IAEA-SM-183/27

Review Paper

OTHER URANIUM DEPOSITS

J. W. von BACKSTRÖM
Geology Division,
Atomic Energy Board,
Pretoria, South Africa

Abstract

OTHER URANIUM DEPOSITS.

Other Uranium Deposits (group 4) includes deposits which could not readily be classified with groups 1, 2 and 3, in the classification of uranium ore deposits established by the International Atomic Energy Agency at Montreal in September 1972. This group makes provision for many diverse types of uranium mineralization, and deposits are classified according to origin as orthomagmatic; diatremes; shear zones and breccias; supergene; brines; marine. In the present paper a number of representative uranium deposits from each group are described. Orthomagmatic deposits cover uranium mineralization associated with granites, syenites, carbonatites and pyroxenite in Scotland, Alaska, Greenland, Brazil, South Africa, Madagascar and the United States of America. Uranium mineralization associated with diatremes in the United States of America, Canada and Italy, is described. Occurrences associated with shear zones and breccias in the two first-named countries and in India are also described. Examples are given of supergene deposits occurring in Canada, Portugal, Spain, Australia and Southern Africa, and of brines in the United States of America. Conditions for the formation of uranium deposits in closed basins are also mentioned. Finally, under uranium of marine origin a summary on uraniferous phosphatic rocks is quoted; the paper concludes with a description of some continental shelf deposits.

Hundreds of uranium deposits have been discovered in many geologic environments. However, significant deposits or districts which have produced large quantities of uranium, or which contain noteworthy reserves, are relatively few. All the most important producing fields have uranium associated with quartz-pebble conglomerates, sedimentary basins or sandstone-type deposits, or veins and similar deposits. It is to be expected that new uranium reserves will be developed by extending existing ore bodies or by exploring favourable areas within known fields.

It will, however, be necessary to discover new uranium deposits in areas which lack the above-mentioned favourable geologic features, since they may hold the clues for major future discoveries. In favour of such an approach is the fact that no one rock type consistently appears as preferred host for uranium mineralization; neither is this mineralization tied to any particular epoch or era or to any form, type or intensity of structural deformation. Such deposits are reviewed in the present paper and may be classified as follows:

1. Orthomagmatic
2. Diatremes
3. Shear Zone and Breccia Deposits
4. Supergene Deposits
5. Brines
6. Uranium of Marine Origin

1. ORTHOMAGMATIC

Vinogradov (1962) gives the following average uranium content for igneous rocks derived from data based on the accuracy of the analytical method, on the largest possible number of determinations and on multiple determinations on standard samples taken from all over the world:

Rock group	Uranium content (ppm)
Ultramafic (dunite, peridotite, pyroxenite)	0,03
Mafic (basalt, gabbro)	0,5
Intermediate (diorite, andesite)	1,8
Felsic (granite, granodiorite)	3,5
Sedimentary (clay, shale)	3,2
Meteorites (chondrite)	0,015
Earth's crust (two parts felsic, one mafic)	2,5

Data for stony meteorites (chondrites) and for sedimentary rocks, clays and shales that constitute most of the earth's sedimentary cover are given for comparison. Very tentative figures for the "average content of the earth's crust", obtained by assuming that the earth's crust is composed of two parts of granite and one part of basalt, are also given. The enrichment of uranium in intrusives rich in silica and alkalis is also observable in volcanics, and it is generally thought that the maximum concentration of uranium is found in the youngest member of the series.

1.1 Granite

1.1.1 Caledonian granites of Scotland

According to Davis *et al.* (1972), of about 2 500 km^2 of northern Scotland which were surveyed, the Caledonian granites of Helmsdale exhibit by far the best evidence of uranium mineralization. Small occurrences of autunite, metatorbernite and kasolite were found, associated with fractures in the Helmsdale granite which was intruded into Precambrian schist. Because of the extensive peat and drift cover, the area is not amenable to investigation by systematic surface or aeroradiometric survey techniques. The technique adopted was therefore based on geochemical sampling of stream water and sediment, and the selective traversing of favourable areas using portable radiation detectors. It showed an association of uranium anomalies in stream sediments with newer Caledonian granites. Numerous radioactive anomalies were discovered in the granite itself. Although secondary uranium minerals were identified locally in the granite, it was not possible to establish the existence of high-grade primary mineralization. Drilling demonstrated the persistence of weathering and low-level radioactivity to a depth of 30 metres in one locality in adamellite. Although this may be regarded as a uranium province, no significant deposit of uranium has been located to date.

1.1.2 Alkali granite of Ross-Adams, Alaska

The Ross-Adams uranium-thorium deposit has been described by MacKevett (1958). It is situated within a small stock or boss of alkali granite about 300 metres from its margin. The age is probably late Cretaceous or Tertiary. The country rocks in order of age are metamorphosed Devonian sediments and volcanics, black slate and hornfels, diorites, granodiorite, aplite and alaskite. The youngest intrusive rock, excluding dykes, is the alkali granite which forms a small stock or boss about 8 km^2 in areal extent. It contains abnormal quantities of certain minor elements, notably uranium, thorium, yttrium, lanthanum, niobium, cerium and rare earths.

The Ross-Adams ore body represents an uncommon type of uranium deposit in mineralogy and shape, and in its genetic affiliation with alkali granite. The dominant ore minerals are uranothorite and uranoan-thorianite. The ore body consists of a core of high-grade ore containing more than 0,50 per cent U_3O_8 and enveloped by a uraniferous zone between one and six metres thick which contains less than 0,50 per cent U_3O_8. Texturally, the ore resembles its alkali granite host rock. The formation of the deposit is attributable to two processes, viz. a local concentration of probably late-stage accessory uranothorite and uranoan-thorianite in the alkali granite, followed by the emplacement of numerous uranium-bearing and thorium-bearing veinlets at the side of the lode.

1.1.3 Midnite Mine, Spokane, Washington, USA

Barrington and Kerr (1961) have described a potentially important deposit of uranium 80 km northwest of Spokane, in which uranium ore occurs at the contact between regionally metamorphosed Precambrian sediments and an intrusive Cretaceous granite. It is a coarse-grained, holocrystalline, intrusive rock with aplitic and pegmatitic phases, but without visible primary uranium mineralization. The latter occurs in a zone along the contact of the granite and the sediments.

Ores are found within and near associated fractures and shear zones. Secondary, oxidized uranium minerals, principally autunite and meta-autunite, lie above a fluctuating water table, while below this water table there occurs a zone of partially oxidized, sooty and compact uraninite with which sulphides are associated. The action of hydrothermal solutions is indicated by the presence of minerals such as kaolinite, illite, montmorillonite and adularia.

Several open-pit mines have been developed in the area since uranium mineralization was first reported in 1954. The average uranium content of the first 710 tonnes shipped was 0,285 per cent U_3O_8. In the period August 1957 to end 1959, 496 716 tonnes of ore were mined and 1 834 030 tonnes of waste stripped.

1.1.4 Austen, Lander County, Nevada, USA

Quartz monzonite of probable Jurassic age are in contact with metamorphosed sedimentary rocks, predominantly quartzite and phyllite, with minor silicified limestone and hornfels in the Reese River silver-mining district, where uranium mineralization was discovered 5 km south of Austen in 1953.

Sharp and Hetland (1954) have described autunite and metatorbernite in faults and fractures in both the intrusive quartz monzonite and the metamorphosed sedimentary rocks, and also as disseminated ore in small roof pendants of the latter near the contact of these units. The quartz monzonite acted as host to narrow siliceous and intermediate dykes, as well as to numerous mineralized fracture zones which served as conduits for ascending uraniferous solutions. Fracture zones are from two to 30 metres wide, and from 20 to more than 1 000 metres long. Uranium minerals are associated with silver, gold, copper and iron in a gangue of sericite with varying amounts of vein quartz.

Select samples from the area contained as much as six per cent U_3O_8, and grab samples averaged 0,151 per cent.

1.2 Syenite

1.2.1 Ilimaussaq, South Greenland

The Gardar province of South Greenland is made up of a number of major intrusions, of many generations of dyke swarms and of basaltic lavas. At Ilimaussaq, Sorensen (1970) has described a highly mineralized agpaitic nepheline syenite intrusion which measures about 100 km^2. It is the youngest major intrusion and has been dated at 1 000 million years. It is a lujauvritic nepheline syenite locally enriched in uranium and thorium and contains potential deposits of eudialite, stienstrupine, monazite, thorite and rare minerals containing beryllium, lithium and niobium. Uranium content ranges from 100–3 000 ppm, and that of thorium from 50–1 300 ppm.

The uranium deposits are low-grade ores characterized by a very heterogeneous distribution of uranium and thorium. The volumes occupied by rocks having more than 400 ppm uranium are rather small. Future exploitation can only be considered in conjunction with occurrences of Nb, Be, Zr, Li, F, etc.

1.2.2 Pocos de Caldas, Brazil

Pocos de Caldas, as described by Távora (1964), is an elliptical laccolith consisting of alkaline rocks which crop out over an area of 800 km^2 close to the boundary of the Mines and Parana basins. The most common rocks are syenites (foyaites), microsyenites (tinguaites), phonolites and associated tuffs.

In the central part there is a dense net of thin veins, from five to 25 cm thick, of so-called "caldesite"—a mixture, in variable proportions, of zircon, baddeleyite and other minerals. Apart from the *in situ* deposit, eluvial and alluvial material cover the slopes surrounding the deposits and are found along the drainages over an area of roughly 450 km^2.

Uranium is either associated with the zirconium minerals as inclusions and chats, which association gives high and fairly cheap recoveries of uranium in extraction plants, or is present in the crystal structure of the zircon, which fact gives rise to an uneconomical refractory "ore". Unfortunately the latter type of deposit, with an average grade of 0,1 per cent, is highly predominant.

1.2.3 Pilanesberg, South Africa

The Pilanesberg intrusive complex, rising abruptly about 600 metres above the Bushveld plain of norite and red granite, is wonderfully regular in outline, is almost circular, and has a diameter of 27 km. The complex contains both extrusive and plutonic rocks which are divisible into two main petrologic groups—alkaline syenites and trachytes, and foyaites and phonolitic rocks. Associated with the extrusive rocks are breccias and tuffs.

Rare-earth mineralization occurs as veins in tinguaite, and as veins and blebs in marginal parts of green foyaites. Average percentage rare-earth oxides (REO) varied between 7,45 and 19,5, ThO_2 between 1,3 to 4,3, and U_3O_8 from 0,005 to 0,025. Although this deposit has been under active investigation for the past five years it is not a viable proposition at this stage.

1.3 Carbonatite

The search for ore deposits in carbonatites was, to a large extent, inspired by discoveries of mineral wealth. Major reserves of metalliferous ores of great importance to the mining industry have been discovered in carbonatite-bearing complexes. The results from a nuclear-mineral economic point of view have, however, been disappointing although minor concentrations of rare-earth minerals, associated with uranium, are being produced from the carbonatite of the Phalaborwa Igneous Complex in the northeastern Transvaal.

A detailed description of the Phalaborwa Complex was given by Hanekom *et al* (1965), and of Ondurakorume, Tweerivier and Glenover by Verwoerd (1967).

1.3.1 Phalaborwa, South Africa

The Phalaborwa Complex consists of pyroxenite, syenite, olivine-diopside-phlogopite-pegmatoid, fennite and carbonatite. Most of the members are intrusive into the granite gneiss of the Archean Complex, but some are regarded as products of metasomatism. The pyroxenite was intruded first, followed by the syenite and lastly 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 mineral constituent of pyroxenite, phoscorite and some of the pegmatoid bodies. Large concentrations of vermiculite occur in the most northerly 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, vermiculite and magnetite are mined intensively, and baddeleyite and uranium are being recovered as by-products. Reserves of copper available for an open-pit mine to a depth of 400 metres, at a grade of 0,7 per cent, are estimated at several hundred million tonnes; of thorium, at a grade of 0,01 per cent, at 36 000 tonnes; and of uranium, at a grade of 0,004 per cent, at 11 000 tonnes.

1.3.2 Tweerivier, Brits District, South Africa

The Tweerivier Carbonatite Complex is a roughly pear-shaped body, 5,4 km long and between 1,6 and 3,2 km wide, entirely surrounded by red Bushveld granite. The most prominent surface manifestations are three volcanic vents. On Tweerivier North the Complex consists of a heterogenous assemblage of dolomitic carbonatite with intercalated sövite and tremolite schist, into which an outer group of bifurcating and coalescing parankeritic beforsite dykes was intruded, whilst on Tweerivier South quite different rock types, viz. gabbro, anorthositic gabbro, white crystalline limestone and a radioactive silicified ferruginous rock are met with.

On account of both the limited resources and the low average grades there is no indication of an economic uranium deposit, as is borne out by the following assay values (per cent) : U_3O_8 : 0,002–0,006; ThO_2 : 0,03–0,18.

1.3.3 Glenover, Thabazimbi District, South Africa

The Glenover Carbonatite Complex is almost devoid of outcrops and occupies a shallow circular depression about 13 km^2 in extent. Owing to differences in vegetation, the outline of the deposit could be traced by means of aerial photographs. A low hill 20 metres high, referred to as Breccia Hill, marks the centre of the plug. It consists of high-grade apatite breccia, and mining operations, together with boreholes and prospecting pits, have exposed the geology of the plug.

Two main types of carbonatite are present, viz. beforsite and sövite. An extensive program of pitting has revealed that carbonatite is subordinate to biotite-pyroxenite and actually occurs in the form of dykes and sills traversing the latter. Large segments of the complex between lines of pits are unexplored and there is some justification for postulating an irregular, pipelike carbonatite body approximately at the centre of a biotite-pyroxenite plug, with core sheets and irregular intrusions of carbonatite emanating from the pipe.

Because of the extensive cover of surficial material, radioactivity is difficult to trace and interpret satisfactorily, but there seems little doubt that the Complex possesses a low but definite radioactivity. Radiometric assays of channel and borehole samples from several exposed radioactive zones ranged from 0,01 to 0,05 per cent U_3O_8.

Green monazite is quite plentiful in some portions of the apatite breccia. It was deposited on apatite, quartz, specularite and brown limonite and is characterized by a very low thorium content of between 0,03 and 0,1 per cent.

There is no production of either uranium or thorium from this deposit and no viable deposits have been proved to date.

1.3.4 Ondurakorume, South West Africa

The Ondurakorume carbonatite is situated 55 km southwest of Otjiwarongo, where it projects as a prominent conical mountain approximately 300 metres above the plain.

The country rock consists of varied formations of the Damara Supergroup, amongst which marble, schist and granite are predominant. The outcrop expression of the intrusive is roughly circular, measuring between 1 200 and 1 000 metres in diameter. Drilling has established the vertical attitude of the body as well as its complex composition. In order of age, the predominant phases are as follows:

1. Intrusive primary white sövite, mainly poorly mineralized calcium carbonate, with cubes and aggregates of magnetite and crystalline apatite.

2. Moderately radioactive greenish-black beforsite, forming an irregular mass near the core and minor outlying lenses and plugs. Contains radioactive iron-rich veins and some apatite.
3. Brown beforsite, consisting of mixed Ca, Mg and Fe carbonates heavily impregnated with apatite which is present as plugs, lenses and ring dykes.
4. Moderately radioactive small lenses and ring dykes of dark grey-blue beforesite heavily impregnated with blue riebeeckite, iron carbonate, strontium and rare-earth carbonates.

Apart from the widespread occurrence of apatite, very little mineralization is seen. Even magnetite associated with sövite is only locally prominent. Detailed mineralogical work showed that, in addition to the carbonates calcite and ankerite, ancylite, strontianite and carbocernaite were developed, as well as accessory amounts of monazite, pyrochlore, cerianite, zircon, columbite, pyrite and riebeeckite.

Owing to certain extraction metallurgical difficulties and low average grades the deposit is not considered to be viable at the present stage, although indicated tonnages of some of the minerals are significant.

Average grades were as follows (percentages): U_3O_8 : 0,002; Th_2O_5 : 0,003; Nb_2O_5 : 0,24; $SrCO_3$: 2,5; REO : 3,0.

1.4 Pyroxenite

1.4.1 Fort Dauphin, Southern Madagascar

According to Raubault (1956), uranium-bearing rocks are located along an arc, approximately 150 km long and between 30–40 km wide at best, between Fort Dauphin and the basin of the Mandrarè River in Southern Madagascar. The uranothorianite is closely associated with masses or lenses of pyroxenite which contain diopside and are interstratified in Precambrian crystalline schists which are very common. Lenses vary in length and may reach several hundred metres. Uranothorianite occurs *in situ*, associated with masses of phlogopite, calcite and anorthite, but may also be disseminated in the pyroxenite. Secondary alluvial and eluvial deposits of uranium are considered to have been derived from earlier deposits.

2. DIATREMES

2.1 Navajo and Hopi Reservations, Arizona, USA

Uranium deposits have been found in, or associated with, diatremes in widely separated parts of the Navajo and Hopi Indian Reservations in Arizona, where some 250 are known to occur. Some of these diatremes have several features in common with the diamond pipes of South Africa and contain pyroclastic material similar to kimberlite in composition. They have been described by Schoemaker (1956).

A fully developed diatreme in its upper portion is filled with bedded tuff and limestone, and in places with thinly laminated clay and siltstone, evaporites and even some bedded chert. Lower in the vent these sediments give way to more massive tuff, breccia, huge blocks of country rock, agglomerate, and ultimately to solid igneous rock.

The volcanic rocks associated with the diatremes are nearly all alkaline basalts which may be classified as manchiquites and minettes. Both types are usually compared with Colorado Plateau olivine basalts and contain average equivalent uranium (eU) of 0,001 2 and 0,004 6 per cent, respectively. Radioactivity is due to concentrations of both uranium and thorium minerals which are largely not acid-soluble.

For the most part the mineralized rock contains no visible uranium minerals; these are so fine-grained that even microscopic identification is difficult. Carnotite, bebigite and metatyuyamunite have been identified, together with trace amounts of silver, cobalt, nickel, lead and thallium. Although small deposits approaching ore grade are present in a few diatremes, no viable deposit is known.

Schoemaker (1956) suggests a syngenetic origin and that the uranium could have been derived from hydrous, phosphate-rich, moderately uraniferous monchiquite magma, situated at depth beneath and in the diatremes.

2.2 Spors Mountain, Juab County, Utah, USA

More than 40 fluorspar deposits containing uranium are known to occur on Spors Mountain, Juab County, Utah, USA. The rocks of Spors Mountain are chiefly marine limestone, shale, quartzite and dolomite, ranging in age from Lower Ordovician to Middle Devonian. These rocks are cut by Tertiary plugs and dykes of latite, rhyolite, and dellenite; volcanic explosion pipes filled with breccia are common along the east side of Spors Mountain. The fluorite deposits are of three types: pipelike bodies, veins and disseminated deposits. The most abundant ore is soft white to dark purple and occurs as pulverulent masses or as boxworks.

The uranium content of the pipes varies considerably between 0,003 and 0,33 per cent uranium. Only four of 19 pipelike bodies from which fluorspar has been produced contained more than 0,01 per cent uranium, and only one of these yielded a sample containing more than 0,20 per cent uranium. There is also a sharp decrease in uranium content with depth.

Both the fluorspar and the uranium are believed to have been derived from the same magma and to have formed during the closing stages of the vulcanism that was responsible for the plugs and dykes of Spors Mountain.

2.3 Mokta, Carswell Area, Saskatchewan, Canada

Three most interesting uranium deposits have been discovered recently very close to the contact of the Archaen basement and younger sandstone in the above-mentioned area, in which uranium is associated with gold, vanadium, platinum, selenium, copper and nickel.

All the deposits are found close to Cluff Lake, which is on the south side of the prominent, circular Carswell structure, within the Athabasca sandstone basin. It is outlined by a discontinuous ring of dolostones (fragmental dolomite) of the Carswell formation that, in contrast to the surrounding flat-lying Athabasca sandstone, are folded and, in places, overturned about axes that commonly parallel the outline of the structure. Outside and inside diameters of the collar or annulus of the structure are 40 km and 29 km respectively. A core of uplifted basement rock underlies the central zone which is about 18 km in diameter.

The Carswell structure has been variously interpreted as a possible cryptovolcano, a diapiric structure and eroded impact crater. Volcanic-like rocks termed Cluff breccias occupy dykes and veinlets in places.

Of the three deposits discovered so far, the one marked "D', although small, is particularly rich, averaging 10 per cent U_3O_8. It measures 100 x 20 metres at surface and is 10 metres deep.

The Cluff Lake deposit occurs close to a fault, and coffinite and uraninite are always associated with organic matter. The deposit is roughly 30 metres long and 50 metres wide. Ore-containing beds are from 0,3 to 3 metres thick in a sequence of 130 metres. Average grades are 1,2 per cent U_3O_8. The third deposit occurs in a highly faulted area between two magnetically different basement-rock types.

No satisfactory explanation for the genesis of these deposits has been forthcoming at this early stage of the investigation. Pitchblende occurs with shale in a shale-sandstone sequence, probably overturned and overlain by basement, the whole structure forming an antiform.

2.4 Quaternary of Central Italy

Mittempergher (1970) has described uranium and iron sulphide exhalative supergenic mineralization from three volcanic districts in central Italy. These volcanics are Pleistocene in age; they are built up by alkaline-potassic rocks and are characterized by the felspathoids leucite, kalsilite and melilite. Ignumbrites and tuffs prevail over lava flows, and petrochemically the volcanites are represented by K-trachytes, undersaturated latites and phonolitic tephrites.

The mean uranium content of the volcanites is 25 ppm, and the maximum 50 ppm, and of thorium 130 ppm and 240 ppm, respectively. The uranium mineralization is related to magmatic H_2S exhalations and to supergenic weathering of exhalative pyrite and marcasite. Furthermore, the ore deposits are controlled by the surficial and underground hydrology. Common to all mineralized areas is the emission of CO_2 gas with small amounts of H_2S.

The mineralized areas all exhibit zonation with thick layers of bleached, silicified and kaolinized volcanic rocks at the top followed by alternate bands containing iron sulphides (pvrite and marcasite) and uranium, at depth. Mineralization follows a hydrostatic and not a stratigraphic horizon, and exhibits a regular slope with respect to drainage valleys. The author classifies the mineralization as exhalative-supergenic and states that

"Uraniferous bodies have been found around small rivers, the thickness of the mineralized beds is between two and three metres and the content of uranium decreases going away from the exhalative zone. The best and most regular deposits are about one km long and some hundred metres wide. Inside these bodies the U content is variable. Maximums have been recorded but the average determined till now has not exceeded 300 to 400 ppm of U".

3. SHEAR ZONE AND BRECCIA DEPOSITS

3.1 Singhbhum Thrust Belt, Bihar, India

Uranium deposits occur in an arcuate thrust zone 160 km long, which swings around the northern margin of the cratonic block of Singhbhum granite in South Bihar. Although the mineralization has been described as hydrothermal in nature and of the vein type, some uranium is also widely disseminated in crush and breccia zones and therefore also qualifies for inclusion under Other Uranium Deposits.

The following description has been culled from the paper by Bhola, K.L. *et al.* (1964):

The Singhbhum Thrust Belt is well known for its copper, apatite-magnetite and kyanite deposits. It trends east-west and traverses Precambrian metasediments comprising closely folded mica schists, quartzites, conglomerates and metamorphosed basic lavas. The rocks have been overfolded and sometimes overthrust, accompanied by severe crushing and mylonization along a zone from 100 metres to 300 metres wide.

Uranium occurs as lenses in *en échelon* pattern both along the strike as well as at depth. The shear zones appear to form the main control for uranium as well as copper, although the lithological characters of the host rocks have also partly influenced the pattern and grade of mineralization. Workable concentrations of uranium are, however, observed only where cross folding and later fractures are dominant.

There are a number of uranium deposits along the belt in various stages of exploration in the rocks of the Iron Ore Series, which were mylonitized to various degrees in various places. At Jaduguda, the main deposit, the thrust zone is composed mainly of quartzite which is crushed, fractured and brecciated. Uranium mineralization is present as disseminations in a 120-metre wide zone in quartzite breccia. The main ore minerals are uraninite, torbernite and autunite which occur frequently in the surficial zone. The average grade is 0,067 per cent U_3O_8.

Studies of mineral paragenesis indicate that mineralization along the thrust belt took place over a long period, the minerals being deposited in two stages, the first to form being apatite and magnetite, closely followed by uranium mineralization, and the sulphides, including chalcopyrite, were the last to be deposited.

3.2 Golden Gate Canyon, Jefferson County, Colorado, USA

Pitchblende and secondary uranium minerals are found in or near Laramide fault zones that cut gneiss, schist and pegmatite of Precambrian age in the above-mentioned area. The fault zones, or "breccia reefs", are extensive structures as much as seven metres wide and possibly many kilometres long. They consist of ankerite and potash feldspar as a matrix enclosing partly replaced rock fragments. Pitchblende and base-metal sulphides occur as thin films, or more commonly as colloform masses less than 0,1 mm in diameter, that densely coat crystals of ankerite of comparable size. They are irregularly distributed through intensely altered wall rock, and are replaced in varying degrees by later sulphides.

The localization of uranium mineralization appears largely to be the result of the composition and texture of the wall rock and was probably effected by the oxidation of ferrous to ferric iron. The studies made during this investigation lead to the conclusion that pitchblende-bearing veins of the carbonate type can be expected where ample ferrous iron is available in the wall rocks, and that, in a sulphide environment, conditions resulting in the oxidation of either iron or sulphur may precipitate pitchblende.

Three mines and several prospects lie in an area of about 8 km^2. Shipments of ore from the Ascension Mine in 1956 amounted to 466,9 tonnes containing 0,23 per cent U_3O_8. In 1960 the mine shipped a further 1 026 tonnes of ore containing 0,27 per cent U_3O_8.

3.3 Gunnar Mine, Athabasca Region, Saskatchewan, Canada

Since the discovery in 1952 of frost-heaved radioactive boulders in muskeg close to St. Mary's Channel, an ore body about 80 metres in diameter, plunging from surface to a depth of 300 metres below the shoreline of Lake Athabasca, was outlined by drilling. Between 1955 and 1961 total production from open-pit and underground mining amounted to 5,6 million tonnes of ore of an average grade of 0,175 per cent U_3O_8 which was remarkably constant throughout the ore body.

The country rock is fine-grained paragneiss overlain conformably by coarse-grained granitized gneisses and metasomatic granite, referred to collectively as the Gunnar granite. Albitization of the latter caused the formation of small, irregular, tabular-shaped bodies less than 500 metres long and 125 metres wide, composed primarily of albite with minor amounts of quartz and dark accessory minerals, termed "syenite", which acted as host to the uranium mineralization. The ore body consisted of brecciated and mineralized parts of the syenite mass. Its surface expression was roughly circular, with a diameter of some 150 metres. It plunged from surface at 45 degrees. The ore minerals were pitchblende and uranophane, the latter representing only a small fraction of the total uranium present. The uranium minerals are finely disseminated in the syenite and are for the most part not visible macroscopically. The only important gangue minerals are calcite and hematite.

The ore was considered to be of hydrothermal origin, and uranophane was believed to be primary except near the surface. The impression is that the breccia pipe bears a spatial relationship to a number of large faults in the area and that one or more of these faults provided a conduit for ore fluids.

4. SUPERGENE DEPOSITS

4.1 Athabasca Region, Saskatchewan, Canada

Supergene occurrences of uranium due to surficial secondary enrichment were widely recognized in the Beaverlodge area of the Athabasca region where there was uranium mineralization; however, they were not economic, probably mainly because most of them were formed since the Pleistocene. The Athabasca region was above sea level during much of the Phanerozoic and underwent a long period of denudation resulting in peneplanation. Supergene deposits undoubtedly formed during this period and their absence at the present time is due to erosion by the Pleistocene sheet. Secondary minerals are found in only minor amounts at or near to the surface of deposits, except in a few of the ore zones located on major faults, where supergene alteration has extended to depths of around 50 metres.

The supergene deposits are generally superimposed on, and transitionally downward into, the other types of deposits. The most common secondary uranium minerals formed are uranophane and liebegite. They invariably form only a thin zone at the surface, and very rarely occur at depth along a fault zone.

The two best-known showings of supergene uranium were at Middle Lake, 16 km east of Stony Rapids, described by Beck (1970), and the 1 525 tonnes of uranium-rich material at Balger, east of Verna Lake, which averaged 0,7 per cent U_3O_8.

4.2 Uranium Deposits in Portugal

Dias and de Andrade (1970) consider all the uranium deposits of Portugal to be supergene in origin. They are correlated with the contact between metasediments, considered to be Precambrian to Neo-Devonian in age, and Hercynian younger granites which have a high radioactivity background.

The aureole of contact metamorphism does not extend beyond a width of 3 km. Uranium deposits are always confined to this aureole and rarely extend further than 50 m in depth.

Mineralization occurs in fractures close to the roof and walls of the granite and in metasediments. These brecciated structures normally originated under tangential tectonic movements which caused shear faults and mylonitization without any recrystallization of the rock elements. The most common associated wall-rock alterations are hematization, limonitization and seritization which all form favourable loci for uranium deposition. Mineralization is also always associated with surfaces of peneplanation, and where this has been destroyed no mineralization occurs.

The most common uranium minerals are pitchblende and coffinite, which are associated with near a dozen secondary coloured minerals of which the most common are autunite, torbernite uranocirate and sabugalite. Rarely found are uranophane, beta-uranophane, saléeite, phoshuranylite, parsonite, uranopilite and zippeite. Only pyrite and marcasite appear regularly as non-uraniferous minerals, and galena, chalcopyrite, sphalerite and arsenopyrite are found only sporadically.

4.3 Uranium Deposits in Spain

Uranium deposits very similar to those described as occurring in Portugal also occur in Spain; they have been described as occurring in the Salamanca Province by Fernandez Polo (1970), and in the Badajoz Province near Don Benito by Ramirez (1969).

At Salamanca, Hercynian granodiorite and adamellite, intrusive into Cambrian pelitic sediments, are responsible for a thermal aureole along which spotted slates and hornfels occur in a succession, together with quartzite and limestone.

Mineralization occurs along bedding and joint planes together with some organic material and, although lenticular in nature and intermittent, is fairly large in size and is economically viable. This mineralization is in the form of stockworks, is of supergene origin and is confined to the metamorphic aureole which may be from 200 metres to a kilometre wide. The uranium ore comprises pitchblende, uranophane, autunite and torbernite, with minor phosphuranylite, renardite, saléeite, ianthenite and uranopilite. Associated accessory minerals are pyrite, chalcopyrite, galena and melnikovite. The gangue minerals are mainly quartz, jasper, barite and calcite.

4.4 Yeelirrie, Western Australia

Yeelirrie is a semi-arid, open scrubland forming part of an ancient plateau approximately 500 metres above sea level, which is underlain by Archaen rocks consisting largely of granite.

During the Tertiary, the area was deeply eroded by a major river system draining in a south-easterly direction toward the Great Australian Bight. Although the average yearly rainfall for the area is 250 mm, permanent surface water has disappeared. The present drainage system contains an aquifer which carries appreciable quantities of subterranean water varying in quality from potable to highly saline.

The Yeelirrie mineralization has formed in sediments comprising sand, clay and calcrete, which fill one of these old river channels. The uranium was deposited as carnotite from ground-water percolating through the river fill, and occurs as thin films in horizontal layers lining the voids and cavities along 45 km of the channel, principally within eight metres of the surface.

Reconnaissance exploration at Yeelirrie has outlined an area of 45 km by 3 km, which contains anomalous uranium values; ten kilometres of the area was tested in detail by drilling. An ore zone measuring 6 000 metres by 5 000 metres, and eight metres thick, was proved; this zone is estimated to contain 46 000 tonnes U_3O_8 at an average grade of 0,15 per cent, of which 24 000 tonnes are above 0,36 per cent. As the ore is close to the surface, is of a high grade and can be easily mined, it is quite clear that an economic operation can be undertaken.

4.5 West Coast, Southern Africa

Semi-arid and desert areas border the coast of Southern Africa from north of the Oliphants River mouth (approximately 32 ° south latitude) for more than 1 500 km, throughout South West Africa and into Angola. It forms a windswept, barren, desolate belt varying in width from 25 to 150 km. The coast is for most of its length either rock-bound or, as is more often the case, bordered by great expanses of yellowish sand, often piled up into hills as high as 200 metres in the area south of Walvis Bay. Raised beaches, salt-pans and dried-up lagoons, the surfaces of which are covered with crystals of gypsum and encrustations of salt, are encountered at numerous localities along the coast and testify to its recent uplift relative to the sea. This uplift has been dated as post-Miocene by Wagner (1916), but he also states "that it has been in progress for a very considerable time".

The desert everywhere rises fairly rapidly towards the interior and, in consequence, attains a considerable elevation within a comparatively short distance of the coast. It therefore has the character of a sloping plain, underlain by eluvial material derived from ranges of hills of characteristic jagged outline, half-smothered in their own débris, and by isolated eminences of the inselberg type.

The area as a whole is poorly watered, as the rainfall is generally extremely low. Mean annual rainfall is less than 100 mm. The many episodic rivers north of Walvis Bay, which rise near the escarpment edge, are normally run-off courses and are effectively barred to the sea by coastal dunes. Over wide areas they effectively cover ancient dry river courses which, like all those exposed at surface south of the Cunene River, provide evidence of Pleistocene pluvial and interpluvial periods. There can be little doubt that the continental margin at present receives considerably less terrigenous sediment that has been the case in the past.

Groundwater, where encountered in certain parts of the desert, has a high content of various salts, particularly carbonates and bicarbonates, which are effective uranium solvents. Destruction by weathering and erosion of uranium-rich rocks and veins have, over a considerable period of time, released uranium, some of which has become reconcentrated in suitable environments—over a hundred localities have been traced by aerial spectrometer surveys—whilst an unknown amount of uranium has been transported to the sea by circulating waters.

A number of factors, both continental and marine, exerted a strong influence upon the sedimentation, stratigraphy, structure and history of the west coast. The history of the formation of the coastal plain probably began in Cretaceous times, or even earlier. There is evidence of marine transgression in Upper Cretaceous times and in the Eocene, of uplift in the Miocene, and of intermittent movements during the late Tertiary and Quaternary. Along its inner edge inselbergs of old rocks are frequent. Stocken has indeed shown that, since the Pleistocene, there have been four marine regressions, each followed by successively smaller transgressions accompanied by differential longitudinal warping.

It can thus be taken for granted that the plain was submerged over long eons of time during the Eocene (16 million years) and Oligocene (19 million) years. The basement rocks constituting the plain must have been completely filled with water and circulation must have been at a minimum, if not zero. This means that, under these conditions, oxidation was non-existent for a period of 35 million years. Diffusion was the only important operative mechanism and probably caused the introduction of various salts into the rocks. At times of uplift above sea level, potential sites of uranium deposition could be removed by denudation, and uranium concentration of groundwater and seawater would again increase.

Over a considerable period of the Quaternary up to the present time, these rocks have experienced an arid climate and have been above the permanent water table which is adjusted to the number of large rivers, such as the Swakop and Khan, which drain the plain. There is much sulphate left, e.g. gypsum and other minerals, but the chlorides, which must have been present, have disappeared. The sulphates are intimately associated with uranium minerals, but gypsum is just as common in places not containing any uranium.

There is no reason to doubt that a number of marine transgressions affected the plain from Upper Cretaceous times, through the Eocene and Miocene, right up to the Pleistocene, but, as the above speculation illustrates, it would be nigh impossible to reconstruct the history of sedimentation and denudation of older uraniferous plain deposits, even granting that such deposits were preserved at all.

The historical evidence indeed strongly endorses the results of field observations and of study of these surficial deposits which all bear the stamp of being very recent in origin. Many of them are confined to present-day water courses and it would not come as a surprise if most of them were formed since the last Pleistocene transgression.

5. BRINES

5.1 Oil Field Brines Containing Uranium, USA

About 200 asphalt-bearing Paleozoic and Mesozoic rocks from 49 areas in south, central and western United States were analyzed for uranium. The average uranium content for seven areas ranged from 0,028 to 0,376 per cent. In 13 additional areas the average uranium content ranges from 0,02 to 0,068 per cent uranium in the ash of the extracted oil. Although petroleum is therefore capable of transporting small amounts of uranium, this process is not important in the formation of uranium ore deposits.

Uranium related to petroleum-bearing and gas-bearing structures have been described as occurring in Texas, Wyoming, Utah, New Mexico and Oklahoma. The important uranium-producing areas of Wyoming, Utah and New Mexico are underlain in part by oil-producing and gas-producing formations which give rise to asphalt and gas seeps with which deposits of uranium are often closely associated. Uraniferous asphaltite or pirobitumen is a very common type of uranium ore at Ambrosia Lake, Temple Mountain and other places on the Colorado Plateau. It has been suggested that this uraniferous asphaltite represents dead oil left behind in a breached or partially flushed oil trap.

Host rocks in which the asphalt is found include sandstone arkose, tuff, limestone, diatomite and alluvium. The uranium was concentrated as an organo-uranium complex in the asphalt, and not in the host rock. Apparently the uranium occurred as an original constituent of the oil or was introduced during the migration of the oil. Several uranium ore deposits are located above or near producing oil fields such as Lance Creek, Wyoming and Cement, Oklahoma.

5.2 Closed Basins

Uranium, like other elements, can be concentrated in mineralized water in a closed basin. For this to occur, it is necessary to have special conditions, viz.:

1. The environment must consist of uranium-bearing rocks.
2. The area must be a desert or semi-desert where the evaporation of water is higher than the rainfall. Because of this, the rainwater in this basin flows in deep levels beneath the basin and is concentrated.

The uranium content of the liquid depends on the length of time during which the basin is closed. High concentrations are found only in very old basins. These conditions exist not only now, but also prevailed in earlier geological times. It is, therefore, necessary to know the paleogeographical and paleoclimatological conditions of an area. The closed basin is found in both banded deserts and semi-deserts such as occur in Asia, Africa and Australia. It is recommended that geochemical studies be made in these regions to find this unusual type of uranium occurrence.

6. URANIUM OF MARINE ORIGIN

Marine areas constitute 71 per cent of the world, as against the 29 per cent consisting of solid earth, so it is easy to understand why speculation concerning mineral resources in this largely unexplored region generates a high interest.

Seawater contains 0,000 15–0,001 6 ppm of uranium. Although this is a very low concentration, the total amount of uranium in seawater is very large. It seems reasonable to suppose that a small amount of byproduct uranium will be recovered in the near future from desalination plants or from plants recovering magnesium from seawater.

The continental shelves, which form the near-shore division of the continental margins, were almost entirely exposed as dry land during Pleistocene time when much of the world's water was locked up in ice caps and glaciers, causing the oceans to retreat almost to the shelf edges. Fluvial sand and gravel, deposited at this time, were reworked by wave action as the sea rose again and inundated the shelves at the close of the Ice Age.

Mineable concentrations of minerals (diamonds, tin, iron, limestone, sulphur, barite) occur on the continental shelves in buried river and beach placers, in submerged residual concentrations, in surficial deposits of bulk commodities such as sand and gravel, and in consolidated stratified deposits, either exposed or buried beneath the sea.

As has been demonstrated by the diamond-dredging operations which were conducted off the west coast of South West Africa between 1961 and 1971, offshore mining of semi-consolidated deposits using conventional mining equipment adapted to the marine environment is technically feasible in shallow water, although operating costs are high in a hostile physical environment.

6.1 Uraniferous Phosphatic Rocks

Finch *et al* (1972) give the following excellent summary on uraniferous phosphatic rocks:

"Most phosphatic rocks are uraniferous and their uranium content generally increases with the phosphate content. Marine phosphorite is the dominant source of phosphate and constitutes a very large resource of uranium. In such rocks, geosynclinal facies tend to be more uraniferous than platform facies. Uraniferous marine phosphorite deposits, commonly 5–10 feet thick, underlie hundreds of square miles, and their uranium content generally ranges from 0,007 to 0,07 per cent U_3O_8. Phosphorite beds in the Phosphoria Formation of Permian age underlie 135 000 square miles of Idaho, Montana, Utah, and Wyoming (McKelvey and Carswell, 1956). Their uranium content ranges from 0,001 to 0,075 per cent U_3O_8, but beds more than three feet thick and with more than 31 per cent P_2O_5 generally average 0,012–0,024 per cent U_3O_8. Phosphorite in the Bone Valley Formation of Pliocene age in the land-pebble phosphate field in Florida ranges in thickness from six to seven feet over several hundred square miles and averages 0,012–0,024 per cent U_3O_8 and 20–30 per cent P_2O_5 (Altschuler and others, 1956). Uranium in marine phosphorite deposits was probably deposited from seawater during sedimentation, or in some places possibly later by downward percolating groundwater.

"Large portions of extensive deposits of marine phosphorite in countries along the Mediterranean Sea from Morocco to Israel contain at least 0,01 per cent U_3O_8 (Davidson and Atkin, 1953). Near Recife, Brazil, deposits of phosphorite somewhat like those in Florida yield phosphate products that contain 0,02 per cent U_3O_8. Phosphorite that fills large depressions formed by solution of dolomite in the Central African Republic are also uncommonly rich in uranium (Mabile, 1968). Deposits of aluminium phosphate in Senegal and Nigeria are also uraniferous. Marine phosphorite of Cambrian age in the Kara-Tau Mountains, Kazakhstan, USSR, resemble the Phosphoria Formation and are probably uraniferous."

6.2 Continental Shelf Deposits off Walvis Bay

A number of investigators have described four separate basins on the continental shelf opposite the coast of South West Africa, which contain offshore muds. By far the best developed basin extends north and south of Walvis Bay, with a protrusion, representing a sediment-filled scour channel, opposite the Swakop River at Swakopmund. Similar smaller basins exist off the coast between the Unjab and Hoanib Rivers (bisected by latitude 20 ^{o} south); north of Hollams Bird Island (bisected by 24 ^{o} 25′ south latitude) and opposite Naribus (bisected by 25 ^{o} south latitude).

The bathymetric maps show a depth of water of between 50 and 150 metres over these basins, and depths of diatomaceous mud of from less than two up to 15 metres thick have been proved in them by core drilling.

The results of a shallow-penetration seismic and bottom-sampling program, in an attempt to outline the distribution and thickness of uraniferous muds found off the west coast of Southern Africa during a Scripps Institution compaign in 1968, have been described by Meyer (1973).

The survey was undertaken with the "Gemsbok", a 314-ton, 45-metre-long vessel, equipped with a Decca Mark 21 navigation system, a 18-kHz ELAC echo sounder and a 10-metre barrel-length pistol corer plus handling device.

Within less than a month, four mud basins with a total surface area of 19 000 km^2 and a mud thickness of 15 metres at maximum, were traced within a total area of nearly 40 000 km^2 which was surveyed. At the same time, distribution and thickness of mud were continuously evaluated on board with the help of seismic records which covered a length of nearly 4 000 km.

The mud is generally olivine-green-grey, soft, and homogeneous, with an ubiquitous smell of H_2S. The mud was sampled and examined with the help of 41 piston cores (201 metres in length) of which 21 penetrated the whole mud sequence and reached the underlying strata which consists of hard siltstone, stiff clay and brecciated terrestrial material. The mud is extremely fine-grained, with 70–80 per cent grains finer than six microns. It consists for 53–73 per cent of siliceous matter, the rest being made up of material derived from foriminifera, ostropods, pteropods, gastropods, lamellibranchs, bentonite and sharks' teeth. The highest uranium concentrations of 44–51 ppm occurred opposite 22 ^{o} 50′ and 25 ^{o} south latitude. Values ranged between five and 93 ppm, with an average value of 21 ppm, which exceeds the maximum of the range (10–20 ppm) for the Black, Caspian and Baltic muds.

The only other significant values obtained were for molybdenum (range 20–120 ppm, average 62 ppm) and vanadium (range 60–180 ppm, average 112 ppm).