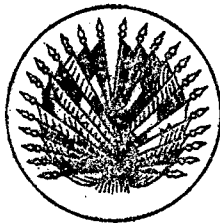


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COMISION INTERAMERICANA DE ENERGIA NUCLEAR Y
COMISION NACIONAL DE ENERGIA ATOMICA DE LA REPUBLICA ARGENTINA



**CURSO LATINOAMERICANO DE CAPACITACION
PARA LA PROSPECCION Y EXPLORACION
DE YACIMIENTOS URANIFEROS**

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DEPOSITOS URANIFEROS MUNDIALES

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COMISION NACIONAL DE ENERGIA ATOMICA

BUENOS AIRES
OCTUBRE 1978

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URANIUM: AN INTRODUCTION

Uranium is a lithophile element combining in nature with oxygen. It is distributed in the earth's crust in rocks of all ages but is distinctly enriched in acid igneous rocks such as granites as compared with basic igneous rocks.

Uranium also tends to concentrate in the uppermost portion of the earth's continental crust. As indicated by Ruzicka^{1/}, of the total 40,8 trillion (American) tonnes of uranium calculated to be present in the earth's crust, 33 trillion occur in the continental crust and 7.8 in the oceanic crust. The highest average geochemical concentrations of uranium (2.68 g/t) are within the uppermost part of the crust. The average percentage (abundance) of uranium in the earth's crust (the clarke) is 0.0002. Uranium in the earth's crust is approximately twice as abundant as molybdenum or tungsten and ten times more abundant than antimony and bismuth and four hundred times more abundant than gold. The relative abundance of uranium and typical occurrences is illustrated in Figure 1 taken from a paper by P.H. Dodd^{2/}.

The matter of importance to the economic geologist and the mining industry is the location of concentrations of uranium with economic tenors. The formation of deposits has been attributed to a limited number of well recognized geological processes, physical and/or chemical controls. In the case of uranium, one major factor in the distribution of deposits appears to be association with the early evolution of the earth's crust. Over 90% of the known low-cost uranium deposits of the world occur either in Precambrian rocks or in Phanerozoic rocks immediately overlying the basement. (Figure 2 and Reference 3/). The really large contributions to ore reserves are made by only a few well defined areas of the world (Figure 3). Such areas are known as metallogenic provinces and such provinces have, of course, been defined for many different metals.

The chemical and physical aspects of uranium ore formation are extremely important and also very diverse. In regard to the chemical aspects the most important is the solubility relationships of the minerals of uranium deposits as a function of solution composition, pressure, temperature

RELATIVE ABUNDANCE OF URANIUM AND TYPICAL OCCURRENCES GRAMS/TON OR PPM

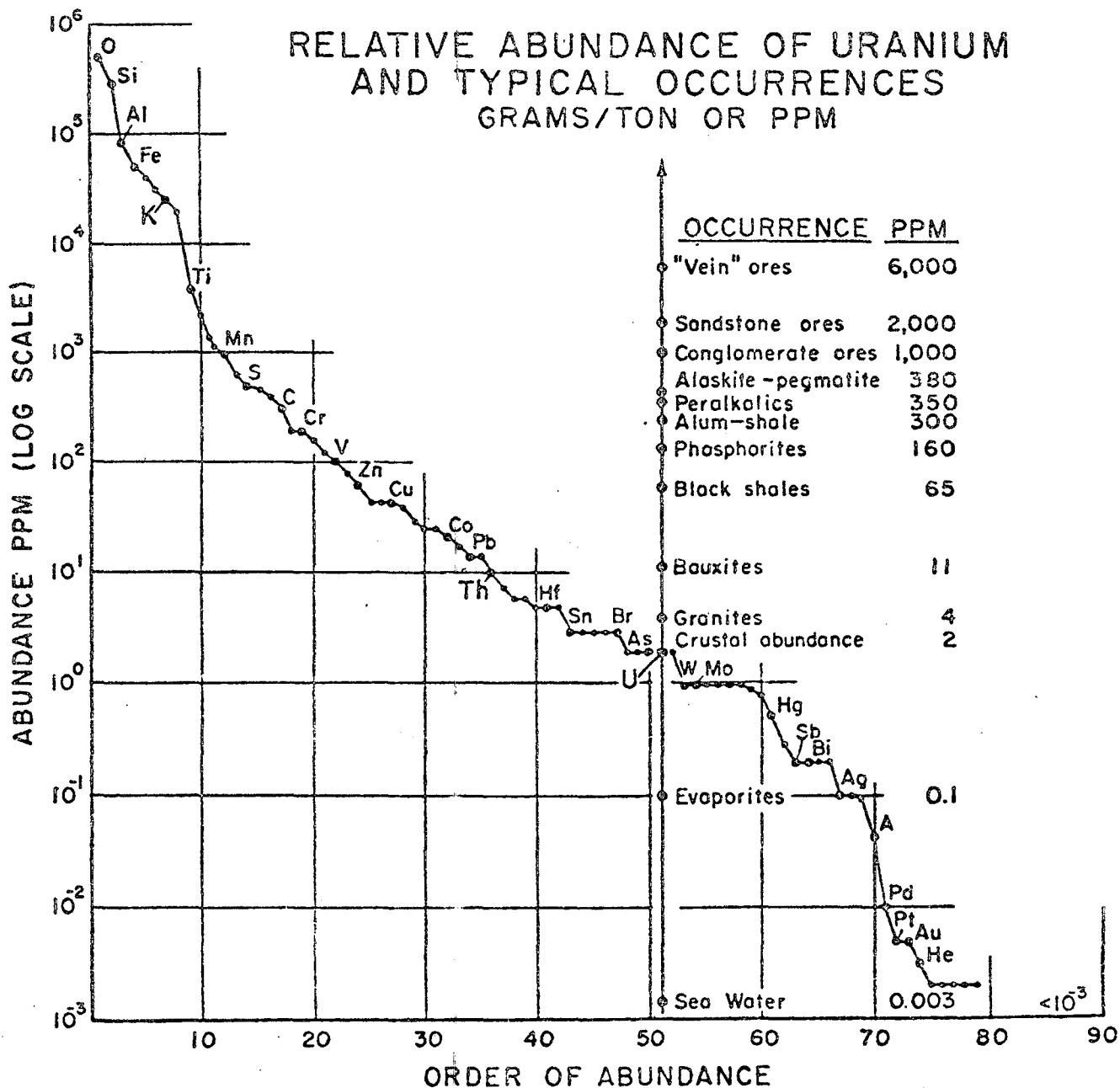


Fig. 1. Relative Abundance of Uranium and typical Occurences (Grams/Ton or PPM)

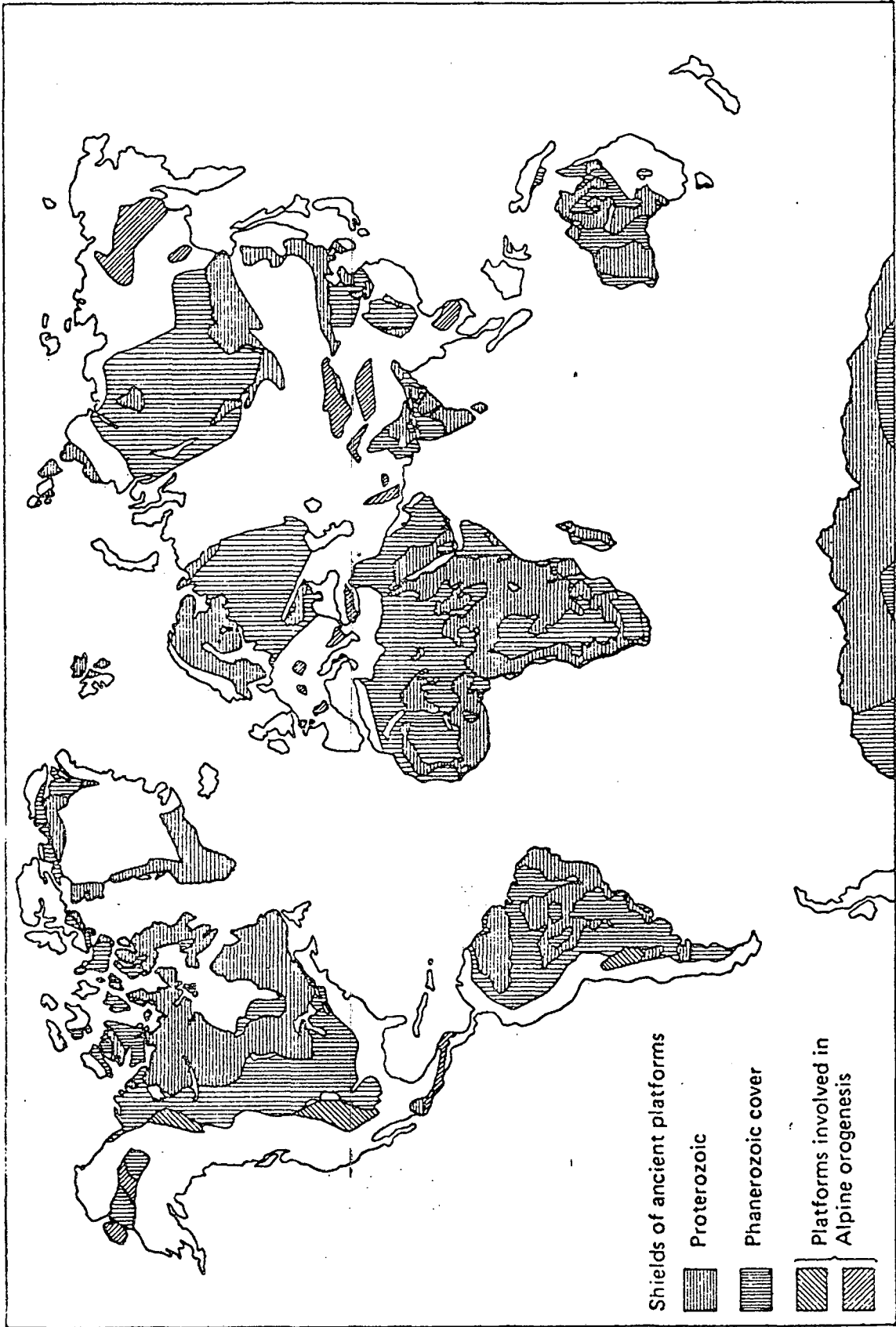


Fig. 2. Tectonic map showing Shield areas of sedimentary cover and regions involved in Alpine orogenesis. After Khain V. E. and Muratou M. V. Crustal movements and tectonic structure of continents. In "The earth's crust and upper mantle" Hart P. J. ed. (Washington, D. C.: American Geophysical Union, 1969), 523—38 (Geophys. Monogr. 13)

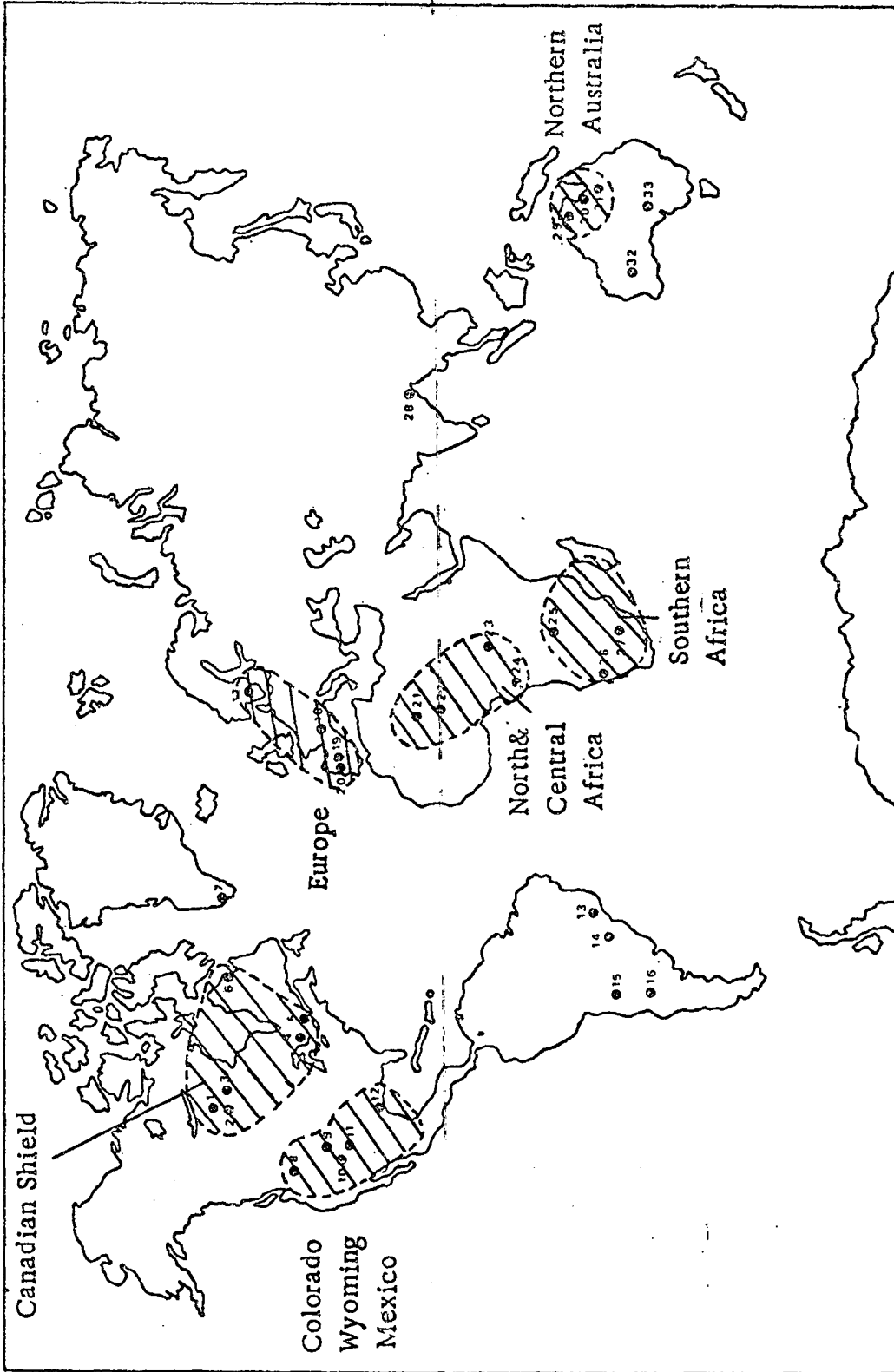


Fig. 3. Major uranium deposits and provinces (non-Communist countries): 1, Beaverlodge; 2, Cluff Lake; 3, Wollaston belt; 4, Elliot Lake-Agnew Lake; 5, Bancroft; 6, Makkovik; 7, Ilimaussaq; 8, Spokane; 9, Wyoming basins; 10, Uravan; 11, Grants; 12, Texas; 13, Pocos de Caldos; 14, Figueira; 15, Salta;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

oxidation potential, etc. The leachability of well known detrital minerals is a factor. The physical conditions of topography, climate, ground-water levels, permeability of rock systems, whether the potential host is a sediment or a fracture system, whether a geothermal gradient exists, whether organic matter is present, are all of importance in the formation of uranium ore deposits. All these factors, and many more have allowed for the formation of many diverse types of uranium deposits. However, with admittedly many ill-defined boundaries the IAEA has, through recent meetings of world experts attempted to define six main types of uranium deposits. It has also been recognized that the really large contributions to the world's uranium ore reserves are made by only a few well defined areas of the world (Figure 3) known as uranium metallogenic provinces. Within these six presently recognized uranium metallogenic provinces there are, in each, several different examples of the six types of uranium deposits.

GEOLOGICAL DISTRIBUTION OF URANIUM ORE TYPES

Table 1 and Figures 2 and 3 show the geographic distribution of the principal uranium metallogenic provinces but within each of those provinces there may be several different types of uranium deposits.

The meetings which the IAEA has convened on uranium geology in the last few years have led to a subdivision of the presently known major uranium resources of the world into six categories of ore types based on their geological setting. These are:-

1. Quartz-pebble conglomerate deposits
2. Proterozoic unconformity-related deposits
3. Disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks
4. Vein deposits
5. Sandstone deposits
6. Other types of deposits

The main features of these deposits are:-

1. Quartz-pebble conglomerate deposits

Known quartz-pebble conglomerate ores are restricted to a specific period of geologic time. They occur in basal Lower Proterozoic beds unconformably situated above Archaean basement rocks composed of granitic and

Table 1. REASONABLY ASSURED RESOURCES
(1,000 tonnes U)
Data available 1st January, 1977

COST RANGE	< \$ 80/kg U (< \$ 30/lb U ₃ O ₈) RESERVES	\$ 80-130/kg U (\$ 30-50/lb U ₃ O ₈)
Algeria	28. ✓	0
Argentina	17.8 ✓	24
Australia	289 ✓	7
Austria	1.8 ✓	0
Bolivia	0 ✓	0
Brazil	18.2 ✓	0
Canada ¹	167 ✓	15
Central African Empire ²	8 ✓	0
Chile	0 ✓	0
Denmark (Greenland)	0 ✓	5.8
Finland	1.3 ✓	1.9
France	37 ✓	14.8
Gabon ²	20 ✓	0
Germany, F.R.	1.5 ✓	0.5
India	29.8 ✓	0
Italy	1.2 ✓	0
Japan	7.7 ✓	0
Korea	0	3
Madagascar	0	0
Mexico ³	4.7 ✓	0
Niger	160 ✓	0
Philippines	0.3 ✓	0
Portugal	6.8 ✓	1.5
Somalia ⁴	0 ✓	6.2
South Africa	306 ✓	42
Spain	6.8 ✓	0
Sweden	1 ✓	300
Turkey	4.1 ✓	0
United Kingdom	0	0
United States	523 ✓	120
Yugoslavia	4.5 ✓	2.0
Zaire	1.8 ✓	0
Total (rounded)	1,650	540

1. The material reported as Reserves is minable at prices up to \$ 104/kg U and the other Reasonably Assured Resources are minable at prices between \$ 104 and \$ 156/kg U.
2. Source of data: Uranium Resources, Production and Demand; Paris 1975.
3. Data refer to resources "in-situ", rather than recoverable.
4. Costs of recovery are not known so the resources are arbitrarily assigned to the higher cost category.

metamorphic strata. Commercial deposits are located in Canada and South Africa, and subeconomic occurrences are reported in Brazil. (Figure 4)

2. Proterozoic unconformity-related deposits

Deposits of the Proterozoic unconformity-related type occur spatially close to major erosional unconformities developed during a generally world-wide orogenic period about 1,800 - 1,600 m.y. ago. They are represented by the ore bodies at Cluff Lake, Key Lake and Rabbit Lake in northern Saskatchewan, Canada, and those in the Alligator River area in northern Australia. (Figure 5)

3. Disseminated magmatic pegmatitic and contact deposits in igneous and metamorphic rocks

The deposits included in this grouping are those associated with granites, migmatites, syenites, pegmatites, carbonatites and volcanic rocks. The largest known deposit in this grouping is Rössing in Namibia, which is associated with pegmatitic granite and alaskite. (Figure 6)

4. Vein deposits

The vein deposits of uranium are those in which uranium minerals fill cavities such as cracks, fissures, pore spaces, breccias and stockworks. The dimensions of the openings have a wide range, from the massive veins of pitchblende at Jachymov, Shinkolobwe and Port Radium to the narrow pitch-blende-filled cracks, faults and fissures in some of the ore bodies in Europe, Canada and Australia. (Figure 5)

5. Sandstone deposits

Most of the ore deposits of this type are contained in rocks that were deposited under fluvial or marginal marine conditions. Lacustrine and eolian sandstones are also mineralized but uranium deposits are much less common in these rocks. The host rocks are almost always medium to coarse-grained poorly sorted sandstones containing pyrite and organic matter of plant origin. The sediments are commonly associated with tuffs. Unoxidized deposits of this type consist of pitchblende and coffinite in arkosic and quartzitic sandstones. Upon weathering, secondary minerals such as carnotite, tyuyamunite and uranophane are formed.

In Tertiary, Jurassic and Triassic sandstones of the western cordillera of the USA account for most of the uranium production in that country.. Cretaceous and Permian sandstones are important host rocks in Argentina. Other important uranium deposits are found in carboniferous deltaic sandstones in Niger; in Permian lacustrine siltstones in France; and in Permian sandstones of the Alpine region. The deposits in Precambrian marginal marine sandstones in Gabon have also been classified as sandstone deposits by some authors.

(Figure 7)

6. Other types of deposits

Included in this grouping are deposits that cannot readily be classified with the ore types already mentioned. Recently discovered uranium deposits, associated with calcrete, occur in Australia, Namibia and Somalia in semi-arid areas where water movement is chiefly subterranean. Other uranium deposits occur in limestones and limestone karst terrain as phosphatized fractions of the limestone. Uranium also occurs at low concentrations in marine phosphorite and shales. (Figure 8).

FUTURE DISTRIBUTION OF URANIUM RESOURCES

It must be emphasized that the known geographic distribution of provinces and the geological distribution of ore types are the summary of today's knowledge based on thirty years of extensive exploration in the more readily available and richer part of the world. What is the likelihood that these provinces and these types of deposits will remain as the world's main source of uranium supply? Some thought has been given to this problem. Firstly, it seems obvious that the main uranium provinces are in areas and countries where the greatest exploration expenditure has been made; therefore, there is no reason why other parts of the world with equally favourable geological conditions should not contain major uranium deposits which could be found if an equivalent exploration expenditure were made. In regard to ore type, Robertson^{5/} has suggested that, because uranium is a lithophile element, its distribution is geologically limited and resources in sandstones and conglomerates may be restricted to additional deposits of the type with which we are familiar. He suggested that conglomerate deposits are restricted in geological time and the sandstones by special depositional conditions. If this is so, expansion must come about through discoveries of these types

in entirely new areas of the world and it is this incumbent on the young uranium geologists, particularly those from developing countries, where most of the unexplored favourable ground exists, to learn all they can about the known deposits of the world, the favourable host rocks and the ore controls which have defined and brought about the existence of these deposits.

As a contribution to this knowledge a few examples of the six principal types of deposits as defined by the IAEA uranium geology working parties are described.

1. QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

Known quartz-pebble conglomerate ores are restricted to a specific period of geologic time. They occur in basal Lower Proterozoic beds unconformably situated above the Archaean granitic and metamorphic basement. Commercial deposits are located in Canada and South Africa, and subeconomic occurrences are reported in Brazil in the Cobalt Embayment, Ontario, and at Sakami Lake, Quebec (Canada), in India and in Australia. (Figure 4)

The conglomerates are highly pyritic, compact, and slightly metamorphosed. The quartz-pebbles are firmly cemented by chlorite and sericite. The uranium occurs in the matrix primarily as uraninite associated with other heavy minerals, some containing thorium and/or uranium. Carbon occurs in the deposits of both Canada and South Africa, in particular in the latter, and may have played a role in the formation of the ores. Gold is present in the South African deposits, where it is the chief ore mineral, but it is not present in the Canadian deposits.

The uraniferous conglomerates are light to dark grey in colour throughout their entire sequence with virtually no evidence of oxidation except by superficial weathering.

Only conglomerates older than 2,300 m.y. are likely to contain uranium in the form of uraninite in placer assemblages. The stability of primary uranium minerals during fluvial transport from source rocks to host rocks may have been made possible, at that time, by the suggested absence of atmospheric oxygen. Younger conglomerates are considered unfavourable for

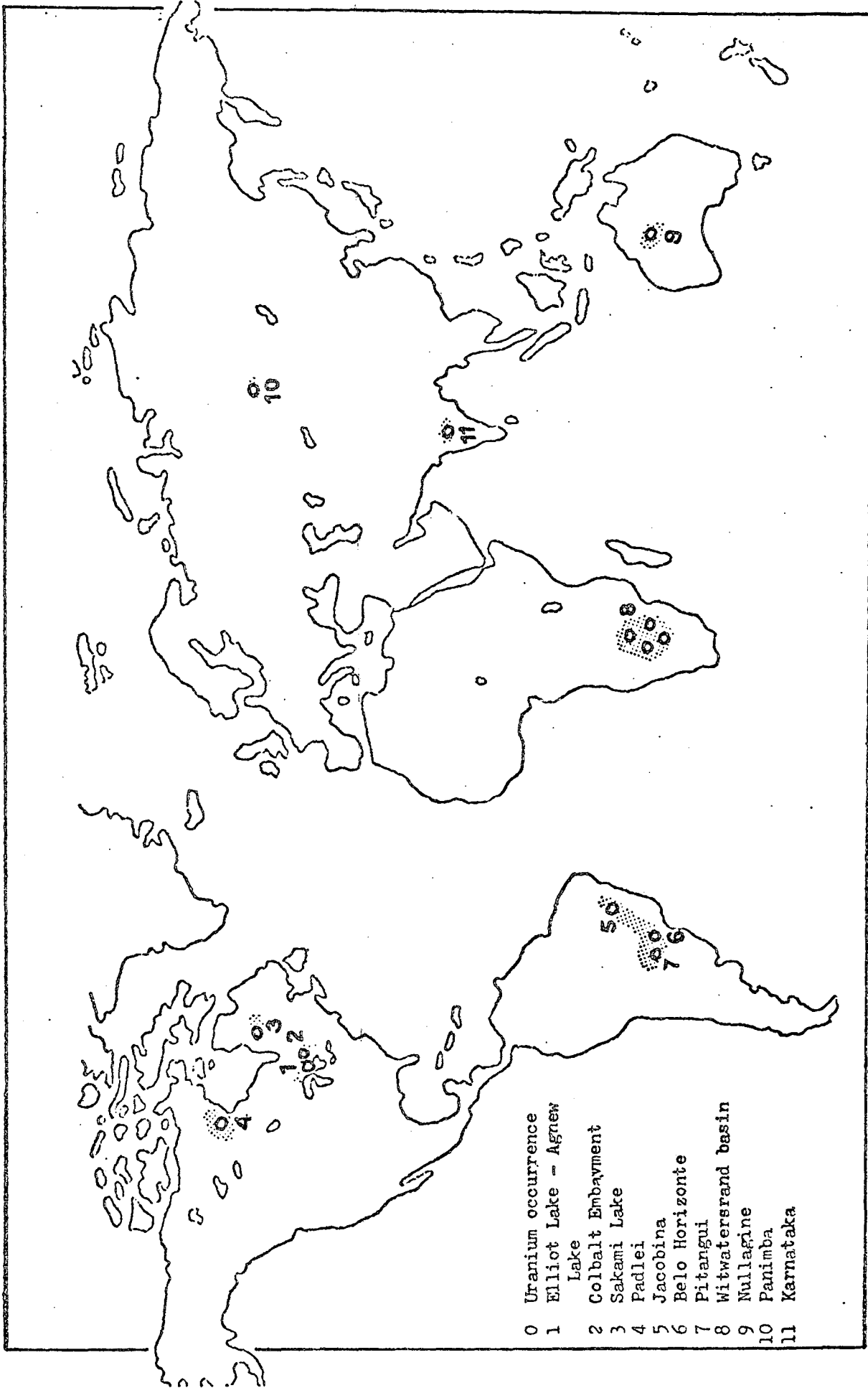


FIG. 4 Areas with uranium occurrences and deposits in Early Proterzoic quartz-pebble conglomerates.

detrital uranium as they were deposited under an oxidizing atmosphere and typically contain hematite rather than pyrite. Certain Phanerozoic conglomerates contain minor uranium deposits, but these are geologically similar to sandstone deposits and bear little or no resemblance to the deposits discussed in this section.

Quartz-pebble conglomerates are among the lowest grade uranium deposits mined. Where uranium is recovered as a by-product of gold mining, the grade may be as low as 0.01% U_3O_8 . Deposits mined exclusively for uranium may contain as much as 0.15% U_3O_8 . Individual deposits range in size from 5,000 - 150,000 tonnes of contained uranium.

South Africa

In South Africa uranium and gold are confined to relatively thin conglomerate or carbon bands, from a few to a hundred centimetres thick, within a sizeable body of otherwise barren sediments. The ore-bearing conglomerate bands are separated by either barren quartzite or conglomerate, but the ore zones are best developed where quartzite forms the underlying strata. The ore occurs in thin layers from a few centimetres to tens of centimetres thick which are generally located along floors of deposition formed along palaeoslopes in shallow-water, fluviodeltaic environments. Mineralization is commonly located along local unconformities representing breaks in the depositional succession. Important metal values are also found in lenticular conglomerate beds between stratigraphic disconformities.

The origin of uranium in the oligomictic and polymictic conglomerates of the Witwatersrand has been the subject of controversy for decades, mainly because there is almost certainly more than one form of uraninite in the sediments. Recent work supports the view that the primary control of the mineralization in the Witwatersrand and Dominion Reef Systems is differentiation of the sialic crust, with uranium enrichment in the upper portions and depletion in the lower charnockitic rocks. The detrital components in the sedimentary pile are concentrated in the high-energy conglomerates of the Dominion Reef System and near-shore parts of the Witwatersrand System. In low-energy environments uranium has been precipitated from solution, particularly in association with organic rich horizons such as the Carbon Leader. The detrital component has an age of about 3050 m.y., whereas the precipitated phase is dated about 2040 m.y.

The uranium is associated with pay amounts of gold and it occurs at a number of horizons throughout the Precambrian systems of the Dominion Reef, Witwatersrand, Ventersdoff, and Transvaal which are unconformable one to the other.

Uranium reserves are given as 200,000 t U_3O_8 but, because the average grade is only about 0.025 percent, uranium can only be recovered as a by-product of gold except in the case of deposits in the Dominion Reef. This is likely to place an upper limit on sustained annual production of 6000 - 7000 t U_3O_8 . Of the total ore, so far treated, some 80% has been mined for gold with uranium as a by-product. In the remainder, both metals were present in amounts of approximately equal value.

Canada

The quartz-pebble conglomerates of the Elliot Lake - Blind River province are somewhat analogous to those of South Africa. Mineralogically, however, they are more like the Dominion Reef assemblage than that of the Witwatersrand System. The main uranium mineral is uraninite, but brannerite, uranothorite, uranothorianite and monazite are quite common. Carbonaceous material (hydrocarbon) is relatively rare, and gold, though present, does not occur in commercial amounts. One of the notable differences between the two provinces is that there are essentially two ages of mineralization in the South Africa deposits, whereas minerals in the Ontario ores give four main ages ranging from 2000 to 600 m.y.

The mineralized conglomerates in Canada are generally thicker than those in South Africa, ranging from less than 2 metres to about 10 metres in thickness. Uranium ore zones may be separated by arkosic, pebble-free quartzite beds a few centimetres to several metres in thickness. Pebbles range from 1 - 5 cm in diameter, but larger pebbles and cobbles occur locally. The conglomerate contains a matrix of smaller particules of quartz and feldspar as well as sericite and chlorite. Channel cross-bedding is common. The surfaces of deposition of the conglomerate have considerable local relief. Valley structures are prominent on the Archaean surfaces, and the conglomerate beds are essentially confined to them. They are developed best on greenstone beds, but occur also on granites. Metamorphism of the conglomerate is weak. Locally, zones of red alteration appear along fractures, but oxidation is not sufficient to effect redistribution of uranium.

The uranium deposits of the Elliot Lake - Blind River area occur in the Matinenda formation at the base of the Huronian Supergroup and within 100 ft of the basement (Figure 2). All except one of the deposits (Pronto) are in troughs, one on the north and the other on the south limb of the Quirke Lake syncline, where the conglomerate is most highly developed. The ore bodies are elongate or tabular and vary enormously in size. Generally the pay sections average about 10 ft in thickness but range from 7 to 35 ft and comprise conglomerates and relatively lean quartzite horizons. The uranium content is variable, but averages about 0.12 percent in the currently mineable areas. Reserves in the \$ 30 per lb category are of the order of 200,000 t U_3O_8 , half of which are contained in the Denison mine.

Brazil

Conglomerates known as the Moeda formation, which occur near Belo Horizonte in the Minas Gerais region of Brazil, average about 200 ppm U_3O_8 , but contain less than 1 ppm gold and could not be economically exploited at present though the resources are of the order of 4000 t U.

The Serra de Jacobina on the north-central part of the State of Bahia in Brazil (Figure 4) has well developed quartz-pebble conglomerates over a strike distance of some 15 miles along the west slope of the Serra. There is a possibility that these may be the same formation and continuous with the Moeda conglomerates of Belo Horizonte some 400 kilometres to the south.

Analogies have been drawn between this occurrence, discovered in late 1953, and the peneconcordant uranium deposits of Elliot Lake - Blind River and the Witwatersrand. They are similar to the extent that the uranium is present in conglomerates and interbedded quartzites that in addition carry gold and pyrite. So far, however, uranium has not been found in quantities that justify working on a large scale.

India

Precambrian quartz-pebble conglomerates in the Aravalli Supergroup have for some time been known to be thoriferous. More recently in the Udaipur area of Rajasthan, interesting uranium anomalies have been detected and the presence of uraninite and brannerite confirmed. These conglomerates are very

extensive and if the uraniferous zones are sufficiently persistent, and the grade adequate, they may prove to be a viable source of uranium. More recently in the State of Karnataka, in southern India pyritiferous oligomictic conglomerates that are uranium bearing have been reported.

Australia

No economically viable quartz pebble conglomerate deposits have been found in Australia, although uranium has been reported in uneconomic concentrations in the Hammersley Basin of the West Australian Platform.

2. PROTEROZOIC UNCONFORMITY-RELATED DEPOSITS

Deposits of the Proterozoic unconformity-related type occur spatially close to major erosional unconformities developed during a generally worldwide orogenic period about 1,800 - 1,600 m.y. They are represented by the ore bodies at Cluff Lake, Key Lake and Rabbit Lake in northern Saskatchewan, Canada, and those in the Alligator Rivers area in northern Australia. (Figure 5)

These deposits are confined to Precambrian shield areas containing Archaean basement rocks overlain by Lower Proterozoic metasediments. Folding and erosion of these rocks was followed by unconformable deposition of Middle Proterozoic sandstones that in most places remain as flat-lying and relatively undisturbed beds. The known deposits are located in the Lower Proterozoic beds, usually within a few hundred metres below the unconformity, but in a few places mineralization is found in the Middle Proterozoic rocks directly above the unconformity.

The host rocks for the deposits are schists and, occasionally, gneisses commonly of pelitic origin that contain both pyrite and graphite. The main control is possibly structural, with the uranium localized by open structures in zones of fracturing shearing and brecciation, though there is evidence of a primary stratigraphic and chemical control. Alteration, chiefly chloritization and sericitization, is a common feature believed to be more or less contemporaneous with uranium mineralization.

The Middle Proterozoic cover rocks, where present, are composed chiefly of coarse-grained porous quartz sandstones and minor conglomerates, siltstones and shales.

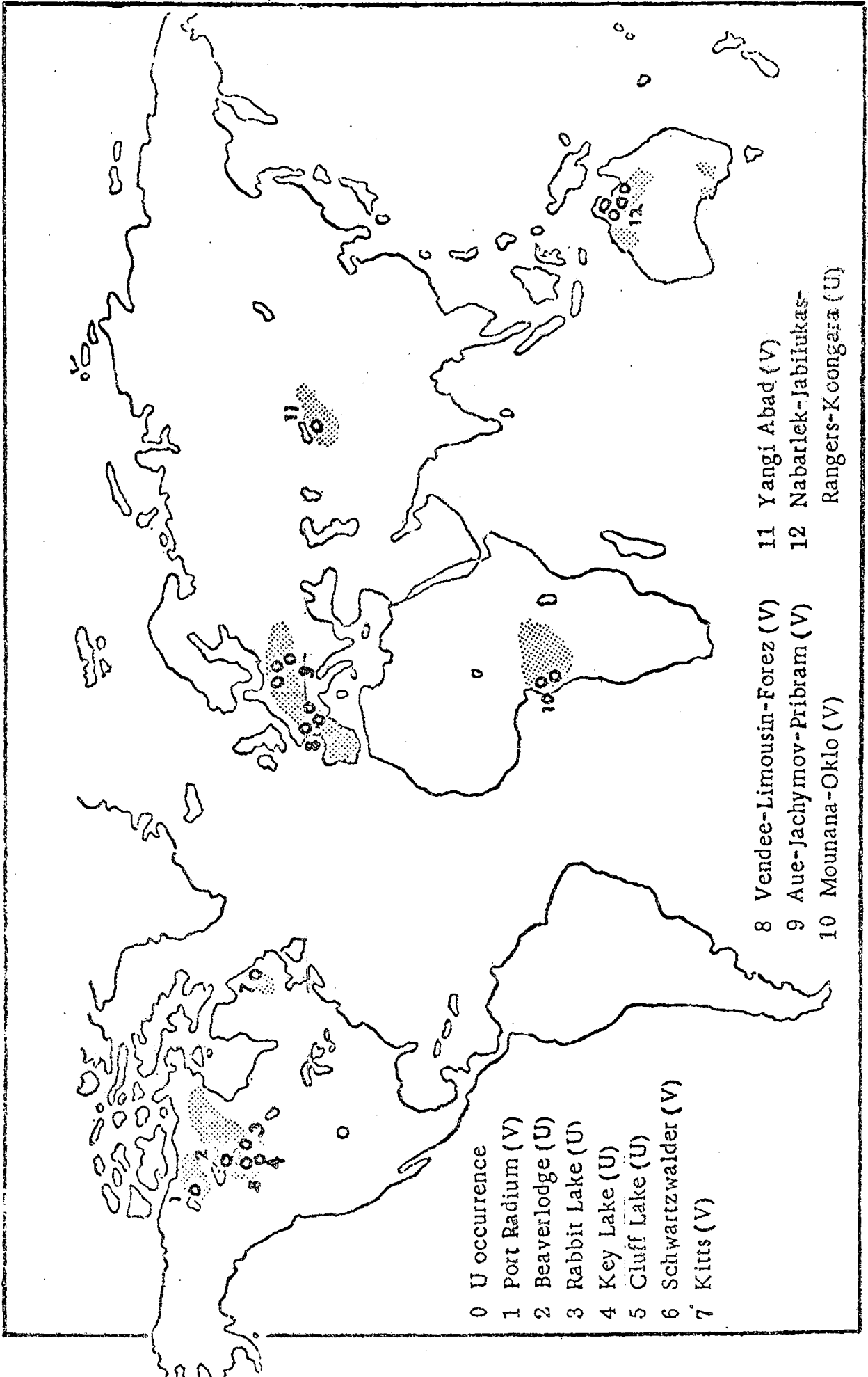


FIG. 5 Areas of Proterozoic unconformity-related (U) and vein (V) deposits.

The ore consists chiefly of pitchblende in both disseminated and massive form. Rich zones are common and commercial quantities of gold, nickel and other metals may be contained in the ores. Thorium is absent from these deposits.

Australia

The Jabiluka, Ranger, Koongarra and Nabarlek deposits of northern Australia occur in the Cahill Formation which is a Lower Proterozoic sequence of schist, amphibolite, carbonate rock and chert. These metasediments represent an original pelitic sequence of montmorillonite-rich shale, carbonate, black shale, chert and mixed chemical/detrital sediments, all with variable amounts of carbonaceous matter, probably deposited in a near-shore marine environment. The deposits preferentially occur in quartz-chlorite or chlorite-graphite schists and breccias. The deposits are structurally controlled. The main ore mineral is pitchblende or uraninite with native gold occurring in significant amounts in all but the Nabarlek deposit.

Canada

The deposits in Saskatchewan also occur in former near-surface Lower Proterozoic metasediments. The host rocks here are, however, more variable with dolomitic-calcareous metasediments and breccias at Rabbit Lake; chlorite and/or graphite schists and breccias at Key Lake, and graphitic quartzose and pelitic gneisses at Cluff Lake. Ore occurs as well in the overlying Athabasca sandstone at Key Lake and in the D Zone (one of the deposits) at Cluff Lake. The ore control is again structural with faulting and brecciation common. Pitchblende and/or unraninite are the main ore minerals with significant quantities of gold in the D Zone at Cluff Lake and nickel at Key Lake.

Some deposits of this type, for example those in the Beaverlodge area of northern Saskatchewan, Canada, occur in a wide variety of host rocks. The largest in this area are in Lower Proterozoic quartz-feldspar gneiss. Arkose, argillite, metavolcanics, amphibolite, meta-argillite, chlorite-epidote rock, and chlorite schist are also mineralized. Red hematite alteration is a striking feature of the pitchblende zones and is a characteristic guide to ore. Although these (Beaverlodge) deposits have appropriately been considered as vein deposits, their occurrence in Lower Proterozoic rocks beneath the Lower Proterozoic/Middle Proterozoic unconformity is recognized as a basis for their inclusion here.

The most widely supported theory regarding the origin of deposits of this type involves the initial deposition of uranium in Lower Proterozoic pelitic and chemical sediments, derived from the erosion of Arachean granitic basement, followed by remobilization and reconcentration of the metal during subsequent orogenic episodes. Diagenetic process could also have significantly affected the distribution of the uranium and the wide range of ages obtained during studies of these deposits. In many instances, the overlying Middle or Upper Proterozoic formation has helped to preserve the deposits.

Proterozoic unconformity-related deposits are the largest and richest of the known uranium ores. They range in size from 5,000 - 200,000 tonnes U and range in average grade between 0.3% and well above 2.5% U_3O_8 .

3. DISSEMINATED MAGMATIC PEGMATITIC AND CONTACT DEPOSITS IN IGNEOUS AND METAMORPHIC ROCKS

Deposits in this category range from less than 1,000 - 100,000 tonnes U in size and from about 0.05 - 0.15% U_3O_8 in grade. Notable occurrences are found in Namibia, Canada, Greenland, the USA, Brazil, Madagascar and Somalia. (Figure 6)

Namibia

The largest known deposit is Rössing, in Namibia, which is associated with pegmatitic granite and alaskite, of wide textural variation, that were intruded into a thick geosynclinal series and metamorphosed. The ore-bearing alaskite contains metasedimentary xenoliths hundreds of metres wide. These inclusions maintain regional strike and dip, indicating passive emplacement of the alaskite and metasomatism of the replaced metasediments. The setting is indicative of saturation and replacement of migmatized country rock by granitizing fluids moving along shears, fractures, joints, and bedding planes. The primary uranium mineralization occurs as small crystals of uraninite. Secondary enrichment, due to weathering, is believed to have played an essential role in the formation of the ore body.

Mineralized alaskites can be distinguished from barren granites by deep colouration of weathered surfaces. The mineralized zones are normally reddish to buff coloured, whereas unmineralized zones are usually white to pale pink. The mineralized alaskites contain smoky quartz, darkened feldspars, and commonly more biotite than does barren rock.

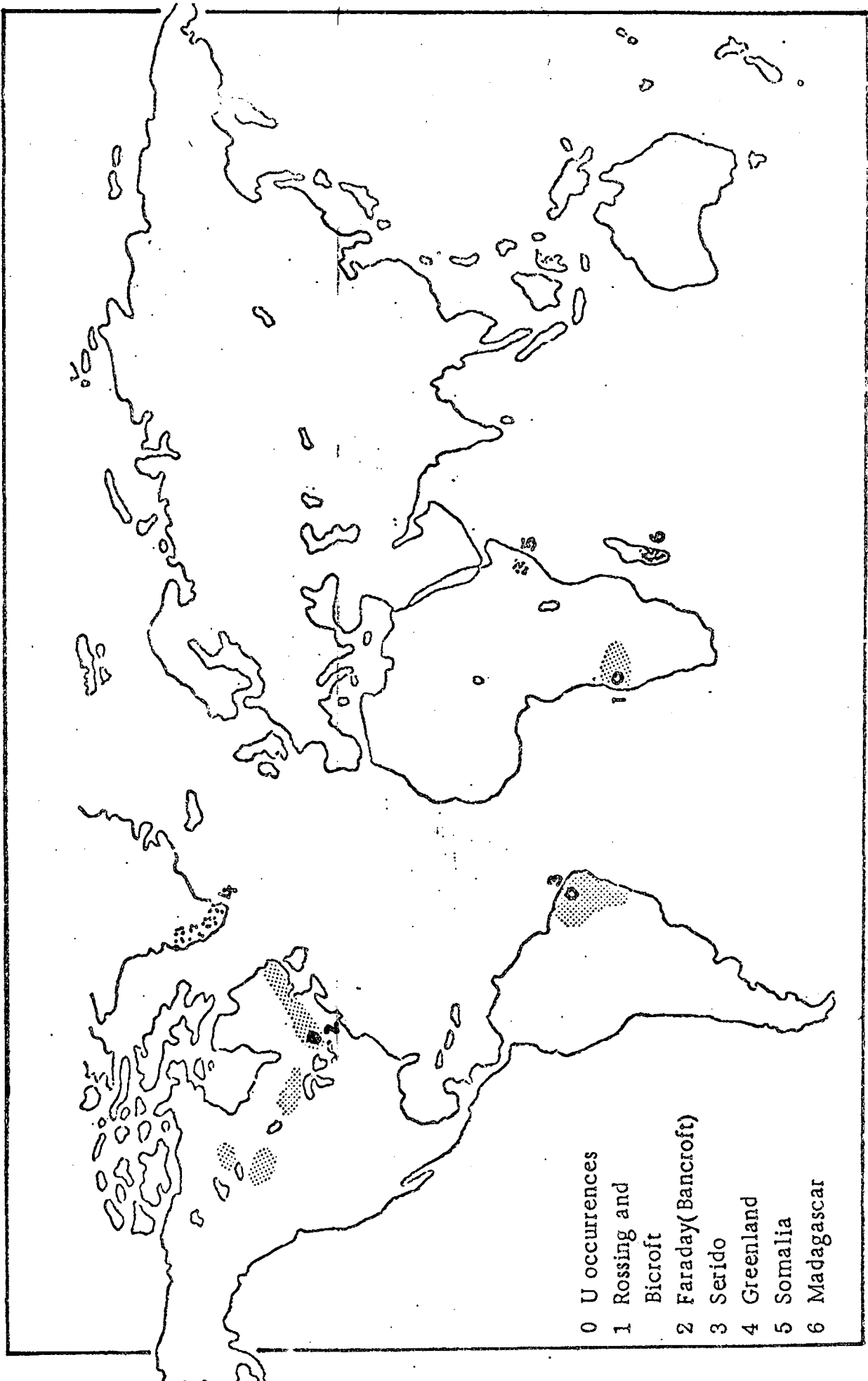


FIG. 6 Areas of disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks.

Canada

Uranium ores with strong pegmatitic affinities occur in the Bancroft region of Canada. These are associated chiefly with pegmatitic granite and syenite dykes. Red colouration of quartz and feldspar, due to hematite, is characteristic and is most pronounced in the uraniferous zones of pegmatitic granite dykes. Uranium occurs chiefly as thorium-bearing uranothorite and uraninite; however, multiple oxides such as betafite and fergusonite are also found. The host rocks are of Precambrian age and consist mainly of amphibolite, metagabbro, granite, syenite and gneiss. The richest deposits are found where the mafic content of the country rock is highest.

U.S.A.

Stocks and bosses of peralkalic granite are known to contain commercial uranium deposits, as for example the Ross-Adams deposit in southern Prince of Wales Island, Alaska. The mineralization (uraniothorite and uranothorianite) is marked by reddish-brown colouration, caused largely by hematite, which contrasts conspicuously with the normal white unmineralized granite host. The ore occurs in numerous small veinlets and in uranium-thorium minerals scattered throughout the granite. Faults apparently provided the channelways for mineralization. The mineralized granite occurs in a setting of pyroxenite, syenite, diorite, and quartz monzonite. Late-stage hydrothermal solutions associated with pegmatitic and aplitic facies of the granite appear to be involved in the mineralizing process.

Greenland

Alkalic rocks of syenitic composition are also favourable for uranium, as in the Illimaussaq region in southwestern Greenland. The peralkaline nepheline syenites have unusual amounts of uranium and thorium, mainly contained in the mineral steenstrupine - a silicate and phosphate of rare earths, sodium niobium, tantalum, thorium and uranium. The deposits are low grade (200 - 250 ppm U_3O_8), however, as well as refractory.

The main development of uranium is in recrystallized zones where the mineral steenstrupine (a silicate and phosphate of rare earths, soda, niobium, tantalum, thorium and uranium) is found.

Resources of the order of 250,000 tons U_3O_8 are contained in zones where the grade is about 200 ppm U and, because of the ease with which the uranium minerals can be concentrated by flotation methods, it is possible that a substantial tonnage of uranium might be recoverable.

Brazil

In the Pocos de Caldas region along the boundary between the states of Minas Gerais and Sao Paulo, in the Precambrian shield, the mineralized rocks are characteristically rich in eudialyte and sodic silicates. The uranium is concentrated in late hydrothermal veins of limited extent carrying such uranium-bearing minerals as baddeloyite and zircon. Nepheline syenites make up the bulk of the alkalic complex and may be accompanied by foyaites, naujites, and similar alkalic rocks. Weathering may concentrate uranium into pitchblende and coffinite.

Somalia

The Alio Ghelle radioactive mineral occurrence is situated about 200 kilometres WNW of Mogadiscio in the Republic of Somalia. The country rock is Precambrian biotite schist gneiss or granofels intruded by granitic gneiss bands. Radioactive mineralization is mainly due to a thorite replacement but the nature of the ore controls has not yet been determined. Thorium, uranium, yttrium and small amounts of ytterbium and scandium are the potentially exploitable metals. Grades of about 0.10% U_3O_8 have been found.

Madagascar

Uranothorianite is not generally regarded as a uranium ore mineral. It occurs, however, in southern Madagascar in flat-lying lenticular masses of pyroxenite occurring in Precambrian crystalline schists. Some of the lenses are several hundred metres long and 20 to 30 metres thick. The uranothorianite has a variable uranium content of between 5 and 30% U, but even at this content the average grade of the ore bodies is generally less than 0.1% U_3O_8 and the deposits are now largely worked out.

4. VEIN DEPOSITS

Deposits of this type range in average grade from about 0.1 - 2.5% U_3O_8 and in size up to 20,000 tonnes contained uranium. (Figure 5)

France

France is an excellent example of a country with a number of deposits none of which is large by comparison with major world deposits, but which together contain reserves of 45,000 tonnes of U_3O_8 at a grade of 0.22%. The principal developments are in the districts of Limousin, Forez and Vendée and are regarded by the majority of geologists as typical vein deposits associated with Hercynian granites with their emplacement controlled by tectonic factors.

The main uranium mineral is the relatively poorly crystallized variant of uraninite, pitchblende, and various more oxidized varieties of the same species which are associated with pyrite, chalcopyrite, galena, fluorite, and with gangue minerals such as quartz and chalcedony. The most important developments of uranium are mineralized masses associated with zones of brecciation up to 70 ft wide.

Spain and Portugal

The deposits of Spain and Portugal, like those of France, are associated with Hercynian granites. They occur both as veins in the granite and as veins and disseminations in the surrounding metasediments. The vein deposits contain pitchblende in various states of oxidation which is usually associated with different types of quartz-hematite, pyrite, sphalerite and galena. Emplacement is clearly related to a well defined fracture pattern developed as a result of Alpine movements. The deposit at Urgeiriça in Beira Alta, Portugal, produced radium as long ago as 1911 and is a typical mesothermal vein.

In recent years numerous medium-size uranium ore bodies have been discovered in schists especially in the Province of Salamanca in Spain and in the Alto Alentejo district of Portugal. The deposits lie within the metamorphic aureole of the granite. Estimates of reserves in the Spanish deposits of this type are of the order of 4000 to 5000 tonnes at a grade of 0.1%. Those so far examined in Portugal probably contain 3000 to 4000 tons of U_3O_8 .

Congo

The famous deposit of Shinkolobwe in the Congo is now exhausted, though to the west two small deposits genetically similar to Shinkolobwe occur at Swambo and Kalongwe. All the deposits in the Congo lie in the Zambezi-Damaran mobile belt to the north and west of the Kaapvaal craton, which extends through Zambia to SW Angola and into SW Africa and is considered to be a favourable area for further uranium discoveries.

Czechoslovakia and Germany

In Czechoslovakia, uranium mineralization again associated with Hercynian granites, occurs in both the above-mentioned types of veins and here silver is occasionally included in the polymetallic veins. In the hydrothermal veins of the Erzgebirge and Black Forest, uranium is concentrated in veins of the five element paragenesis (Ag, Bi, Co, Ni, U) and there preferentially in the uranium-quartz phase of mineralization.

U.S.A.

Veins in the western US, e.g. the Schwartzwald mine in Colorado, are predominantly in fractures in fine-grained biotitic Precambrian schists that appear to have been derived from pelitic sediments. The host rocks are graphitic and pyritic. Pitchblende is the dominant ore mineral.

Canada

Other vein deposits occur in sedimentary pyroclastic rocks of Lower Proterozoic age. Deposits in the Great Bear Lake area, Northwest Territories, Canada, are associated with faults and fissures in metasediments and acid volcanics that form an elongated roof pendant in intrusive granites. The host rocks are banded, waterlain tuffs that are locally brecciated and mineralized with actinolite, hornblende and magnetite. The uranium, as pitchblende, is a component of complex uranium-nickel-cobalt-silver-copper mineralization of the arsenide-sulphide type. The veins are encompassed by thin alteration aureoles up to 3 m wide consisting of chlorite, hematite, white mica, microcline, and carbonate. Alteration believed to be related to a quartz-hematite stage of mineralization is widespread, and is considered to be a guide in exploration.

5. SANDSTONE DEPOSITS

Deposits of this type range in average grade from 0.05 to 0.30% U_3O_8 . Some are small but others contain up to 40,000 tonnes of uranium. (Figure)

U.S.A.

Uranium deposits in sandstones are collectively the most important type presently known, since they comprise 35% of the total reserve at a cost of \$ 50/lb U_3O_8 . The bulk of the uranium in this type of deposit occurs in the Colorado - Wyoming province in sediments of Triassic to Eocene age. Favourable lithologies are clastic sediments of continental or marginal marine origin. In many ways the main characteristics of the deposits resemble those in Precambrian sediments in that they generally conform to the bedding. They are associated with unconformities, troughs, and ancient stream channels, and interfaces between sandstone and shale. Deposits are generally best developed where there is an abundance of carbonaceous remains of sulphides, which accelerated precipitation of uranium. The well-documented 'roll-type' deposits of the province occur at oxidation-reduction boundaries and are probably of secondary origin.

The irregular tabular bodies vary in size from small pockets to masses several thousand feet in lateral dimensions and up to a hundred feet in thickness. The larger deposits are commonly of the order of 10 ft thick and contain more than one million tons of ore at a grade around 0.2% U_3O_8 . The bulk of the ore reserves is contained in deposits less than 800 ft deep, and approximately half the total could be mined by open pit methods. Similar deposits occur in the Gulf Coastal Plain of Texas.

The primary uranium-bearing minerals are uraninite and coffinite, with the latter playing a more significant role than it does elsewhere except in some vein deposits. A large number of secondary minerals are present but the most prevalent species is carnotite. Vanadium and copper are commonly associated with uranium in considerable abundance and there are also significant amounts of molybdenum and selenium present.

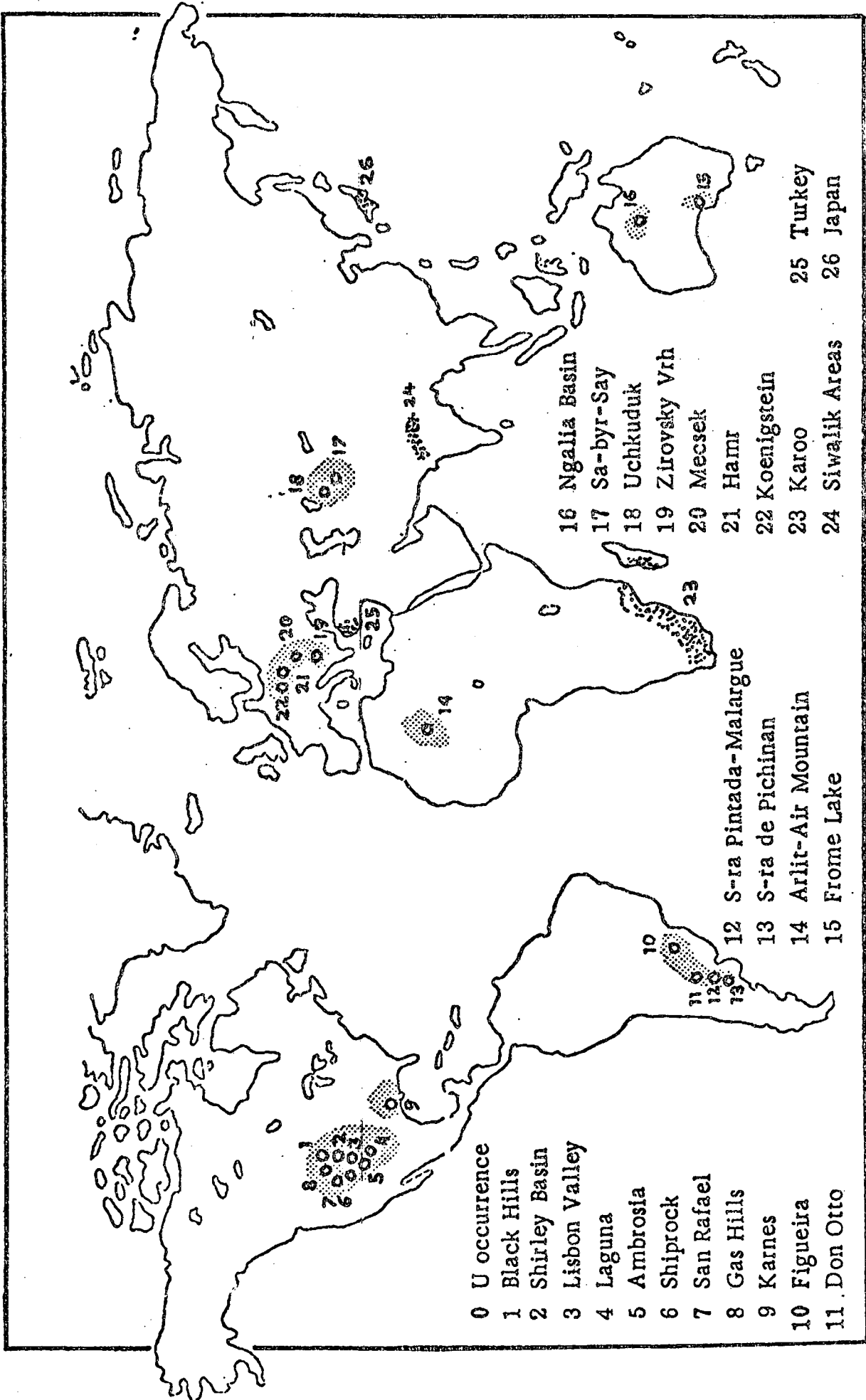


FIG. 7 Areas with uranium deposits in sandstones.

Niger

The Mesozoic sandstone deposits near Arlit in the Niger tend to occur in ancient river beds and the most favourable of them can be worked by open pit methods. The ore bodies are similar to those occurring in sandstones in the Colorado Plateau both with regard to their general disposition and grade ($\approx 0.25\% \text{U}_3\text{O}_8$). Reserves are estimated by the CEA to be at least 160,000 tonnes U.

The sedimentary basin of Agadès, is bordered to the east by the Precambrian rocks of the Air Massif and to the north and northwest by the Hoggar craton. The sediments are deltaic, fluvial to lacustrine in nature and the deposits are essentially confined to traps created by the response of the sediments to tectonic movement.

Gabon

The uranium deposits of Mounana and Oklo occur in the Francevillian basin of Precambrian age in coarse feldspathic sandstones with intercalated conglomerates. The location of mineralization is determined in the light of sedimentary and structural factors. The mineralization is essentially of uranium and vanadium with pitchblende in various states of oxidation, uranium secondaries and several vanadium minerals. Reserves are of the order of 20,000 tonnes U. However, modern thinking tends to place the Gabon deposits in Proterozoic unconformity related type of deposits.

Australia

Another important example of uranium in Phanerozoic sediments immediately overlying Precambrian basement is the province of Lake Frome-Yarramba, Australia.

The Beverley deposit is a subsurface deposit in Tertiary sediments east of the Flinders Ranges where uranium rich granite basement crops out. Additional sedimentary uranium deposits occur in the southern part of the Frome Embayment in Pleistocene river channels cut into basement rocks of Precambrian to Tertiary age. Small roll front type deposits have been outlined at Gould's Dam, Honeymoon and East Kalkaroo.

In Central Australia uranium prospects have been found in Carboniferous sandstone of the Ngalia Basin and Devonian-Carboniferous sandstones of the Amadeus Basin. Exploration is continuing and there are prospects of establishing significant reserves.

Argentina

Peneconcordant uranium occur at many locations in Argentina, mainly along the eastern flank of the Andes. The principal deposits occur in Permian, Trias, Middle and Upper Cretaceous and Tertiary sediments. The host rocks vary in composition and grain size. Important deposits occur in the Sierra Pintada area near San Rafael in Mendoza Province where ore bodies 2 - 12 metres thick occur in relatively coarse sandstones of Permian age. The uranium mineralization is pitchblende and no other metallic minerals occur. Other deposits occur in the Cordoba and Salta provinces. Total ore reserves stated for Argentina are 10,000 tons U_3O_8 .

Brazil

Sedimentary deposits of Middle Permian age containing secondary uranium minerals and uraninite occur in the Figueira area in the State of Parana and over 2000 tonnes of uranium have been outlined.

Mexico

Systematic field prospecting has confirmed reserves of the order of 1300 tons U_3O_8 in sandstone type deposits which are similar to and essentially a continuation of the deposits in Texas.

Europe

Locally, commercial-quality uranium mineralization occurs in continental clastic deposits mainly in Lower Permian non-marine rocks.

In the Federal Republic of Germany several small occurrences are known to exist in Lower Rotliegende rocks in the Saar-Nahe Trough. Pitchblende and coffinite are accompanied by pyrite, marcasite, chalcopyrite and sphalerite and the uranium is closely associated with carbonaceous material.

In France the most well known occurrences are in the Lodève basin to the south of the Massif Central. The close association of uranium with carbonaceous material is very evident. In Italy, the major occurrences are at Val Rendena and Val Daone and in Switzerland at Murtshcenalp, both groups of occurrences being roughly in the same Verrucano province. In Austria at Forstau and Tweng in Salzburg province similar uranium occurrences are found in the grey fine grained sandstones of rocks which range in age from Upper Carboniferous to Permian-Lower Triassic. In Yugoslavia uranium is concentrated in lenses in grey fluviatile sandstones of the Lower Permian Graden formation. Similar occurrences are also known in Hungary.

Pakistan

Surface carnotite mineralization and pitchblende-coffinite mineralization at depth has been found in poorly cemented Siwalik sandstones of Lower Pliocene to Upper Miocene age in the foothills of the Sulaiman range in West Pakistan.

India

In India, uranium occurs in sediments both in the Precambrian meta-sediments of the Singhbhum district in Bihar and in the Siwalik sediments of Tertiary age in northern India.

Turkey

In south-western Turkey ore deposits have been discovered consisting of secondary uranium mineralization in loosely consolidated sands, gravels, silts and clays of Neogene age. The secondary uranium minerals occur interstitially coating pebbles or in cracks in the muds of clays. The ore grade is of the order of 0.05% U_3O_8 but the mode of occurrence favours economic recovery.

Japan

Uranium occurs in Japan in Palaeozoic to Mesozoic sediments in the region of granite massifs. The most important are in the vicinity of the Chugoku Massif in Southern Japan where mines have been opened up at Ningyotoge and Kurayoshi. The deposits are of sandstone type similar to those of the Colorado Plateau with pitchblende and coffinite as the main primary minerals occurring mainly in conglomerate horizons. Reserves are of the order of 500 tons U_3O_8 at an average grade of 0.05%.

Southern Africa

The Karoo sedimentary system covers one half of South Africa, Lesotho, large areas of Swaziland, is present in Mozambique, Tanzania, Kenya, Madagascar, Zambia, Rhodesia, Botswana and Namibia. Numerous sedimentary uranium occurrences have been recorded in South Africa, Zambia, Madagascar, Lesotho, Botswana and Kenya. Occurrences of both secondary and primary minerals are associated with both fine grained and coarse sandstones frequently related to bedding.

6. OTHER TYPES OF DEPOSITS

Included in this grouping are deposits that cannot readily be classified with the ore types already mentioned. (Figure 8)

Calcrete deposits range in average grade from 0.05 to 0.3% U_3O_8 and in size from 100 to 40,000 tonnes of contained uranium. The grade of limestone deposits is about 0.2 - 0.35% and their size varies from less than 10 tonnes to 10,000 tonnes of contained uranium. Uranium deposits in shales are usually of low grade but some are very large. The Ranstad deposit, with its grade of around 300 ppm, contains over 300,000 tonnes of extractable uranium.

Australia

Carnotite mineralization is widespread in calcrete deposits which occur as valley fill-in channels in the salt lake internal drainage system of the southern half of Western Australia. A large uranium deposit has been outlined at Yeelirrie and several smaller occurrences are known. These deposits are at shallow depth and the extensive exploration conducted to date has reduced the probability of establishing further large reserves in the low cost category although there are potentially large resources in the high cost category.

At Yeelirrie reserves are estimated to be 40,700 t U at an average grade of 0.15% U_3O_8 . The deposit occurs in the Archaean Yilgarn Block 65 km southeast of Wiluna, and is confined to a NNW-SSE trending channelway which parallels greenstone belts in the region. The channelway is surrounded by granite-gneiss cut by quartz veins, pegmatites, dolerites and aplites. The uranium, which is entirely in the mineral carnotite, is mainly dispersed throughout earthy calcrete and on the cavity walls of porcellaneous calcrete.

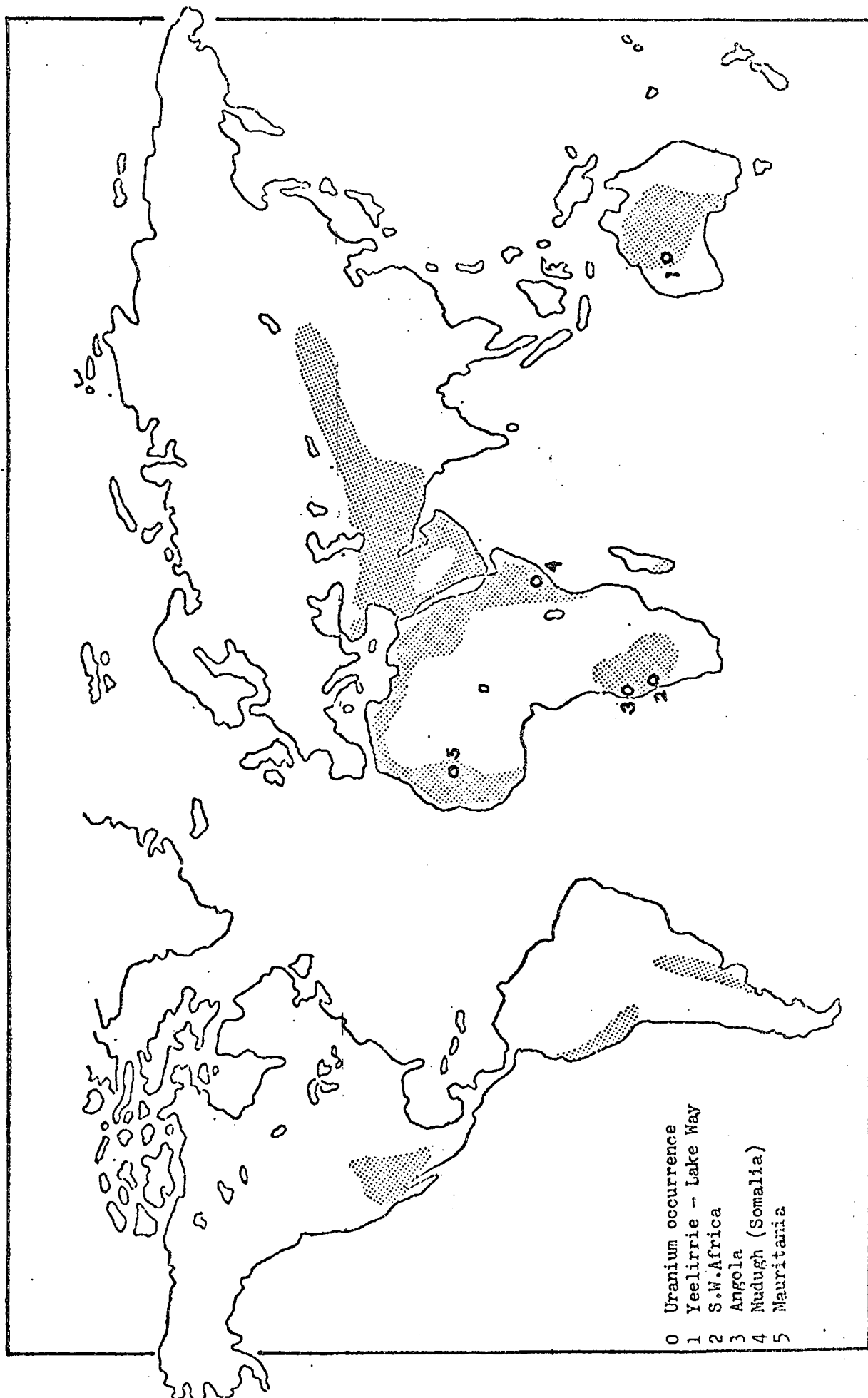


FIG. 8 Areas favourable for uraniferous duricrusts.

Somalia

Concentrations of the secondary uranium mineral, carnotite occur in the Mudugh area of Somalia along a 240 kilometre N-S orientated zone. The mineral is located in superficial lime-clay, marl, bentonite, gypsum and sand in a semi desert area. Some 500 tonnes U_3O_8 have been proven in these deposits.

Other areas

Similar deposits are known in Namibia, South Africa and Mauritania, and there are many other potential host areas in the desert areas of the world.

Other deposits

Some uranium deposits, of minor importance are formed in limestones. The geologic settings vary, and it is likely that these deposits are formed by several different processes.

Deposits in thin, petroliferous, marine Jurassic limestone, overlain by relatively impermeable shales and underlain by red aeolian sandstone, are known in the Grants district of New Mexico in the USA, the upper beds of the sandstone are bleached white almost everywhere they underlie the limestone. Bleaching is attributed to reduction of hematite by hydrogen sulphide released from the limestone. Mineralization consists of pitchblende, attributable to reduction, and metatyuyamunite as a near-surface oxidation product.

In Wyoming (USA) deposits occur in Mississippian limestones within a complex cavern system. Secondary minerals, such as tyuyamunite and metatyuyamunite coat fractures and fill vugs in limestone breccias and are also associated with calcite interbedded with silts and clays deposited in the cavern openings. Uranium redistribution is occurring locally at the present time.

Uranium is also associated with a limestone karst terrain at Bakouma, Central African Empire. The uranium deposits occur in steep-sided pits formed by dissolution of limestone by ground-waters. These pits are partly filled with Cretaceous to Tertiary sands and clays that are cemented by limestone and phosphate. The phosphate, as carbonate fluorapatite, constitutes as much as fifty per cent of the rock. The uranium occurs within the phosphatized fractions of the limestone. Autunite and tobernite have been formed near the surface by weathering.

Uranium commonly occurs at concentrations of 100 to 150 ppm in marine phosphorite. These sediments occur on every continent and commonly form phosphate deposits, most notably in Morocco and other North African countries; some countries in the Middle East; and in Florida, Idaho, Utah and Wyoming in the USA. When these deposits are developed for the production of phosphoric acid, uranium can be extracted as a by-product.

Uranium also occurs in low concentrations in bituminous shales, in particular in the Ranstad area of Sweden. Here the Upper Cambrian shale, which is virtually horizontal over an area of around 500 km², contains about 22% organic matter and 1% pyrite. The uranium bearing seam is 2.5 - 4.0 m thick and contains around 90% of the uranium. Uranium also occurs in significant concentrations in shales in the Tasjo Lake area in Sweden. In shales in Norway and in the Chattanooga shale of Central Tennessee (USA), uranium is also concentrated but values below 100 ppm are common.

Lignites, such as those of North and South Dakota (USA), the Permian-Carboniferous coals of Bohemia and the lignite deposits of Oligocene age in Spain contain between 500 and 2,000 ppm U₃O₈. Difficulties in extracting the uranium affect the economic viability of these deposits.

Uranium occurrences have been found in an area of Recent volcanism (less than 1 m.y. old) in the Upper Latium region of Italy. The source rocks are pyroclastics and other volcanics which have a uranium content of 20 - 60 ppm. The mineralization is controlled by the redox activity of the water table and by late volcanic activity in the form of hydrogen sulphide and carbon dioxide rising through tectonic discontinuities.

FUTURE POSSIBILITIES FOR THE DISCOVERY OF URANIUM DEPOSITS
ANALYZED ON A CONTINENTAL BASIS

The IAEA and the NEA (OECD) have recently completed a study entitled the International Uranium Resources Evaluation Project (IUREP) which was designed to review and evaluate the potential for discovery of additional uranium resources, to identify areas favourable for such resources and to suggest new exploration efforts which might be carried out in promising areas.

The following is a summary, on a continental basis, of the views of the group who carried out the study.

1. AFRICA

Future resources are expected to occur mainly in deposits of the quartz-pebble conglomerate type in South Africa and possibly in Botswana, in deposits of the Proterozoic unconformity-related type in the Lower Proterozoic of Botswana and Ghana and in Middle Proterozoic rocks, mainly of the Francevillian or equivalents, in Angola, Cameroon, Congo, Ethiopia, Gabon and Zaire. Deposits of this last type may also occur in the Precambrian rocks of Burundi, Central African Empire, Mozambique, Rwanda, Togo and Uganda. Disseminated deposits similar to these at Rössing may occur elsewhere in Namibia. Vein and disseminated deposits similar to those known in the Hoggar Massif may occur in other areas of Algeria and in Mali and Chad while vein deposits similar to that at Shinkolobwe (Zaire) could occur in the Upper Proterozoic sediments of the Katanga System or its equivalents in Angola, Burundi, Congo, Ghana, Rhodesia, Rwanda, Zaire and Zambia. Uranium also occurs in veins in the "Younger Granites" in Chad, and may occur in the equivalent plutonic rocks in Cameroon, Nigeria and Sudan. Vein deposits may be associated with Hercynian granites in Morocco and in Precambrian metamorphic rocks in this country and also Cameroon and Mozambique.

Uranium can be expected to occur in sandstones of several ages. Uranium is found in the basal conglomerates of the Tassili Series (Late Cambrian to Early Devonian) south of the Hoggar Massif in Algeria. Other occurrences

would be expected in Chad, Mali and Niger. Uranium deposits occur in Carboniferous argillaceous sandstones in Niger and equivalent sediments are found in Angola and Mali. The Upper Carboniferous to Lower Jurassic sediments of the Lower Beaufort part of the Karroo Supergroup contain several hundred uraniferous occurrences in South Africa. Uranium occurrences are also known in the Karroo of Botswana, Madagascar and Zambia and could be prospected for in Angola, Ethiopia, Lesotho, Kenya, Tanzania, Mozambique and Rhodesia. The "Continental Intercalaire" sediments are widespread in Africa and are mainly of Lower Cretaceous age. Uranium has been discovered in a basal sandstone of Lower Cretaceous age at Azelik in Niger and similar deposits could occur in the Cretaceous sediments of Algeria, Angola, Cameroon, Central African Empire, Chad, Ethiopia, Gabon, Libya, Mali, Niger and Nigeria. Uranium also occurs in Permian red beds, at Imouraren in Niger and in Permi-Triassic rocks of the western and central parts of the High Atlas region in Morocco. The mainly Mesozoic Nubian Sandstone of Sudan may be prospective. The Tertiary sandstones, mainly Kalahari Sandstone of Angola, Botswana, Central African Empire, Chad, Zaire and Zambia should also be prospected for uranium especially as these areas could also contain uranium in surficial deposits. Other countries where surficial deposits could occur are Ethiopia, Madagascar, Mauritania, Namibia, Rhodesia, Somalia and South Africa.

Uranium could also occur in pegmatites in many areas of Africa, in carbonatites as at Palabora in South Africa and associated with phosphate bearing rocks as at Bakouma in Central African Empire.

2. ASIA AND THE FAR EAST

Uraniferous quartz-pebble conglomerates occur in Early Proterozoic metamorphosed sediments in India, though these have yet to show ore grade uranium values. The Early Proterozoic Wutai Group which outcrops in North China and in East China, Shantung and Tarim may also contain deposits of this type. Proterozoic unconformity-related deposits have not been reported from this continent but the North China - Korea and South China Shields (mainly outcropping in China) and Indian Shield may all contain favourable environments for such deposits.

Disseminated and vein type deposits could occur in many parts of Asia and occurrences are known in Burma, India, Indonesia, Pakistan, Saudi Arabia Thailand and Turkey and these countries should be prospected further. Dissemination in metamorphic rocks represent the most important deposits in India and occur in three provinces, Singhbhum, Rajasthan and Madhya Pradesh. The majority of future resources of Indonesia should occur in these types of deposits where granites intrude a wide range of sedimentary-volcanic environments in the Malaya, West Kalimantan and Sumatra Orogens.

There is the possibility of locating uranium in sandstones of many ages. The Lower Cambrian Lalun sandstone of Iran is continental and has some potential. The Permo-Carboniferous palaeochannel deposits of the Madhya Pradesh Province, India, are being studied further. Triassic sandstones in the West Kalimantan Orogen of Indonesia are locally carbonaceous and weakly radioactive and anomalies have been detected in the Lower Permian Wajid Sandstone and sandstones of Triassic age in Saudi Arabia. Mineralization is known in the Jurassic-Cretaceous sandstones of the Khorat Plateau, Thailand, and in Upper Cretaceous to Tertiary beds in India. The Lower Jurassic Shemshak Formation of Iran is also favourable. Uranium occurs in Tertiary sandstones in many countries as in the Palaeogene sandstones in India and Turkey, in the Neogene in Afghanistan, Iran, Pakistan and Turkey and in the extensive Pliocene-Pleistocene Siwalik Series and equivalents of Bangladesh, northern India and Pakistan. Sandstone deposits of Tertiary age also occur in China and many other basins in this country, ranging in age from Devonian to Miocene, contain favourable environments for deposits of this type.

Uraniferous calcretes have not been described from Asia, but the extensive arid regions of Afghanistan, the Arabian Peninsula, Iran, Iraq, India and Pakistan could be favourable. Bituminous shales occur in several countries, in particular Iran, India and Pakistan and there is the possibility of locating uranium in carbonatites in other countries, especially Saudi Arabia.

3. AUSTRALIA AND OCEANIA

The great majority of the future resources of this area will be located in Australia which has environments favourable for all types of uranium deposits. The potential for the discovery of uraniferous quartz-pebble conglomerates is thought to be low though uranium has been reported in uneconomic concentrations in this type of environment.

The greatest potential for additional resources occurs in the Lower Proterozoic rocks in the Pine Creek Geosyncline of the North Australian Orogenic Province. There is additional potential for Proterozoic unconformity-related deposits in the other blocks of this orogenic province and also in the Georgetown and Gawler Blocks.

The only deposit from which uranium is presently being produced in Australia is the Mary Kathleen deposit in Queensland. Here the uranium occurs disseminated within a metamorphosed sequence of Middle Proterozoic age. There is the possibility of finding disseminated deposits in all four of the Australian orogenic provinces. Uranium occurs disseminated in Precambrian gneisses in New Zealand.

Vein type occurrences are common in Australia in the Palaeozoic rocks of the Tasman Geosyncline, in the Gascoyne Block and in the Mt. Painter Inlier of the Central Australian Orogenic Province. All the Australian orogenic provinces have potential for vein mineralization. Vein type deposits could also be prospected for in or around the major shear zones in New Caledonia, many of which are mineralized, and in the mineralized areas of the Solomon Islands.

Deposits have been found in sandstones in the Lake Frome Embayment, South Australia, and the Ngalia and Amadeus Basin in the Northern Territory. Work is continuing in these basins and in the Eucla Basin and there is considerable potential for further deposits of this type in these areas and in other parts of the platform covers. The Miocene platform sediments of Papua New Guinea, which overlie the Permian and Triassic granites, have limited potential for uranium deposits as do the Lower Cretaceous sediments of New Zealand where they directly overlie the uraniferous Precambrian gneisses previously mentioned.

Uranium in the form of carnotite is widespread in calcretes which occur in valley-fill channels in the salt-lake internal drainage system of the Arachaeian and Pilbara Blocks. These blocks and parts of other Precambrian orogenic belts remain to be fully explored.

The Maureen deposit in the Georgetown area and the deposits in the Westmorland area, both in Queensland and the new uranium occurrence at Olympic Dam in South Australia are difficult to classify and much work will be required to assess the full potential of these and similar areas.

4. EUROPE

No deposits of uranium in quartz-pebble conglomerates or related to Proterozoic unconformities are known in Western Europe. The only areas with potential for deposits of this type are parts of the Fennoscandian Shield in Norway, Sweden and Finland.

Deposits occur as disseminations in igneous and metamorphic rocks in Denmark (Greenland), Italy and Sweden. There is the possibility of additional deposits, similar to the ones described here, being found in each of these countries.

Uranium deposits occur as disseminations in, at, or close to the contacts between pre-Devonian metamorphosed sediments and Hercynian granites in Portugal and Spain. These deposits have been referred to as of the "Iberian Type". Occurrences of this type are also known in France and could be prospected for in southwest England.

In addition to the countries already discussed, there is potential for the discovery of disseminated type deposits in Austria, where magmatic intrusions have occurred in different parts of the Alps and in the Precambrian migmatized and granitized areas of southern Norway or in the carbonatite rocks of the Fen district (Norway).

Approximately 70 per cent of the uranium resources of France occur in vein type deposits associated with granites distributed almost entirely within the Moldanubian zone of Hercynian orogen.

In addition to the countries such as France, Spain, Portugal, Germany and Sweden, containing known deposits of this type having potential for additional discoveries there is a possibility that other deposits could be discovered in Austria, Italy, Norway and the United Kingdom.

The majority of uranium ore deposits and occurrences in the Eastern Alps are in sandstones and schists of the Lower Permian as at Forstau in Austria. Similar targets could also be examined in the French Alps. Sandstone deposits in France are located in Permian continental or sub-continental formations preserved in collapsed basins of the Moldanubian zone or at its periphery and in Palaeogene molasse type sediments of the Moldanubian zone. Uranium concentrations are found in Late Carboniferous - Lower Permian intermontane continental sediments of the Black Forest, northern Franconia and the Nahe Trough (F.R.G.). Sandstone deposits in Yugoslavia occur in Tertiary fluvia, lacustrine or shallow marine sediments and in Permo-Triassic continental sediments.

There is also the possibility of locating economic deposits of uranium in the Permian sandstones of the Bergamasco Alps (Italy), in Portugal in the Portuguese Depression, the Tagus and Sada Basins and small basins scattered over the Meseta, and in Spain in the post-Hercynian continental basins and the Permo-Triassic sandstones of the Pyrenees. The potential of the Devonian Old Red Sandstone of the United Kingdom and the Precambrian and Early Proterozoic of Sweden is more limited.

The black shale deposit at Ranstad represents one of the largest deposits in the world. Uranium is also found concentrated in shales in other areas of Sweden and in Norway and, to a lesser degree, in the United Kingdom and Germany.

5. SOUTH AND CENTRAL AMERICA

Uranium occurs in quartz-pebble conglomerates in Brazil, though these occurrences have not yet been proven to be economic. Conglomerates are however widely developed around the Sao Francisco Craton and the possibilities of finding economic uranium deposits in these Precambrian conglomerates appears promising. Further work should also be undertaken on the

Moeda Formation in the Quadrilatero Ferrifero and the geology of the Cavalcante-Tocantins mining district appears promising. There is a more limited possibility of finding deposits of this type in the Guyana Shield areas of Colombia and Venezuela.

The most favourable area for the location of Proterozoic unconformity-related deposits in South America is that underlain by the Guyana Massif and overlain by the Roraima Formation. Here, in parts of Brazil, Venezuela, Guyana and Surinam, the geological conditions of the sub-Roraima unconformity closely resemble those of the sub-Athabasca and sub-Kombolgie unconformities of the Wollaston Fold Belt (Canada) and the Pine Creek Geosyncline (Australia). Other areas of interest in Brazil include the post-Minas Series unconformity in the Quadrilatero Ferrifero and areas underlain by the Serido Geosyncline. In Colombia areas within the Interior Zone, in eastern Colombia, and also in Precambrian areas of the Cordillera Central, in particular the Garzon and Santander Massifs, may also have some potential.

In Argentina, several uranium deposits are found in Precambrian and Palaeozoic crystalline schists, metamorphosed slates, argillaceous or arenaceous sediments and eruptive rocks especially along the contacts of these rocks. There is a good possibility of finding additional deposits of both the disseminated and vein type in Argentina where granites, in particular those of Late Palaeozoic age, intrude these rocks. The areas of highest potential could be within the provinces of Cordoba, La Rioja, San Luis, Mendoza and Nuequen.

Disseminated mineralization occurs in Brazil in alkalic rock complexes at Pocos de Caldas and at Araxa. At the former uranium also occurs as uranium oxide in veins. The alkalic belt of the Tunas Group, which extends from Sao Paulo through Parana to Santa Catarina, and the alkalic rocks in the States of Rio de Janeiro and Sao Paulo and at Ipanema should also be studied. Uranium also occurs in granite and pegmatoid granite in the Serido Geosyncline and the mineralization here resembles that at Rössing in Namibia.

There is the possibility of discovering additional uranium deposits of both the disseminated and vein type in the areas discussed above and also in Precambrian, Palaeozoic or even Mesozoic metasediments intruded by

granites in Bolivia, Colombia, Peru and Venezuela and also in Chile, Ecuador, Guatemala and Jamaica. Uraniferous vein deposits do in fact occur in the Santander Massif of Colombia. Uranium also occurs in fractures or disseminations in Tertiary volcanic rocks of the Cordillera de Los Frailes and associated with tin and tungsten in veins in the Central Cordillera (Bolivia).

Most of the known resources of South America are located in sandstones. The major part of Argentina's resources are in Cretaceous and Permian sediments in Mendoza Province and the Cretaceous and Tertiary sediments of Jujuy and Salta Provinces. Exploration to date suggests that such sediments, which are exposed in many areas in the Cordillera of Western Argentina, are very promising for the discovery of new deposits. Significant uranium deposits have been found in Permian sediments in the Parana Basin of Brazil. This basin, the two other large sedimentary basins (the Piaui-Maranhao and the Amazon), and the smaller Mesozoic and Cretaceous basins along the east and northeast coast should also be prospected further. There is the possibility of finding similar deposits in the Paraguay and Uruguay portions of the Parana Basin. Sediments ranging in age from Upper Palaeozoic to Tertiary are potential host rocks in the Cordillera Oriental and the Eastern slopes of the Andes in Bolivia, Colombia and Peru. Tertiary red beds elsewhere in these countries may also be favourable hosts in particular in the Altiplano of Bolivia. The red beds of Chile and Ecuador and other Mesozoic or Tertiary sandstones in Honduras and Jamaica also have some potential.

Radioactivity has been recorded in black shales in areas of Bolivia, Brazil, Colombia and Venezuela. Yellow uranium minerals have been noted in Quaternary travertines from Tolar Grande, Argentina. These occurrences could be further studied.

6. NORTH AMERICA

A substantial portion of Canada's uranium resources occur in the Basal Huronian (Lower Proterozoic) quartz pebble conglomerates of the Elliot Lake and the Agnew Lake areas. Geological environments similar to those containing these deposits also occur elsewhere in the Penokean Fold Belt and in the Cobalt Embayment of the Southern Structural Province, in some intracratonic

basins of the Superior Province, and in the Padlei Belt of the Churchill Structural Province.

The most recently discovered uranium deposits in Canada are of the Proterozoic unconformity-related type. These include the Rabbit Lake, and Key Lake deposits in the Wollaston Fold Belt and the Cluff Lake deposits. The deposits in the Beaverlodge area are somewhat different but there are sufficient similarities for them to be classified as this type of deposits. Similar geological environments are found in other fold belts of the Churchill Structural Province and in portions of the Bear, Slave, Nain and Superior Structural Provinces. There is little potential for this type of deposit to be discovered outside of Canada within the North American continent.

Deposits occur disseminated in igneous and metamorphic rocks in all the countries described here. Favourable environments for further deposits of this type can be found in many parts of the North American continent especially in areas of intense igneous activity.

At the Schwartzwald mine in the Front Range of Colorado, USA, pitchblende and coffinite veins occur in Precambrian metamorphic rocks together with minor amounts of sulphides. Vein deposits also occur in Tertiary volcanics in Marysvale district of Utah and in Breccia pipes in Nevada, Utah, Arizona, and New Mexico. The deposits at Port Radium, North West Territories, Canada, occur in fractures in Lower Proterozoic metasediments and volcanics. Veins containing uraninite, together with gold occur in Tertiary andesites to the northeast of Chihuahua City, Mexico. Areas considered favourable for further discovery of vein deposits include several regions of the Cordillera, parts of the Southern Canadian Shield and the western edge of the Bear Province.

A very large percentage of the US uranium resources occur in sandstone uranium deposits of the Colorado Plateau, the Wyoming Basins, the Western Gulf Coast regions and the northern part of the Great Plains. The main hosts are Tertiary fluvial sediments in the Wyoming Basins, Late Triassic and Late Jurassic sediments in the Colorado Plateau, the Eocene to Pliocene sands in the coastal plains of Texas and the Early Cretaceous, Dakota and

Fall River Formation in the Black Hills of South Dakota and Wyoming. Deposits in Mexico occur in the Oligocene Frio Formation of the Coastal Plain, an extension of the Gulf Coastal Plain of Texas. Areas considered favourable for additional deposits of this type are mainly those around the areas already producing but other areas, in particular parts of Mexico, Alaska and Canada, should be studied further:

The Jurassic Todilto limestone contains uraninite in anticlinal structures and fracture zones. There is the possibility of finding additional deposits in limestone in the Grants Mineral Belt and the Sierra Madre Oriental and in calcretes of the Basin and Range Province and parts of the northern Mexico.

CONCLUSIONS

Uranium deposits are not uniformly distributed in the earth's crust but occur in well-defined provinces, mainly in Precambrian terrain and in association with acid igneous rocks and the uranium resources of the world can be assigned on the basis of their geological setting to the following six categories of ore types: Quartz-pebble conglomerate deposits, Proterozoic unconformity-related deposits, disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks, vein deposits, sandstone deposits, other types of deposits.

The requirements for uranium into the next century are very great and the presently known uranium provinces may not be able to fulfill these requirements. There are large areas of the world that are virgin or lightly explored, particularly in the developing countries which may offer even greater promise for new discoveries of the conventional types of deposits or for new types of deposits.

In the present state of knowledge and on the basis of the various theories, the most favourable geographic areas of the world might be stated as follows:

- (1) The whole eastern side of the North, Central and South American Cordilleran belt from Alaska through USA, Central America to the south of Argentina. Much of this belt has already been explored with success in the USA and Argentina, but there are favourable areas so far almost untouched, e.g. the difficult geographic areas of the Upper Amazon basin in Bolivia, Peru, Ecuador, Brazil, Colombia and Venezuela.
- (2) In the Alpine-Himalayan mobile belt the accessible parts of the flanks of the main mountain chain are generally favourable, e.g. Morocco, Algeria, Tunisia, Italy, Yugoslavia, Greece, Bulgaria, Turkey, Iran, Afghanistan, Pakistan, India, Burma, the USSR and China.
- (3) In the rest of Europe the most favourable countries are considered to be Portugal, Spain, France, Austria both the Federal and Democratic Republics of Germany, Czechoslovakia, Poland, Hungary and the USSR.
- (4) Based on the shield theory, other hospitable areas are Canada, Guyana, Brazil, Scandinavia, Greenland, West Africa, Central and East Africa, Southern Africa, India, Australia and the USSR.

Obviously this covers a large part of the world but even so, it could not be regarded as exclusive because of the ubiquitous nature of uranium and the multiplicity of its mode of occurrence.

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