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

Uranium in South Africa and South West Africa (Namibia)[and Discussion]

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Uranium in South Africa and South West Africa (Namibia)

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A number of genetically different uranium deposits occur in South Africa and South West Africa in rocks of widely differing ages. Early Proterozoic clastic rocks contain sedimentary uraninite, whose deposition in auriferous quartz-pebble conglomerates and carbon seams can be related to fluvial fans and algal mats. Recently discovered deposits of uranium in the Phanerozoic Karoo Supergroup occur as widespread but small bodies in channel sandstones of fluvial association. Carnotite deposits are developed in Cainozoic calcretes in the western, more arid, regions of southern Africa in which the uranium has been precipitated epigenetically from circulating groundwater.

Uranium mineralization in magmatic rocks is present to a small extent in phoscorite and carbonatite of the middle Proterozoic Phalaborwa Igneous Complex, and is associated with alkaline lavas and intrusive rocks in the Pilanesberg alkaline complex of middle–late Proterozoic age. Multicyclic processes of ore formation have produced extensive deposits of uraninite-bearing alaskitic pegmatitic granites, of Phanerozoic age, in the Pan-African Damara metamorphic belt.

In the southern part of Africa, resources of uranium comprise a large number of ore deposits (von Backström 1976) which are basically of five types (see figure 1 for localities): (1) quartz-pebble conglomerates in sedimentary basins of Proterozoic age; (2) sandstone-type deposits in sedimentary basins of Phanerozoic age; (3) deposits in superficial calcretes; (4) carbonatites and associated alkaline rocks of various ages; (5) intrusive alaskitic pegmatitic granites of early Phanerozoic age.

1. Quartz-pebble conglomerates

It is common knowledge that in South Africa, uranium is primarily recovered as a by-product of gold mining. It was realized in 1944 that the Witwatersrand might prove to be a source of uranium and, after extensive extractive metallurgical tests, production started in October 1952.

The average uranium content in the different quartz-pebble conglomerate reefs that have been consistent producers is fairly uniform, but the grade is low. Over the year 1976 it averaged 0.179 kg U_3O_8 per tonne (for all eight producing mines), with an average range of between 0.118 and 0.229 kg/t for individual producers. Until the end of 1976 uranium produced as a by-product of gold mining amounted to 74726 t uranium metal, from a start of 34 t U in 1952, a maximum production of 4959 t U in 1959 and 2639 t U in 1976.

Important concentrations of uranium minerals occur in auriferous conglomerates present in four contiguous Precambrian Supergroups, namely, the Dominion Reef, Witwatersrand, Ventersdorp and Transvaal, of which the first two are important because of their relatively large uranium resources. These four formations do not conform to one another, and cover

some tens of thousands of square kilometres in the Provinces of the Transvaal and Orange Free State.

The Dominion Reef Group, disconformably overlain by the Witwatersrand Supergroup, crops out in four separate areas in the Western Transvaal. It consists essentially of a basal sedimentary formation up to 90 m thick, which contains two important uranium-bearing quartz-pebble conglomerate horizons known as the Upper Reef and the Lower Reef; an

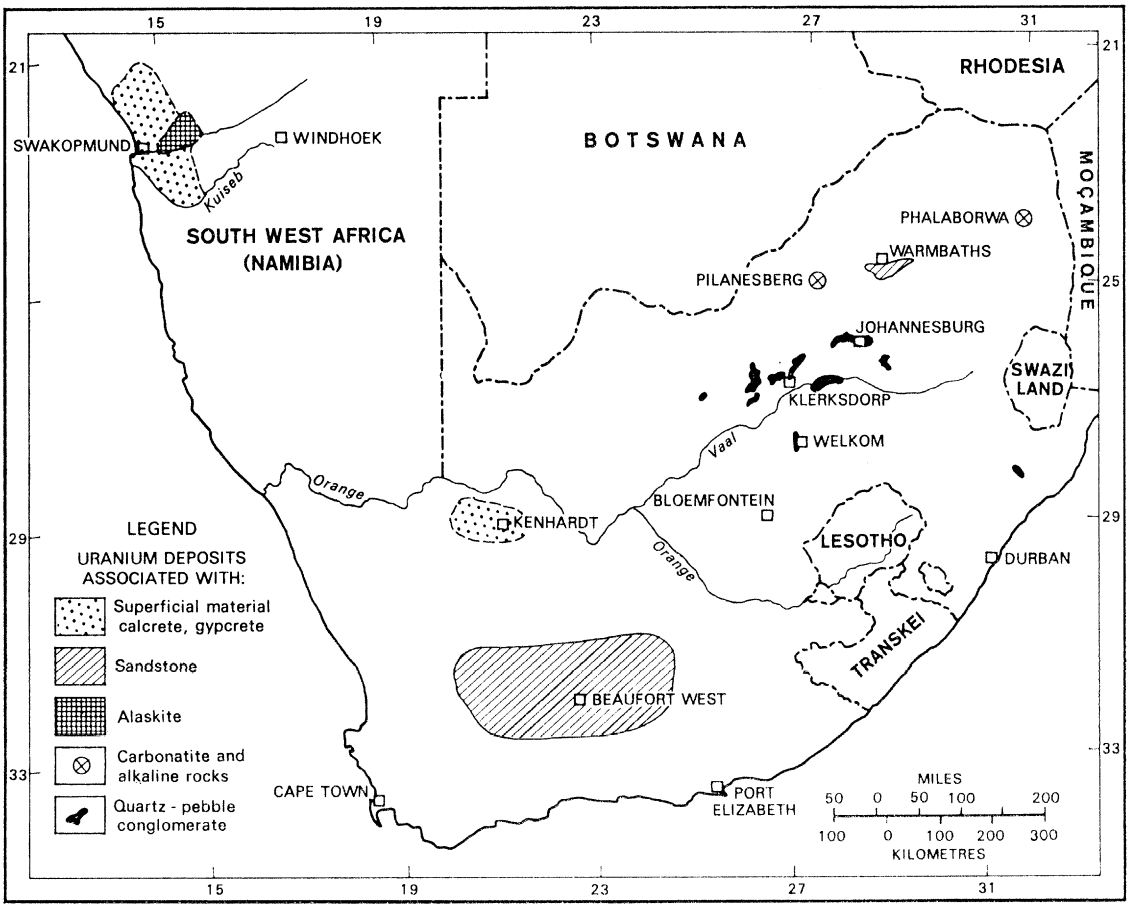

FIGURE 1. Map of South Africa and South West Africa showing main areas of uranium mineralization.

intermediate formation of altered andesitic lava flows up to 650 m thick with some intercalated beds of tuff, and an upper formation of altered cherty rhyolites and dacites with a thickness of at least 1500 m. The basal sedimentary formation of the Dominion Reef Group represents the earliest Proterozoic sedimentation in the region (2800 Ma), pre-dating that of the Lower Witwatersrand Group (2700 Ma). Exploration of the mineralized Reefs at depths from 100 to 1000 m indicated average grades of uranium between 0.25 and 1.25 kg/t, but associated gold values were low.

When the Dominion Reef mine was closed down in 1961 because of world overproduction of uranium, more than 1150 t of uranium metal and R13 million worth of gold had been produced. Most of the gold was produced from the Lower Reef which initially yielded 5 g/t but stood at less than 2 g/t when the mine closed down.

Should uranium maintain or increase its price, large areas in the Western Transvaal, underlain by rocks of the Dominion Reef Group and already proved by drilling to contain at least two mineralized reef zones, constitute a promising target area for further possible viable uranium deposits (von Backström 1978*a*). They would have to justify their exploitation as primary uranium producers, with possible by-product production of gold and minor lead, copper and zinc which occur as the sulphides galena, chalcopyrite and sphalerite.

The Witwatersrand Supergroup *sensu stricto* encompasses the most extensive gold mining district in the world (Pretorius 1974*a*, *b*, 1975; von Backström 1978*b*). It accounts for nearly 60% of the world's annual gold production and contains large potential reserves of gold and uranium-bearing ore. It covers an area of several thousand square kilometres in the Transvaal and Orange Free State and from the base to the top of the succession it includes nearly 7500 m of sedimentary rocks consisting of quartzite, grit, conglomerate and argillaceous rocks.

Quartz-pebble conglomerate beds vary in abundance in the different regions, being most frequent in the Central Witwatersrand where they constitute 600 m of the 7500 m thickness of sediments. Most of them contain both gold and uranium, and they have probably been sampled and explored more fully and systematically than any other group of mineral deposits in the world. Uranium is from 10 to 50 times more plentiful than gold and although these two metals are strongly consistent in their association, the highest gold and uranium values within a mineralized zone need not necessarily coincide. Important uranium and gold-bearing conglomerate beds occur on flat planes of intraformational diastems, disconformities and unconformities. Each of these conglomerates represents a deposit formed after a break in the process of sedimentation, and they occur as complex palaeo-channel deposits in braided stream systems related to alluvial fans. They obviously consist largely of reworked and restored detritus derived from the erosion of underlying unconsolidated pebble and quartzite beds. The remarkably close relationship of the concentrations of the gold and uraninite with sedimentary features strongly suggests that the gold and uraninite were deposited at the same time as the pebbles and other detrital components of the conglomerate.

However, uranium is a by-product of gold mining and it stands to reason that the entire industry is geared to the maximum production of its principal product, which is gold. Conglomerate reefs selected for development are those with the highest gold values, with uranium content scarcely being taken into account, especially over the past decade when there was practically no demand for it and the price of gold rocketed. Viewed in the above context as well as the large number of quartz-pebble conglomerate reefs present in the Witwatersrand Supergroup, there is a distinct possibility that potentially viable uranium-rich reefs may exist in present-day and/or abandoned gold mines, which have been overlooked because emphasis for so many years has been on maximum gold production and extraction.

There is little information on the uranium content of the sedimentary rocks outside the quartz-pebble conglomerate reefs or the so-called 'Carbon Leader'. The average uranium content of certain zones of sedimentary rocks within the Upper Witwatersrand Group based on core samples from comparatively few boreholes drilled in the Klerksdorp and Orange Free State areas gave results of 100 and 170 parts $U_3O_8/10^6$ at a cut-off value of 30 parts/10^6. However, the actual average uranium content of the sections which carry less than 30 parts $U_3O_8/10^6$ is not known at present. A significant fact revealed by these figures is that the important concentrations of uranium are to be found only in certain narrow zones which usually

form less than 5% and average 2% of the whole upper Witwatersrand sequence. The remainder of the sequence is not barren and generally shows a 'normal' on the radiometric logs, which is higher than that of the igneous material intrusive into the sedimentary rocks. In fact the average uranium content of the remainder would appear to be significantly higher than that of the many billions of tons of granite in the world which, on average, contain 3.5 parts uranium/10^6 and which have been mooted as very low-grade potential uranium resource rocks.

Origin of the uraninite

Significant contributions to the understanding of the genesis of the Witwatersrand gold–uranium deposits have been made by a number of researchers, notably Brock & Pretorius (1964), Pretorius (1974*b*, 1975) and Minter (1976).

The origin of the uraninite is best explained by the placer hypothesis, favoured by the majority of South Africa geologists, which holds that the uraninite and gold were originally mechanically deposited with the pebbles as detrital particles under oxygen-poor atmospheric conditions in ancient placers, some of whose original constituents have been modified or have had most of their detrital characteristics obliterated by subsequent recrystallization. Their metasomatism would be related to the metamorphism of the formations in which they occur, as the result of deep burial and deformation. Ores dissolved since their primary deposition did not move far before reprecipitation took place. This hypothesis would explain features such as the initimate connection between distribution of the ores and the sedimentary characters and structures of the rocks; the regular and widespread distribution of the uraninite and gold in the conglomerates; the relation of the distribution of the gold and uraninite to that of undoubtedly detrital minerals in the bankets; the fact that mineralization does not transgress across surfaces of stratification or follow planes of fractures; the occurrence of boulders of impervious cemented Witwatersrand quartzite and ore-bearing conglomerate in Ventersdorp conglomerate and volcanic breccia; the presence of gold and uranium in some of the Witwatersrand conglomerate reefs at the time they were cut by intraformational stream channels; and the absence of known feeder channels and of a magmatic source for hydrothermal mineralizing solutions. A fair degree of consensus now prevails on deposition having taken place along the interface between a fluvial system that brought the sediments and heavy minerals from an elevated source area to the northwest and a lacustrine littoral system that reworked the material and redistributed the finer sediments along the shoreline. The goldfields were formed as fluvial fans that built up at several points along the northwestern periphery of the intermontane, intracratonic lake or shallow inland sea. Each fan was the result of sediment accumulation at the mouth of a river, which discharged through a canyon and flowed across a relatively narrow piedmont plain, before entering the basin.

Hallbauer (1975) presented strong evidence that the carbon in the conglomerate represents the remains of algal colonies that flourished at certain times about the mouths of large rivers. He established that a well differentiated plant life existed during Witwatersrand times, including bacteria, algae, fungi and lichen-like plants. Such plants, more complex than simple filamentous organisms, were present during the deposition of the Witwatersrand conglomerate and played an important rôle in the concentration of gold and uranium. Investigations indicated that some of the gold and a large proportion of the uranium were concentrated biochemically in plant matter. However, most of the gold and heavy mineral content of the carbonaceous matter in reefs can be explained by mechanical trapping in a plant carpet.

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Filamentous microorganisms found in intimate contact with uraninite particles appear to indicate a digestion of inorganic matter by the organism. Detailed observations in a scanning electron microscope combined with energy dispersive X-ray analysis of particles and filaments support this theory.

Schidlowski (1978) likewise, in a review of the available ore-microscopic evidence pertaining to the origin of the main uraniferous constituent of the quartz-pebble conglomerates, comes to the conclusion that the uraninite, which occurs principally in the footwall portions of the conglomerate as rounded or muffin(disk)-shaped grains (100 μm in diameter), leaves little doubt as to its water-worn, abraded nature. He furthermore states, 'It can be demonstrated by comparison with detrital monazite grains from present-day beach placers that particularly the muffin-shaped displayed by individual uraninite particles constitutes an unquestionable sedimentary abrasion form'.

2. Sandstone-type deposits in sedimentary basins

The Karoo Supergroup covers more than 50% of the Republic of South Africa and since 1969 a large number of occurrences of uranium, of variable grades, has been discovered in the Lower Beaufort Group (Upper Carboniferous – Jurassic) over widespread areas. Intensive exploration is being carried out in the southern Karoo around Beaufort West in the Cape Province, and elsewhere in the Karoo basin.

The more significant occurrences are restricted to the southwestern part of the country around the town of Beaufort West. From limited information available there appears to be some relation between the famous Beaufort reptile environments and the potential uraniferous beds in the Beaufort succession. The Lower Beaufort consists of alternating beds of sandstone and mudstone in the approximate ratio of 30 : 70. The sandstones are typically lenticular and can generally not be traced along strike over more than 3 or 4 km. They are usually about 5 m thick, show fluvial cross-bedding, and consist of grains of quartz, weathered feldspar, clay minerals, biotite and chlorite. Lensoidal 'clay-pebble' conglomerate, up to 1 m thick, is often developed at the base of sandstone beds. The sandstones are typical 'ribbon' sandstones consisting of multiple sand bodies deposited in braided stream systems.

Mineralization is generally only found in the coarser sandstones and siltstones, which are either dark grey, black weathering and calcareous, often with visible sulphides, or they are limonite stained and light weathering (Moon 1977). The first type always has carbonaceous debris and frequently carries plant impressions and silicified wood. Uranium mineralization is erratic and occurs in small lenses separated by barren sandstone. Lenses are several tens of metres in length, from a few centimetres to about 5 m thick, peneconcordant to the bedding and elongated in the direction of sedimentary transport. They thin rapidly and interdigitate with argillaceous sediments. In addition to the channel sandstone occurrences, uranium also occurs in overbank deposits, again as very thin lenticular bodies.

The mineralized sandstone is enriched in uranium, copper, arsenic, molybdenum, lead and calcium, but appears to be depleted in iron compared to the unmineralized rocks. From available information, there appears to be an intimate relationship between uranium and molybdenum concentrations (over 0.1% in some cases). Uranium minerals are intimately associated with a variety of sulphides (but mainly pyrite) and with calcite, and are present in discrete grains predominantly as uraninite and coffinite and probably also as uranium–carbon

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complexes. Secondary uranium minerals are present along bedding planes and joints and the following radioactive minerals have been identified in the Karoo sandstone deposits: arsenuranylite, boltwoodite, carnotite, coffinite, meta-autunite, metatobernite, metauranospinite, metazeunerite, phosphuranylite, uraninite, uranophane, uranospatite, uranospinite.

Source of the uranium

Deep drilling in the search for oil, and geological mapping in the Britstown areas, have shown the Karoo rocks to rest directly on granite in some areas. Sediments containing material of volcanic origin (shards?) occur intercalated in the uraniferous zone. Fisher (1970, 1974) and Grutt (1972) indicate that uranium may be derived from such sources. In the Karoo, uranium minerals mostly replace coalified plant remains or carbonate cement in calcareous sandstones, and mineralization appears to be spatially related to the thickest and coarser sandstone units, sandstone–mudstone contacts and major depressions caused by fluviatile channelling. The absence of any influence or control by the large number of dolerite intrusions or small folds points towards early deposition. This is also borne out by the presence of unflattened cell structures in plant fossils replaced by uranium as shown by Kübler (1977).

Although the origin of uranium in the Karoo rocks is still unproved, the presence of volcanic rock fragments and the high feldspar content of the sandstones, suggest that the uranium was derived by leaching of these components in the host sediments. Another possible source for the uranium is the granitic rocks of the Cape west coastal area, and the concentration of molybdenum in particular would lend support to this idea, as molybdenum is commonly associated with granitic rocks.

3. Calcretes and other superficial deposits

Superficial deposits and calcrete (see definition in Goudie 1972) unconformably overlie the African erosion surface of Senonian to Miocene age in many parts of the country, especially the semi-arid to arid northwest Cape Province and Namib Desert regions. These deposits consist predominantly of calcite, quartz, feldspar and micas together with chips and pieces derived from the underlying country rock, and the following minerals have been identified: garnet, anatase, amphibole, pyroxene, fluorite, tourmaline, epidote, goethite, psilomelane, pyrolusite, barite, wulfenite, mottramite, zircon, ilmenite, magnetite and haematite.

In South West Africa the Namib Plain started forming during the African erosion cycle under humid conditions (King, 1963). After uplift off the present coast, terrestrial clastics in the form of gravels, arkosic debris and sand were deposited during the Post-African cycle to form part of the Namib Plain. The deposits were cemented under a dry climate by calcite, and in places by gypsum, to produce calcretes and gypcretes of Tertiary age, which locally contain epigenetic uranium mineralization mainly in the form of carnotite.

Younger calcretes occur and were formed from Upper Pliocene times to the present during which time cyclic movements and climatic changes occurred, resulting in a complicated morphology and many intraformational unconformities. According to seismic surveys, accumulations of debris are up to 200 m thick in places, especially within broad and extensive drainage channels, now choked by calcareous and arkosic sediments that form calcareous grits and calcretes containing scattered pebbles and trace amounts of uranium.

The calcretes are rather porous and the carnotite occurs as open-space fillings in pore spaces, as coatings around pebbles and grit fragments and as replacements of the matrix. In

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several respects the deposits in calcrete are very similar to the Yeelirrie deposits of Western Australia (Langford 1974).

Secondary uranium mineralization also occurs in unconsolidated lacustrine sediments of impeded palaeo drainages within broad aeolian sand-filled valleys. Often there is some impediment or barrier that crosses the drainage direction underneath the sand cover which can be observed from aerial and satellite photographs. Such barriers reduce the gradient and form 'morphological dams' or traps for uranium deposition on the upstream side. Uranium is still migrating through these sediments since dating on different deposits gave ages between 8000 and 100000 years with optimum values between 30000 and 40000 years.

Mention should also be made of large flat hollows known as pans or as 'vloere' in Bushmanland which are prevalent along drainage divides or watersheds. They occur in very flat country and have characteristic closed or centripetal drainage systems without any outlet or interconnection. The floors of such pans are covered by thin lime-rich soil that contains anomalous amounts of uranium although no deposits of economic value have been found to date.

Origin of the carnotite

The controls of carnotite mineralization in calcretes are not simple and considerable research needs yet to be undertaken (Dall'Aglio, Gragnani & Locardi 1974; Premoli 1975).

In most cases the mineralized calcretes directly overlie, or occur very close to, granites and granitic gneisses that were formed during earlier orogenies. Most of the deposits occur in areas where the granitic rocks exhibit radioactivities higher than average and in several cases these granitoids display graphic and myrmekitic textures and contain red-stained perthitic K-feldspar, biotite and Fe–Ti oxides.

In all cases the uranium appears to have been derived from the granitic 'basement' through leaching of uranium in the uranyl form by groundwaters. Potassium is in plentiful supply from the surrounding granites and a source of vanadium can probably be found in the granites, biotite schists and gneisses in the vicinity.

Studies by Hambleton-Jones (1976) indicated that uranium was leached by ephemeral subsurface water, and was transported in the form of uranyl–carbonate complexes. Its solubility was controlled by pH and concentration of carbonate. The crystallization of carnotite occurred after the calcite cement had formed in the calcretes and its segregation was brought about through decrease in the partial pressure of CO_2 and disproportionation of the uranyl–carbonate complexes as a result of upward diffusion caused by soil suction processes. Precipitation occurred by nucleation of uranyl and vanadate ions on montmorillonite, which acted as seed crystals. Thus the shape of orebodies is governed primarily by the height and profile of the watertable above the basement (Hambleton-Jones 1976).

4. Carbonatite and associated alkaline rocks

Many of the calcitic, dolomitic and ankeritic intrusives in Southern Africa, known as carbonatites, are characterized by the presence of thorium, and to a lesser extent of uranium (Verwoerd 1967).

In 1952 uranoan thorianite was discovered by the Atomic Energy Board in the carbonatite at Loolekop, which forms the central core of the Phalaborwa Igneous Complex. Drilling and prospecting soon proved that the carbonatite body held little promise as a source of radioactive

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minerals alone, but contained a large body of low-grade copper ore to a depth of at least 1200 m, the depth reached by drilling.

The Phalaborwa Complex consists of pyroxenite, syenite, olivine–diopside–phlogopite pegmatoid, fenite and carbonatite. Most of the members are intrusive into the granite-gneiss of the Archaean Complex but some are regarded as products of metasomatism. The pyroxenite was intruded first, followed by the syenite, and finally by a centrally located core of transgressive carbonatite, which is surrounded by a serpentine (olivine)–magnetite–apatite rock to which the name 'phoscorite' has been given. The phoscorite is regarded as original dunite which has been enriched in magnetite and apatite under pneumatolytic–pegmatitic conditions. Apatite is an important constituent of the pyroxenite, phoscorite and some of the pegmatoid bodies. Large concentrations of vermiculite occur in the northern pegmatoid body and the carbonatite forms the host for concentrations of copper sulphides. Small concentrations of baddeleyite and uranothorianite occur in the phoscorite and carbonatite. At present, copper, apatite and vermiculite are mined intensively, and magnetite, baddeleyite and uranium are being recovered as by-products. For an open pit mine to a depth of 400 m reserves of available copper ore at a grade of 0.7% are estimated at several hundred million tonnes, of thorium at a grade of 0.01% at 36000 t, and of uranium at a grade of 0.004% at 11000 t. Uranium and thorium are known to occur in other alkaline carbonatite complexes in Southern Africa, especially in the Pilanesberg Complex near Rustenburg, where complex uranium and thorium mineralization is associated with niobium and rare earths in alkaline volcanic and intrusive rocks. Little is known about the mineralization at this stage although the rare-earth occurrences have been discussed by Lurie (1973).

5. Intrusive alaskitic pegmatitic granites

A type of uranium mineralization which may prove to be of increasing economic importance in the future is exemplified by uraniferous granites in the central part of the Damara metamorphic belt of South West Africa (von Backström 1970; Jacob 1974*a*; Berning *et al.* 1976). This belt forms part of the Pan-African system of metamorphic belts and extends along the Atlantic coast with an arm branching off northeastwards into the interior. Within the Damara arm, which trends northeast, Martin (1965) recognized a miogeosynclinal facies in the northwest and a eugeosynclinal facies in the central and southern parts. The eugeosynclinal division is over 300 km wide and within it a high-grade 'central granite zone' can be recognized, flanked by lower-grade rocks on the northwestern and southeastern sides.

Intense deformation and high-grade metamorphism in the central granite zone have produced complex fold structures, including dome-and-basin features, and an abundance of migmatites and anatectic granitoids (Smith 1965; Jacob 1974*b*). Inliers of 2000 Ma basement (Abbabis Complex) are commonly found as mantled gneiss domes (Jacob 1974*a*,*b*, 1975; Jacob, Kröner & Burger 1978) and these are unconformably overlain by late-Precambrian quartzites, metaconglomerates and gneisses of the Nosib Group, and marbles, calc-granofelses and schists of the Swakop Group.

During the Damaran metamorphism a variety of granitic rocks was emplaced (Jacob 1974*b*). The Red Granite–Gneiss and Salem Granite suites constitute the two major groups of syn-to-late-tectonic granitoids. The Red Granite–Gneiss comprises a variety of granitic gneisses, gneissic granites and homogeneous red granites which often contain skialiths and xenoliths

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of basement augen granite–gneiss. An apparent structural/stratigraphic control appears to exist in that the suite is restricted to anticlinal structures at or below the level of the Nosib Group. It is interpreted as having been derived largely through basement reactivation and anatectic processes during the Damaran orogeny. The Salem Granite suite generally occurs in synclinal structures at the stratigraphic level of the Swakop Group and comprises non-porphyritic gneissic granite/granodiorite, porphyritic biotite granite/granodiorite and leuco-granite. An origin through anatexis of Swakop Group metasediments has been suggested for the suite (Miller 1973; Jacob 1974*b*), but has not been proved.

Late- to post-tectonic intrusive granitic rocks include the large Donkerhoek Granite batholith, small stocks of granodiorite and granite, pegmatites and the uraniferous Alaskitic Pegmatitic Granite (A.P.G.), exemplified by the Rössing deposit (Berning *et al.* 1976).

The A.P.G. occurs in the form of veins, dykes and irregular bodies, generally small in comparison with the other granitic units mentioned above. These granites are fairly well confined to areas of maximum Damaran metamorphic grade and are found emplaced into the Abbabis gneisses, the Red Granite–Gneiss, and Nosib and Swakop Groups. They exhibit a tendency to occur in anticlinal, dome and mantled gneiss dome structures, close to, and normally just below, the prominent marbles of the Swakop Group. Some of the alaskites are syntectonic and have been folded whereas others, generally better mineralized, are later. The Rössing deposit itself has been dated, by the Rb–Sr method, at 468 ± 8 Ma (Kröner & Hawkesworth 1977).

The rocks are medium- to coarse-grained granites and alkali–feldspar granites (Streckeisen 1973) with variable grain size from less than 1 cm to more than 5 cm. Graphic and myrmekitic textures typical of pegmatites are very common but zonal features (Cameron, Jahns, McNair & Page 1949) are absent.

Xenoliths of schist and gneiss in various stages of assimilation are common. Mineralogically the alaskites consist of quartz, abundant perthitic microcline and subordinate plagioclase (albite–oligoclase). Minor to accessory minerals include biotite, muscovite, chlorite, apatite, monazite, zircon, sphene, garnet, magnetite, ilmenite, haematite, and fluorite; pyrite, chalcopyrite, bornite, molybdenite and arsenopyrite are occasionally found (Berning *et al.* 1976; Jacob 1974*a*).

The primary uranium minerals are uraninite and betafite which occur as tiny grains (less than 0.3 mm) both interstially and in quartz, feldspar and biotite. They are preferentially associated with zircon and biotite. A large proportion of the uranium (40 %) is present in secondary minerals such as uranophane, beta-uranophane, gummite, torbernite, metatorbernite, carnotite, metahaiweeite and thorogummite (Berning *et al.* 1976). Mineralized bodies are normally brownish to reddish in colour on weathered surfaces, in contrast to the pale pink to buff colours of barren bodies and they contain smoky quartz, more biotite and less plagioclase, and in many cases biotite schist xenoliths and the immediate country rocks are more heavily mineralized than the granitic host. The suggestion by Armstrong (1974) that such bodies be referred to as 'porphyry uranium deposits' seems inappropriate.

Origin

The alaskitic pegmatitic granites are relatively enriched in incompatible elements and geochemical work in progress indicates that they are crystallization products of highly fractionated residual melts.

The generally coarse grain size demonstrates that the melts had high water contents at the time of crystallization and the high Sr isotope initial ratio of 0.7592 (Kröner & Hawkesworth 1977) points to derivation from a crustal source. The occurrence of mineralized alaskites in the Abbabis Complex shows that at least some, and possibly most, of the melts originated at least at the level of the pre-Nosib basement.

The granitic gneisses of the Abbabis Group and Red Granite–Gneiss suite are the most highly radioactive rocks on a regional scale. Most of the radioactivity is caused by thorium (monazite is present) but the contents of both uranium and thorium in the suites are significantly greater than most granitic rocks elsewhere in the world, and there is thus a ready source of uranium. Precisely why these rocks are anomalously radioactive is not known at this stage.

The processes leading to the formation of uraniferous alaskitic pegmatitic granites are considered below. During the Damaran regional metamorphism high temperatures (over 650 °C) and moderate pressures (3–5 kbar†) (Nash 1971; Jacob 1974*b*) in the central belt produced high-grade metamorphic assemblages, migmatites and anatectic granites. Basement reactivation occurred to produce the syn- to late-tectonic Red Granite–Gneiss suite. The progressive remobilization of basement can be seen in Abbabis inliers as one proceeds from the margins of the high-grade zone towards the centre, where the distinction between Abbabis and Damaran rocks becomes arbitrary. Depending on composition and water content, variable amounts of melt were produced at depth and these slowly rose. Some of this crystallized syntectonically as the Red Granite–Gneiss, while fractional crystallization led to the upward accumulation of residual melts enriched in incompatible elements. It should be mentioned here that there is much field evidence that some of the A.P.G.s are products, not directly of the main Damaran regional metamorphism, but of a later thermal event that postdated this metamorphism (Nash 1971; Jacob 1974*a*,*b*). Geochronological evidence for a later thermal event has also been presented by Kröner & Hawkesworth (1977) and by Kröner, Halpern & Jacob (1978), but more dating is needed on other bodies of A.P.G. Nevertheless, the basement and Red Granite–Gneiss remain as source rocks.

It is well known that uranium does not occur as discrete minerals when its concentration is low but occurs as isomorphous substitutions in lattices, in lattice defects, adsorbed along crystal imperfections and grain boundaries, as inclusions of microcrystals of uranium minerals or in liquid inclusions in major rock-forming minerals (Adams, Osmond & Rogers 1959; Rogers & Adams 1969). During progressive metamorphism, uranium is released in several ways (Yermolayev 1971), e.g. through recrystallization of minerals causing them to rid themselves of uranium in lattice sites and defects; through desorption of uranium adsorbed onto grain surfaces and along interfaces; through breakdown of uranium-carrying minerals such as biotite and sphene and probably also monazite to a certain extent, and through anatexis. Available uranium and thorium could be expected to partition into the melt phase in view of their incompatible character.

The oxidation state of the uranium at the time of anatexis is not known but it was probably present as the uranous ion (U^{4+}). However, if present in the uranyl form (U^{6+}) it could have been incorporated into early solutions and anatectic melts more readily than thorium. The fact that the Th/U ratio in the A.P.G. is very low (0.01–0.05) in comparison with the basement (1–10) suggests that possibility, although the ratio in the A.P.G. may have been altered through secondary processes (see later).

† 1 kbar = 10^8 Pa.

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In addition to partial melting of the basement the feldspathic quartzites and psammitic gneisses of the lower part of the Nosib Group, representing erosion products of the basement, suffered anatexis and may possibly have contributed to the melts together with any feeble syngenetic uranium mineralization that may have been present in the metasediments. Further investigation on this point is needed.

Depending on water content, composition and temperature, the various bodies of melt rose different distances. Saturated melts would have moved only over a limited vertical distance (Cann 1970). Those that rose highest could be expected to have fractionated most and to have the highest content of incompatible elements like uranium. Some of these bodies intruded up to the level of the Swakop Group and were then trapped under marble bands, which exerted a damming-up effect.

In addition to the controls of falling temperature and pressure, crystallization of uraninite may have been effected, in places, by the following reaction, because there is locally an association of haematite and uraninite:

$$3H_2O + 2Fe^{2+} + (U^{6+}O_2)^{2+} = Fe_2O_3 + U^{4+}O_2 + 6H^+$$

(McKelvey, Everhardt & Garrels 1955). A number of uraniferous alaskitic pegmatitic bodies contain mineralized xenoliths of biotite and hornblende schists and the immediate country rocks are also mineralized. This probably resulted from hydrothermal activity at a very late magmatic stage.

An important point is that about 40 % of the uranium at Rössing is in the form of secondary minerals. Although it is still not established whether the secondary minerals are due to hypogene or supergene (secondary enrichment) processes, the climate of the Namib Desert may have played an important rôle in upgrading the ore. The desert has been in existence for many millions of years and has experienced climatic changes in that time (see §3). Thus plenty of time has been available for secondary enrichment to occur. Uraninite is not stable in an oxidizing, near-surface environment and its oxidation would release uranium into meteoric water in the soluble uranyl form. The elements required to precipitate the secondary minerals mentioned above include Si, K, Ca, V and P and these would have been readily available from weathering of the A.P.G., schists, marbles and amphibolites.

In conclusion it can be stated that the genesis of the uraniferous alaskites appears to have resulted from multi-stage processes of ore formation (Krauskopf 1971) involving several cycles of concentration leading initially to the anomalously radioactive Abbabis granite–gneisses and then through further metamorphism, anatexis and fractionation to the uraniferous Alaskitic Pegmatitic Granites. These in turn appear to have undergone further enrichment and, although it is not yet certain whether this enrichment is due to hypogene or supergene activity, it is possible that the climate of the Namib Desert has played an important part in this enrichment.

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Discussion

M. Davis (*Nuclear Energy and Electricity European Communities*, 200 *rue de la Loi*, 1040 *Brussels*, *Belgium*). At the beginning of this Discussion Meeting, Professor Bowie said that one of the main objectives of theoretical and practical geology must be the identification of uranium provinces. Professor Sutton's paper gave a stimulating introduction to such an objective with the insights he showed into the behaviour and influence of the Precambrian. Professor Bowie himself laid much stress not only upon the well known close association of uranium occurrence with the Precambrian, but also upon the key significance he attaches to relative ages.

These basic points, together with the observations on features of uranium mobility in oxidizing conditions, of the fixation of uranium by organic material and/or pyrite and other materials, have been referred to by most subsequent speakers. We have also heard the perennial argument about detrital or other origin. I feel that we are not yet making enough progress with the objective identified by Professor Bowie.

My impression is rather like somebody viewing a slide which has been projected onto a screen by a projector that is too close to the screen so that the picture is out of focus. One can discern the vestige of a pattern, but a stronger lens is required to help to bring the picture into focus.

Can we not expect a contribution from laboratory experimentalists who can show results bearing on the movement, transfer and deposition of uranium in various environments? I hope that the result of this Discussion Meeting will disclose such a contribution, or other contributions to bring the pattern into clearer focus.

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