite, cassiterite and smaller amounts of chromite, garnet, zircon and ilmenite. Gold also occurs but generally at too low a grade to be mined. The host rock tends to be a quartzite rather than a conglomerate and the uranium and thorium minerals are all apparently of detrital origin. This is confirmed by age dating which indicates that the radioactive minerals are about 3060 Ma old (Nicolayson 1962) or virtually the same as a whole-rock Rb–Sr age of 3100 Ma for the Archaean granite which underlies the Witwatersrand System in the Central Rand. This makes the Dominion Reef concentrations the oldest known in the world as they were probably formed before 2740 Ma ago (Rundle & Snelling 1977).

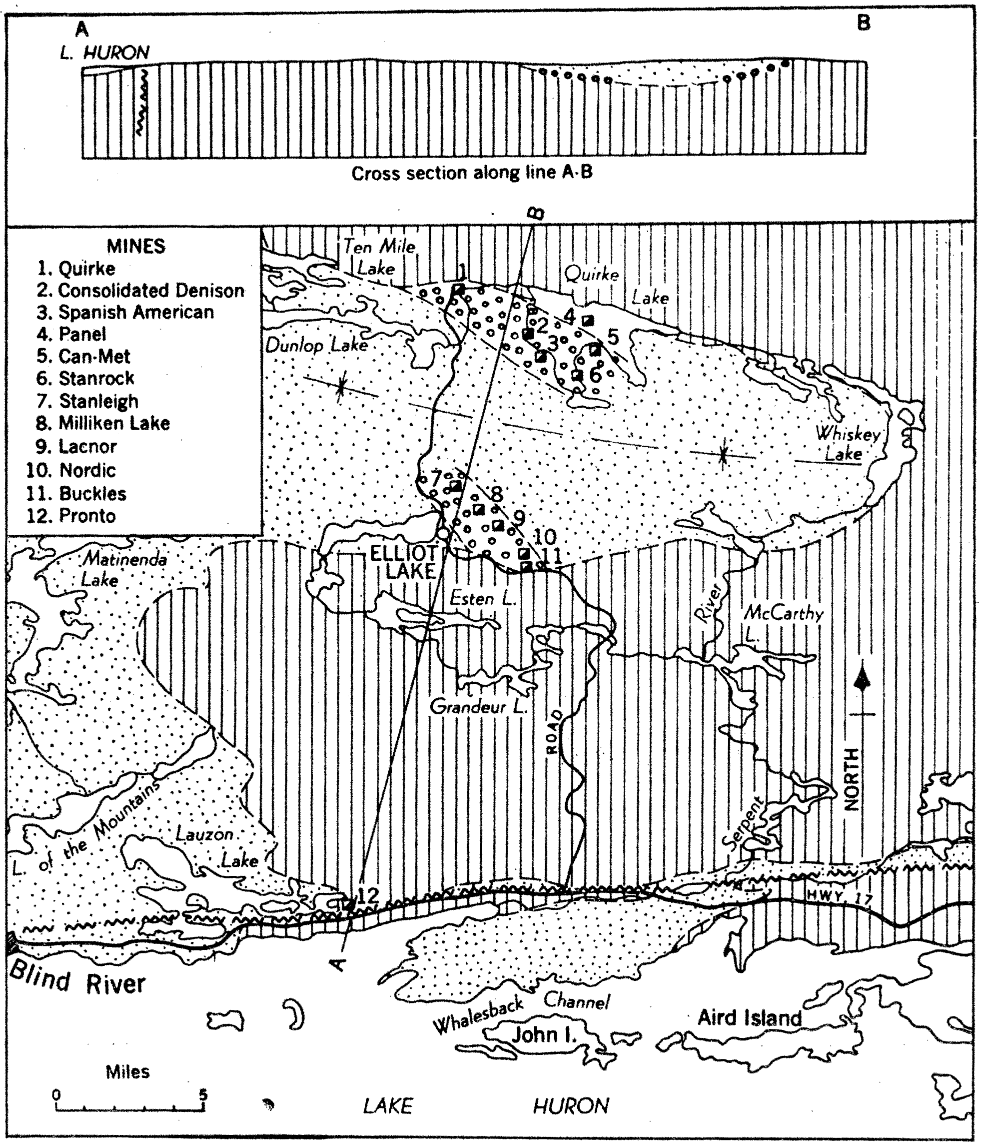

Figure 4. Diagrammatic geological plan and cross section, Blind River area, Ontario. Stippling, Huronian sedimentary rocks and some intrusive rocks; vertical hatching, pre-Huronian basement rocks; open circles within broken lines, outline of thickest known part of lower Mississagi (Matinenda) formation including ore beds (projected to surface); 〰, fault (approximate); ✱, syncline (approximate); ◪, shaft. After Lang, Griffith & Stacey (1962).

In the Witwatersrand System, which is about 7500 m thick in the Central Rand, there are five main uranium-bearing horizons associated with unconformities. Uranium occurs in grains averaging about 50 μm in diameter in association with gold, pyrite, various other sulphides, chlorite, sericite and carbonaceous material. The distribution of uraninite and gold is related to sedimentary features. They tend to occur in quartz-pebble conglomerates, continuous over large areas, that rest on unconformities or intraformational breaks. But, not infrequently, the highest grades are at the top of the conglomerate horizon.

I suggested many years ago (Bowie 1956) that there was probably more than one generation of uraninite in the Witwatersrand conglomerates. However, this has only recently been verified by Simpson & Bowles (1977) who demonstrated that detrital components are concentrated in the high-energy conglomerates in the near-shore portions of the basin. In low-energy environments they indicate that uranium precipitated from solution particularly in association with organic-rich horizons such as the Carbon Leader. The precipitated phase is that dated by Burger *et al.* (1962) at 2080 Ma and more recently by Rundle & Snelling (1977) at 2040 Ma.

Uranium reserves in the Witwatersrand basin are of the order of 200000 t.

The major deposits of uranium in quartz-pebble conglomerates which occur in the Blind River–Elliot Lake province of Ontario were discovered in 1953 by direct geological analogy with the Witwatersrand deposits. The uranium in this field is concentrated in the Matinenda Formation within 30 m of the Archaean basement. The ore bodies, which are elongate or tabular and vary greatly in size, are nearly all located in two troughs, one on either side of the Quirk Lake syncline (figure 4). The main uranium minerals are uraninite and brannerite which are associated with varying amounts of monazite, uranothorite, uranothorianite, coffinite, allanite, anatase, rutile, zircon and sphene. Th : U ratios change from 1 : 4 to 4 : 1 depending on the proportion of thorium to uranium minerals. At Agnew Lake, for example, uranothorite and monazite predominate over uraninite and brannerite. The average grain size of uraninite is about 100 μm and of brannerite 300 μm. Grades are generally about 0.1% U_3O_8 and reserves and more than 100000 t U. An important feature of the deposits is that the ages of the uranium minerals post-date the age of the basement. The basement is dated as younger than 2500 Ma but older than 2150 Ma whereas the brannerite is 2000–1800 Ma old and the uraninite 1740–1680 Ma (Mair 1960). Earlier determined ages on uraninite from Algom Quirke and Pronto showed a spread of near-concordant ages ranging from 1200 to 600 Ma. These ages are of special interest as the monazite and zircon, which were almost certainly derived from the basement, have been dated at 2500 Ma making this the most probable age of the formation of the basement complex.

Uranium which occurs in quartz-pebble conglomerates of Lower Proterozoic age at Belo Horizonte, Minas Gerais, Brazil, has many similarities with the Blind River–Elliot Lake deposits. The grade, however, is of the order of 200 parts $U_3O_8/10^6$ and therefore not economically viable at present. Recently, uranium has been reported to occur in Cambro-Ordovician conglomerate and sandstone south of Ahaggar, Algeria, but the extent of the development is not yet known.

Other uranium deposits

The most important deposits in this omnibus category are the quartz, alkali–feldspar pegmatites (alaskites) which form dyke-like structures in Precambrian schists and other metasediments at Rössing in South West Africa. The pegmatites are unzoned and contain uranium in the form of fine-grained uraninite, betafite and davidite. Near-surface rocks contain an assemblage of supregene uranium minerals including betauranophane, metatorbernite, metahaiweeite, uranophane, carnotite, thorogummite, and gummite. The alaskites are considered to be early syntectonic to post-tectonic in their formation (Smith 1965). However, age determinations (Nicolayson 1962) on uraninite, davidite and biotite indicated a provisional age of 510 ± 40 Ma.

Somewhat akin to, but chemically distinct from, the dyke-like pegmatites of Rössing are the unzoned pegmatites of the Bancroft area of Ontario. Generally the grain size of these bodies is no coarser than that of a granite but coarse-grained pockets occur giving the term 'pegmatite'. The main ore minerals are uraninite and uranothorite, but betafite, allanite, and fergusonite are also present. Uranium-bearing minerals are best developed in zones of hematization. The grade of the deposits averages about 0.1% U_3O_8 and reserves are of the order of 2000 t U.

The uranium concentrations in the peralkaline nepheline syenites of Ilímaussaq provide the best example of uranium and thorium enrichment clearly associated with magma crystallization and differentiation. The latest intrusive phases contain up to 0.1% U and 0.5% Th (Bohse *et al.* 1974) and there are late veins rich in radioactive minerals in the roof zone on the northern side of the intrusion where the rocks are strongly fenitized. The uranium occurrence of Kvanefield, which is part of this complex, contains uranium resources of 14500 t at an average grade of 300 parts U/10^6 mainly contained in steenstrupine (Steenfelt *et al.* 1977).

Uranium is also known to be concentrated in carbonatites, but, to date, only the deposit at Palabora in northeast Transvaal has proved to be capable of sustaining a small production of uranium as a by-product. The Palabora complex consists essentially of pyroxenite, syenite, olivine–diopside–phlogopite pegmatoid, fenite and carbonatite which are intrusive into Archaean granite gneiss. Uranium is mainly confined to the carbonatite and a serpentine–magnetite–apatite rock and occurs in the form of baddeleyite and uranothorianite. Reserves are estimated to be 11000 t U at a grade of 0.004% U_3O_8.

Another occurrence similar to that at Ilímaussaq is Poços de Caldos, Brazil, where a nepheline syenite pipe of Upper Cretaceous age contains uranium mainly in zircon and baddeleyite. However, late-stage vein development appears to have progressed further than at Ilímaussaq and has resulted in vein deposits with appreciable uranium enrichment associated with fluorine and molybdenum. The latter deposits contain about 4000 t U at a grade around 0.2% U_3O_8.

A unique uranium deposit of pyrometasomatic origin is that of Mary Kathleen in Queensland. The mineralization is essentially of uraninite with rare-earth silicates and sulphide minerals occurring in a garnetized zone of calc-silicate rocks of Middle Proterozoic age. The mineralization is controlled by faulting and shearing and is probably related to the Mount Burstall granite. The grade is 0.12% U_3O_8 and reserves are of the order of 7600 t U.

Uranium, in addition to occurring in deposits that might be considered as being magmatogenic, is present as a syngenetic constituent in sedimentary rocks and may be locally enriched by diagenetic or metamorphic processes. Examples are uranium in shale, phosphate rock and lignites. The best example of uranium concentration in shale is that of the Upper Cambrian alum shales of Southern Sweden which were deposited in a shallow epicontinental sea under strongly reducing conditions (Armands 1972). Molybdenum, vanadium, copper, lead and zinc were also enriched in these shales. Reserves of uranium in the Västergötland and Närke districts total over 1 Mt U at a grade of 0.03 % U_3O_8. Of this total about 300000 t U could be recovered. Other well known uraniferous shales, but with less than a quarter of the average uranium content of the alum shales, are those of Chattanooga, Tennessee, Arkansas and adjoining states which average 60–70 parts $U_3O_8/10^6$ over large areas in a horizon some 5 m thick.

Uranium is also concentrated syngenetically in phosphate rock, for example, the phosphorite deposits of the Phosphoria and Bone Valley formation of Idaho, Montana, Utah and Wyoming as well as in the land-pebble phosphates of Florida. The richer horizons in these occurrences are up to 1 m thick and average 100–200 parts $U_3O_8/10^6$. Similar phosphate deposits that occur in a belt stretching from Morocco through Algeria, Tunisia, Egypt and Israel are of a slightly lower average grade. The richest known concentrations are in the phosphatic sediments in Cabinda, Angola and Central African Republic where uranium contents range from 0.05 to 0.3 % U_3O_8.

Lignites also have concentrations of uranium ranging up to 0.25 % U_3O_8. Examples are the lignites of North and South Dakota which average 0.2 % U_3O_8 over widths of 0.5 m. The Tertiary lignites of the Ebro Valley, Spain, also contain large quantities of uranium at grades of between 0.05 and 0.25 % U_3O_8.

Another category of occurrence among 'other uranium deposits' which is of more immediate economic potential than lignites or phosphorites is supergene concentrations in calcrete. Small occurrences of this type have been known for many years, but their significance changed dramatically with the discovery of the Yeelirrie deposit in Western Australia in 1972. Here, carbonate- and sulphate-cemented sediments occur within granitoid–gneiss terrain in Archaean rocks of the Yilgarn belt about 700 km northeast of Perth. The uranium is in carnotite dispersed throughout earthy calcrete and on cavity walls of porcellainous calcrete as well as on fracture and fault planes in the sediments. The average grade of this material is 0.15 % U_3O_8 and reserves are over 40000 t U.

Discussion

More than 90 % of the known uranium deposits of the world occur in Precambrian rocks or in Phanerozoic rocks immediately overlying Precambrian basement (figure 5). This seems to indicate that the original partitioning of uranium into metallogenic provinces was associated with the early development of the sialic crust. With the exception of the Dominion Reef thorian uraninite and the uraninite of the Witwatersrand System, the first phase of concentration of uranium to economic grades began between 1900 and 1700 Ma ago and this was followed by significant new developments between 1200 and 600 Ma ago. Subsequent concentrations are closely related to well defined orogenic events.

The early appearance of abundant granitic rocks, which Gastil (1960) indicated reached peak developments around 2750–2450 Ma, 1900–1600 Ma and 1150 and 900 Ma, seems particularly significant. It explains the extensive occurrence of quartz-pebble conglomerates in the Huronian and Witwatersrand Supergroups. The tectonothermal events around 1800 Ma could have resulted in further differentiation of crustal rocks with concentration of uranium mainly from solutions rich in fluorine, chlorine and carbonate ions associated with granitic rocks. Later Precambrian dates which indicate uranium mineral formation at around 1100–900 Ma also coincide with orogenic events.

In Ontario, metamorphic events recognized by Van Schmus (1976) show a remarkable coincidence with U/Pb ages on minerals from the quartz-pebble conglomerates. For example, the age for brannerite formation, 2000–1800 Ma, coincides with the Penokean orogeny; the earliest recorded data for uraninite formation, 1740–1680 Ma, coincides with widespread metamorphism at 1700–1650 Ma; and the ages of 1200–600 Ma are related to Grenvillian events.

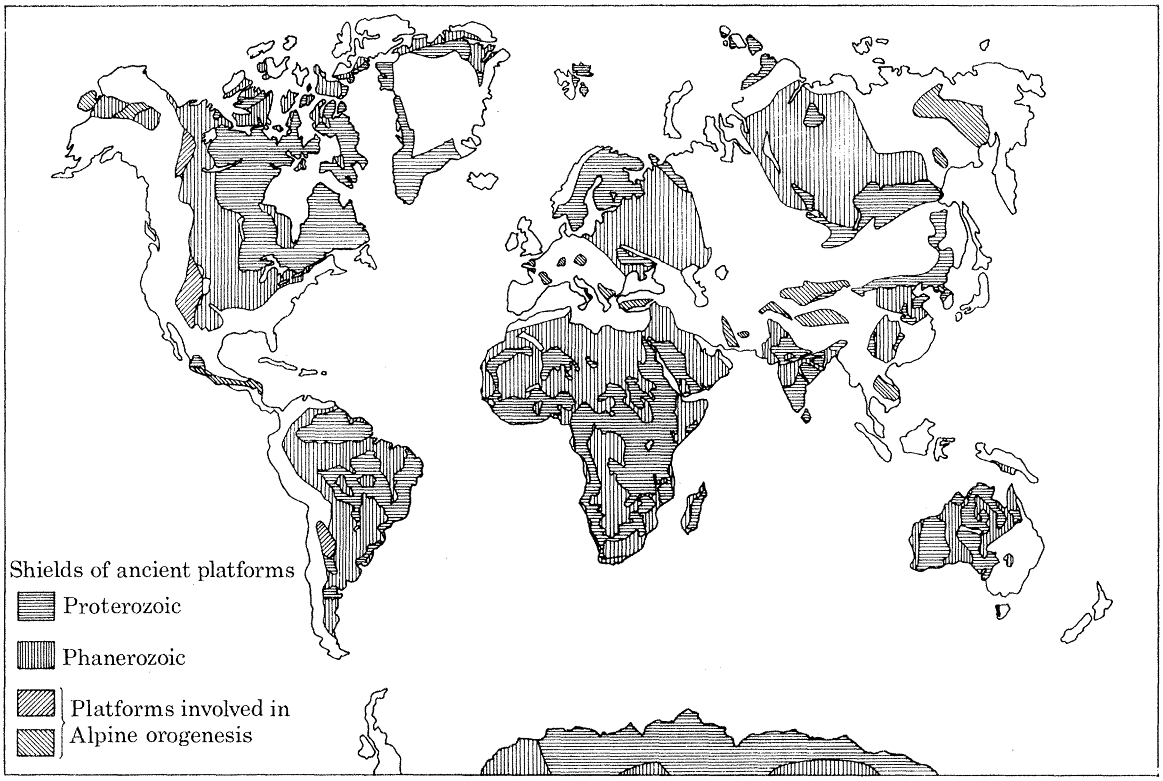

FIGURE 5. Tectonic map showing Shield areas of world with areas of sedimentary cover and regions involved in Alpine orogenesis. After Khain & Muratou (1969).

It is not clear to what extent uranium continued to be introduced from a mantle source or was redistributed in crustal rocks as a result of anatexis or metamorphism. It is fairly well established, however, that it is not mobilized at metamorphic grades below granulite facies.

Relatively young uranium deposits, whether in veins or disseminated in sediments, such as those in France, Austria, Italy and Czechoslovakia, have Hercynian to Alpine ages but are closely associated with Precambrian basement. The same can be said of the deposits of the Colorado–Wyoming province which give Late Cretaceous to Early Tertiary ages coinciding with the Laramide orogeny. The province, however, is underlain by a southwestward extension of the Canadian Shield thus prompting the question as to whether uranium development here is fortuitous or connected with the Precambrian basement. I believe the latter. It is significant to note that the Colorado–Wyoming province remained relatively undisturbed until it was subjected to uplift, folding and faulting during the Laramide orogeny. The upward movement with basin development is considered by Woodward (1976) to require deep crustal or upper mantle volume changes which can be explained best by phase changes.

Some conclusions

(1) The pattern of uranium distribution in the Earth's crust was probably set by relatively small convection cells operating during early crustal evolution.

(2) Uranium deposits are associated with orogenic events or perhaps more closely with the introduction or formation of acid igneous rocks that followed peak orogenic activity.

(3) Orogenic processes associated with the margins of Upper Archaean–Lower Proterozoic or Lower Proterozoic–Middle Proterozoic cratonic masses may have been responsible for many early uranium concentrations.

(4) Uranium deposits in Phanerozoic rocks are likely to be found in regions of basement 'highs' where Precambrian rocks were subjected to crustal thickening and the region was involved in subsequent epeirogenic movements.

(5) Long periods of quiescence can result in early-formed uranium deposits being preserved, as in Northern Territory, Australia; but late orogenic events in such regions might result in uranium remobilization in such a way as to make it more readily available at, or just below, the present surface. An example is almost certainly the Colorado–Wyoming province.

(6) Major fault patterns set in Precambrian times played an important rôle in later uranium concentrations in whatever host rock.

(7) Uranium deposits were probably not derived from granites, but were formed by the processes that produced the granite differentiates. Basic dykes, which are almost always developed in association with uranium deposits, indicate that differentiation was still taking place after the granitic phase, or phases, consolidated.

(8) Uranium was transported in volatile fluoride and chloride complexes, for example uranium silicofluoride, as well as in alkaline carbonate solutions, for example as sodium uranyl dicarbonate.

(9) Precipitation of uranium in sediments was effected under reducing conditions especially in association with iron sulphides, hydrogen sulphide and organic substances.

(10) Most uranium deposits, whether in veins, sandstones, conglomerates or other rocks, formed over a long interval of time.

(11) Uranium in the oxide phase is not remobilized at metamorphic grades below granulite facies.

References (Bowie)

Adler, H. H. 1974 In *Formation of uranium ore deposits* (Proceedings of a Symposium, Athens, 1974), pp. 141–167. Vienna: I.A.E.A.

Armands, G. 1972 *Geochemical studies of uranium, molybdenum and vanadium in a Swedish alum shale* (Stockholm Contributions in Geology, XXVII: 1). Stockholm.

Bohse, H., Rose-Hansen, J., Sørensen, H., Steenfelt, A., Løvborg, L. & Kunzendorf, H. 1974 In *Formation of uranium ore deposits* (Proceedings of a Symposium, Athens, 1974), pp. 49–90. Vienna. I.A.E.A.

Bowie, S. H. U. 1956 In discussion of Davidson, C. F. *Trans. Instn Min. Metall.* **74**, 492–496.

Burger, A. J., Nicolaysen, L. O. & de Villiers, J. W. L. 1962 *Geochim. cosmochim. Acta* **26**, 25–29.

Darnley, A. G., English, T. H., Sparke, O., Preece, E. R. & Avery, D. 1965 *Miner. Mag.* **34**, 159–176.

Dodson, R. G., Needham, R. S., Wilkes, P. G., Page, R. W., Smart, P. G. & Watchman, A. L. 1974 In *Formation of uranium ore deposits* (Proceedings of a Symposium, Athens 1974), pp. 551–567. Vienna: I.A.E.A.

Gastil, G. 1960 *21st Session Int. Geol. Cong.*, pt 9, pp. 162–169.

Khain, V. E. & Muratou, M. V. 1969 In *The Earth's crust and upper mantle* (Geophysical Monographs no. 13) (ed. P. J. Hart), pp. 523–538. Washington, D. C.: American Geophysical Union.

Knipping, D. H. 1974 In *Formation of uranium deposits* (Proceedings of a Symposium, Athens 1974), pp. 531–548. Vienna: I.A.E.A.

Lang, A. H., Griffith, J. W. & Stacey, H. R. 1962 *Canadian deposits of uranium and thorium*, 2nd edn. Econ. Geol. Ser. Can. no. 16.

McMillan, R. H. 1977 In *Geology, mining and extractive processing of uranium* (ed. M. J. Jones), pp. 43–55. London: Institution of Mining and Metallurgy.

Mair, J. A., Maynes, A. D., Patchett, J. E. & Russel, R. D. 1960 *J. geophys. Res.* **65**, 341–348.

Nicolayson, L. O., Burger, A. J. & Liebenberg, W. R. 1962 *Geochim. cosmochim. Acta* **26**, 15–23.

Nicolayson, L. O. 1962 *Geol. Soc. Am. petr. Studies*, Buddington Mem. vol.

Rundle, C. C. & Snelling, N. J. 1977 *Phil. Trans. R. Soc. Lond.* A **286**, 567–583.

Ryan, G. R. 1977 In *Geology, mining and extractive processing of uranium* (ed. M. J Jones), pp. 24–42. London: Institution of Mining and Metallurgy.

Simpson, P. R. & Bowles, J. F. W. 1977 *Phil. Trans. R. Soc. Lond.* A **286**, 527–548.

Smith, D. A. M. 1965 Mem. 3 S.W.A., *Ser. Geol. Surv. S. Afr.*

Steenfelt, A., Neilson, B. L. & Secher, K. 1977 In *Geology, mining and extractive processing of uranium* (ed. M. Jones), pp. 8–12. London: Institute of Mining and Metallurgy.

Van Schmus, W. R. 1976 *Phil. Trans. R. Soc. Lond.* A **280**, 605–628.

Woodward, L. A. 1976 In *Tectonics and mineral resources of southwestern North America.* New Mexico Geol. Soc. Spec. Pub. no. 6, pp. 11–17.