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EUROPEAN ATOMIC ENERGY COMMUNITY — EURATOM

SOME GEOLOGIC CONCEPTS AS A GUIDE FOR THE SEARCH OF URANIUM IN THE PRECAMBRIAN SHIELDS

by

L. VAN WAMBEKE

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Joint Nuclear Research Center
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Metallurgy and Ceramics

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Printed by Van Muysewinkel
Brussels, June 1967.

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Summary

The distribution pattern of the uranium occurrences in the Precambrian shields can be explained mainly on the basis of the geological and paleogeographical evolution of sedimentary basins which are either intracratonic or geosynclinal.

In intracratonic basins, uranium occurs either in sediments, in acid/intermediate volcanics or in veins and is essentially located in the marginal zones of the basins and in the neighbouring basement. Favourable areas for uranium are mainly confined to these marginal zones of sedimentation and attention must be focused especially on intracratonic basins either containing interbedded acid/intermediate volcanics in the stratigraphic series or formed by intense fracturing of the basement.

In geosynclines, the distribution of uranium occurrences is more complicated because these basins have been affected during the orogenies by magmatic-hydrothermal activity and metamorphism. However, a relationship also seems to exist between the location of uranium deposits and marginal zones of sedimentation. This feature is not only valid for uranium mineralizations in sediments but may explain uranium occurrences such as veins and pyrometasomatic deposits.

The distribution of uranium occurrences related to post-Caledonian events in the shields'areas is also discussed.

Geological criteria which may be used for a preliminary evaluation of the uranium outlook in the Precambrian belts are described. Examples of poorly or unprospected areas apparently favourable for uranium are given.

Application of geologic concepts is an important step for the choice of the most promising areas to be prospected for uranium.

SOME GEOLOGIC CONCEPTS AS A GUIDE FOR THE SEARCH OF URANIUM IN THE PRECAMBRIAN SHIELDS +

The Precambrian shields contain 64 % of the total uranium reserves of the free world, recoverable at a price of $ 8 per lb. of U_3O_8 and about 90 % of this uranium occurs in the banket conglomerates. Outside the shields, the main uranium reserves are located mostly in the intermontane and marginal basins of the Laramide orogenic belt in both Americas (U.S.A., Argentina, etc.) and in the Hercynian belts of Europe and Asia.

In western Europe, outside the Precambrian Baltic shield, the outlook for finding new uranium deposits is mainly confined to the late orogenic granite intrusions and volcanics of Hercynian age and to their associated continental basins. These favourable mineralized areas are, however, limited in extension and the uranium resources recoverable at a price of $ 8 - 10 per lb. of U_3O_8 are estimated to total about 100.000 metric tons of U metal of which 45.000 m.t. are already discovered. The main future uranium resources are located in France and Spain.

Good possibilities for new uranium deposits also exist in the eastern Cordillera, which extends from northern Canada to southern Mexico, and in the eastern Andes and

+ Manuscript received on March 20, 1967

subandean regions from Venezuela to southern Argentina, especially in the areas characterized by a series of uplifts and basins formed mainly in the last stages of mountain building. The predominant uranium mineralization is of the epithermal to telethermal type and is mainly confined to sandstones. The total uranium resources of these favourable belts are difficult to predict but are certainly large (1).

For the United States alone the total uranium resources recoverable at a price of $ 8 - 10 per lb of U_3O_8 are estimated at about 310.000 metric tons of uranium metal and the actual reserves at about 110.000 m.t. (2) (3). The main future resources of uranium in the Western Hemisphere outside the shields seem to be located in the U.S.A. and in Argentina, but development of prospecting in other areas such as Mexico and the Andean states will lead certainly to the discovery of new uranium districts.

Besides possible uranium deposits in the Paleozoic Cordillera of Australia, in the Appalachian System and in some of the Alpine Himalayan belts of Asia, the bulk of the remaining recoverable uranium resources of the free world will be mainly found in the Precambrian shields.

With the increasing rate of uranium consumption, the known uranium reserves of the free world at a price of $ 8 - 10 per lb of U_3O_8 shall be exhausted during the 1980's (3). Therefore it becomes necessary to look for new deposits in order to meet the uranium needs. For the European Community alone, the uranium consumption between 1970 and 1999 will exceed 300.000 metric tons of U metal (4) whereas the total uranium resources recoverable at a price of \$ 8 - 10 per lb of U_3O_8 may be evaluated at about 65 to 70.000 metric tons of U metal. These differences between resources and consumption indicate clearly that it will be important for the European Community to insure a medium- to long term uranium supply and that one of the safe solutions remain prospecting.

The need for low-cost uranium will be important in the first stages of the development of nuclear energy in order to compete with other fuels. Therefore, the first steps in uranium prospecting must be centered especially in the search for ore bodies from which uranium can be recovered at a price not higher than \$ 10 per lb of U_3O_8.

The Precambrian shields, which are characterized by the largest uranium deposits in the world, will probably supply important additional reserves. The choice of the regions to be prospected constitutes the principal problem and must first be carefully studied on the basis of geological knowledge. Therefore preliminary geological reconnaissance becomes a decisive factor in most of the unprospected Precambrian areas. Our intention here is to outline where prospecting for uranium in the Precambrian shields must be focused and for what reasons.

I. GENERAL DISTRIBUTION OF THE URANIUM DEPOSITS IN THE PRECAMBRIAN SHIELDS (see fig. 3)

Uranium deposits in the Precambrian shields may be divided into four main types which are listed in order of decreasing importance:

- uranium disseminations in sedimentary rocks or in volcanics
- vein deposits
- pyrometasomatic deposits
- uraniferous pegmatites

With the important exception of the Archean uranium-gold conglomerates of the Witwatersrand, the main deposits are found in Proterozoic rocks or were formed during this era. Some uranium mineralisation is also related to post-Caledonian events. In the Precambrian shields the host rocks of uranium are characterized by low- to medium-grade metamorphism. High temperature deposits are observed only in pegmatites and pyrometasomatic mineralizations.

I.1. DISTRIBUTION OF URANIUM DEPOSITS IN ARCHEAN ROCKS

The granitic-gneissic and charnockitic Archean basements in all the shields' areas are practically devoid of uranium occurrences of economic importance. Uraniferous pegmatites are widespread but the mineralization is generally irregular, of low grade and the reserves are small. In the Archean rocks, economic uranium deposits are confined to sedimentary basins which have not undergone ultrametamorphism and to zones affected by later faulting and by renewal of magmatic hydrothermal activity. In both cases the areas favourable for uranium mineralization are found almost exclusively near the boundary of two geological units.

Uranium deposits of the sedimentary type are restricted to the margin of the Archean basins in low- to medium-grade metasediments. For example, the uranium-gold banket ore bodies of the Witwatersrand are located on the platform area of an intracratonic basin formed by dislocations and warping of the basement complex dated about 3200 m.y. (5) (6).

Hydrothermal uranium deposits are generally found with post-Archean events which especially affect the boundary between the Archean basement and the younger formations. Such are the Proterozoic pitchblende occurrences of the southern margin of the Archean Superior province in the Sault Sainte Marie area, Canada, and the mineralized belt in the Singhbhum district of Bilhar, India, where the uranium deposits of Proterozoic age (7) (8) are believed to be related to sodic granites. In Rajasthan, India, the uranium ore bodies occur in the Aravali geosyncline of Archean age; their age is still unknown. No Archean pyrometasomatic uranium deposits of economic grade are known, but such occurrences may be discovered in the future. This type of deposit would be confined to geosynclinal zones.

I.2. DISTRIBUTION OF URANIUM DEPOSITS IN PROTEROZOIC ROCKS

The main uranium deposits of the shield areas, with most occurrences in the lower unit, are found in rocks formed during the Proterozoic era, which extends approximately from

2.000 m.y. to 550 m.y.

To the first period (2000-1000 m.y.) belong the uranium conglomerates of the Elliot Lake - Blind River area, the majority of the veins of the Canadian shield, the uranium deposits of the Rum Jungle and the Mount Isa-Cloncurry districts in Australia.

To the second period, which must be extended to the lower Paleozoic (about 375 m.y.), belong the uranium occurrences of the Katanga-Zambia belt, the South Alligator, Broken Hill and Pandanus Creed areas, Australia, and the uranothorianite occurrences of Malagasy.

The Proterozoic sediments were laid down in geosynclines or intracratonic basins. The geosynclines are characterized by complex folding and granitic intrusions; the grade of metamorphism varies. On the contrary, in the intracratonic basins, the sediments are of low-grade metamorphism, flat lying, or folded into domes and synclines. Faulting is locally common and granitic intrusions are absent.

The uranium occurrences in the intracratonic basins are limited to disseminations in sediments or volcanics and to veins. Uranium distribution is mostly confined to the platform areas near the contact zone with an older basement. During the development of these basins the border zones were generally faulted, and sedimentation was sometimes accompanied by emission of acid/intermediate volcanics, especially at the beginning of basin formation. Intracratonic basins are characterized by low-temperature uranium deposits, which have been locally subjected to regional metamorphism. Favourable conditions for uranium mineralization in these basins may occur in the volcanics, in the continental sediments, and in the fractures affecting especially the border zone including the older basement. The uranium gold conglomerates of the Witwatersrand constitute an Archean example of uranium deposits in sediments in a composite intracratonic basin.

The stratigraphic series in the Witwatersrand contain important beds of acid/intermediate volcanics (6) (9). Several uranium occurrences are known in acid/intermediate volcanics such as at Wauchope, N. Territory, Australia, or in their associated sediments. Secondary uranium minerals are disseminated in a coarse feldspathic quartzite interbedded between two volcanic series of lower and upper Proterozoic age at Westmoreland, N.W. Queensland (9) (10) (26). The pitchblende veins and pockets of the South Alligator and Pandanus Creek areas, Australia, are found in intracratonic basins containing acid/intermediate volcanics but also extend into the fractured lower Proterozoic basement (12). Age measurements in the South Alligater area indicate that the mineralization was probably emplaced during mild metamorphism at the beginning of the lower Paleozoic (13).

In Canada several pitchblende occurrences may also be related to late orogenic acid igneous and hydrothermal activity penecontemporaneous with the formation of an intracratonic basin, such as in the Beaverlodge-Athabasca area. Uranium prospecting may be confined to the intracratonic basins either containing acid/intermediate volcanics or formed by fracturing of the basement, and to the ancient shore lines and subsiding marginal basins where favourable continental beds for uranium deposition occur. In these areas geological and paleogeographical conditions are very favourable for uranium occurrences in sediments, volcanics or veins. However, outside the margin of intracratonic basins, uranium may occur in sedimentary-volcanic assemblages. In the absence of granite intrusions, redistribution of uranium by groundwater, by a younger metamorphism stage, or by hydrothermal activity is less likely in the intracratonic basins than in the geosynclines.

<u>The distribution of uranium in the Proterozoic geosynclines</u> is quite different because the sediments were affected by folding, partially metamorphized, and intruded by granites. Therefore, the temperature range of formation of the uranium deposits varies widely, and there has been much redistribution of the original uranium mineralization. However, the uranium conglomerates of the Elliot-Lake - Blind River area have the same geological and paleogeographical distribution as those of the Witwatersrand deposits located in an intracratonic basin. (14) (15) (16) (17). Conglomeratic ore bodies occur near the major nonconformities on the platform areas of geosynclines. The basement in all the Proterozoic conglomeratic ore bodies areas is of Archean age, but future discoveries may also be found on Proterozoic basement rocks.

Uranium minerals may be disseminated in sedimentary rocks both in geosynclines and intracratonic basins. They sometimes are associated with such metallic elements as Cu, Co, and Ni. The mineralization is mainly controlled by the lithology. Paleogeographical conditions have played an important role in the formation of such deposits which are generally of low-grade. Black schists and sometimes quartzites are the most common host rocks. The main occurrences are found in the Roan Series, the Katanga-Zambia belt, (18) and the Brocks Creek series of lower Proterozoic age in the Rum Jungle area of Australia (19) (20). In the geosynclines, igneous intrusions or hydrothermal activity have partially redistributed and concentrated the uranium in replacement deposits (Rum Jungle) or in veins (Shinkolobwe, Katanga) (21) (22). The presence of low-grade uraniferous beds in a geosyncline suggests the possibility of recoverable uranium mineralizations which are sometimes associated with Cu and other metals.

Pitchblende veins are mainly confined to sedimentary series which have been preserved from intense metamorphism and more rarely to areas of shallow granitic intrusion in the geosynclines. In the Canadian shield hydrothermal deposits are widespread and are mostly related to the northeast trending faults and fault zones in northeast trending folded sedimentary basins. These structures are considered to offer theoretically the best promising areas for further prospecting in Canada (17). It must also be noted that hydrothermal veins are rarely found in Precambrian granitic intrusions, while this type of mineralization forms the principal uranium reserves of the Hercynian belts in western Europe. This fact seems due not only to the depth of intrusion, or to the degree of erosion, but is also related to the geochemistry of the granites. In central Africa two micaceous granitic intrusions, apparently similar to those mineralized in western Europe, are fairly common, but until now only one uneconomic pitchblende vein has been found in Rwanda (23) (24).

High temperature davidite veins with other titanium minerals are known in the Adelaide geosynclines in South

Australia (25) (26) and near Tete in Mozambique. In Australia this type of mineralization is associated with alkalic metasomatism.

Numerous occurrences partially of the pyrometasomatic type exist in the metasediments of the Mount Isa-Cloncurry geosyncline in Australia (26) (27). The development of this composite geosynclinal zone was accompanied by several stages of ejection of acid and basic volcanics.

I.3. DISTRIBUTION OF URANIUM OCCURRENCES RELATED TO POST-CALEDONIAN EVENTS (see figures 1 and 3)

Lower Paleozoic orogenies have affected both lower Paleozoic and upper Proterozoic sediments as in the geosynclines of Sâo Francisco, Brazil, of Adelaide in South Australia and elsewhere. The uranothorianite deposits of Malagasy and the main davidite veins of the Olary-Broken Hill District (South Australia) are related to lower Paleozoic orogenies.

The Precambrian shields were stabilized in the beginning of the Devonian. However, from the Upper Paleozoic to the Quarternary they were subjected to epirogenic movements which caused radial dislocations of the basement, with formation of grabens, horsts and centers of alkalic magmatic activity. The main alkalic centers such as in Brazil and Central Africa follow these dislocation lines of the earth (see fig. 1). In Canada some of the alkalic centers are considered to be Precambrian. Kimberlite pipes were also emplaced along or near the dislocation lines in the Precambrian shields and in their sedimentary cover.

Uranium and thorium are commonly associated with the final differentiation products of alkalic rocks, which show a higher mean content in radioactive elements than the other igneous rocks. There may be uranium occurrences of some importance, especially with hydrothermally altered hyperalkalic nepheline syenites, such as at Poços de Caldas, Brazil (30) (31), at Ilimaussaq, Greenland (32) and at Lovozero, Kola, USSR. The uranium-thorium mineralization, which occurs mainly in veins or in pockets, was formed by hydrothermal-leaching and partial replacement of the characteristic dispersed radioactive zirconium minerals such as the katapleite, eudyalite, and lovozerite found in these hyperalkalic rocks.

At Poços de Caldas uraniferous baddeleyite and zircon (caldasite) form veins, eluvial and alluvial deposits. At Ilimaussaq the principal radioactive mineral is steenstrupine, mainly concentrated in veinlets.

Large carbonatite bodies are often associated with the alkalic centers and generally have abnormal radioactivity due mainly to the presence of niobium and some phosphate minerals. Uranium and thorium may be recovered in the future as by-products from some of the high-grade deposits having a mean content of 1 to more than 3 % Nb_2O_5. The highest grade deposits, such as Araxa, Brazil, Lueshe and Bingo, also called Mount Home, Congo, are found in Precambrian areas with widespread niobium mineralization of the granitic and pegmatitic types. As the uranium content widely varies in carbonatites, new interesting occurrences may be found in the future, especially in the Gondwana area of Brazil and Central Africa.

Thorium commonly is associated with the last rare-earth-rich carbonatitic stage. Mineralization may be inside the alkalic centers (Poços de Caldas, Ilimaussaq) or outside in vein-type deposits. The thorite veins of the Rocky Mountains belong to this last type. In the Precambrian shields the only significant occurrence is the Pb-Th-rare earth mineralization of Ribeira, Sâo Paulo, Brazil (33).

Good indications exist in the Precambrian shields and sedimentary cover for further discoveries of uranium-thorium mineralizations related to alkalic magmatic activity. Some of them may be of economic interest, especially if linked to hydrothermally altered hyperalkalic nepheline syenites. Brazil, Central Africa and Groenland seem to be the best places for such occurrences.

The dislocation zones of the Precambrian shields characterized by local volcanic and hydrothermal activity also contain grabens and basins that are mainly filled by continental and lacustrine sediments Cenozoic basins lie along the major dislocations in the states of Sâo Paulo, Minas Gerais and Guanabara in Brazil. The Rift Valley in Central Africa shows similar features. Uranium may be leached by hydrothermal or ground-water solutions at depth and redeposited in a favourable lithological environment as epigenetic mineralization or uranium concentrations in the fractured zones of the basement. Epigenetic uranium deposits are known in the Tucano basin, Bahia, Brazil, but probably also occur in many other grabens or basin areas. At Perus, Sâo Paulo, secondary uranium mineralization is found in fractures affecting the granitic basement. Renewal of hydrothermal activity along the dislocations could also be favourable to pitchblende veins especially in the granitic areas that may have undergone retrometamorphism. Uranium deposits may occur in sedimentary inliers overlying a Precambrian basement. The presence of carbonaceous continental beds in a sedimentary series and the acid nature of the basement appear to favour uranium concentration by percolating ground-waters. Sedimentary basins, mainly of Mesozoic or Cenozoic age, with continental formations are rather widespread in the Gondwana shields such as in northeast Brazil, Central Australia, the uraniferous districts of South Alligator and Cloncurry areas, Australia, and also Central Africa. These basins have been little prospected but may contain local uranium deposits.

The presence of radioactive springs constitutes a first indication of possible epigenetic uranium deposits in these basins or grabens, but absence of radioactive outcrops does not signify a lack of uranium.

This short summary of the distribution of uranium deposits in Precambrian shields points out the importance of the boundary between geological units of different age for the location of important uranium occurrences in intracratonic or geosynclinal basins. The economic aspects of the Archean Proterozoic boundaries were already outlined by D.R. DERRY (35), but for uranium the boundary has a much larger meaning.

Favourable paleogeographic and lithologic conditions for sedimentary uranium occurrences in Precambrian rocks are confined to continental sediments deposited in local depressions of the basement (conglomeratic type) or in almost closed subsiding basins (stratiform type) along an old shore at the margin of intracratonic basins and geosynclines. Also in this environment sedimentary acid/ intermediate volcanics could be mineralized.

The intracratonic basins are characterized by a lack of granitic intrusions during the sedimentary cycle and by low-grade metamorphic sediments. They contain uranium mineralization in sediments or in acid/intermediate volcanics or pitchblende veins which also are located preferentially in the fractured marginal zones of the basin and its neighbouring basement. In several mineralized areas pitchblende veins are related to the presence of acid/ intermediate volcanics in the intracratonic basins. Remobilization of the uranium from the fractured basement, from the acid/intermediate volcanics, or from sediments by hydrothermal activity, metamorphism or other processes may explain the formation and the often marginal distribution of such pitchblende veins.

The old marginal zones and subsiding basins favourable for uranium deposition in geosynclines may have been intruded by granites and other igneous rocks during the orogeny. The spatial relationship between veins or replacement deposits with mineralized beds in several Precambrian geosynclines suggests in many cases a partial redistribution of the primary uranium mineralization due to variation of the geothermal-pressure gradient. Such a variation may be affected by granitic intrusions, such as in the Mount Isa-Cloncurry and Rum Jungle areas, or by hydrothermal activities, such as in the Katanga-Zambia belt. There may be redeposition and even concentration of the uranium in favourable host rocks or in open fractures. Low-grade uranium occurrences in sediments sometimes associated with other metals are well represented in several geosynclines. Sometimes the main source of uranium and associated metals may well be the volcanic rocks intruded by granites such as in the Great Bear Lake province. The distribution of veins and of pyrometasomatic deposits in geosynclines seems thus, in part, mainly linked to the preexistence of mineralized beds or acid/intermediate volcanics in the geosynclines. Nevertheless, this generalization does not exclude the formation of veins and replacement deposits by other processes.

Uranium mineralizations in the Precambrian shield also are related to post-caledonian events. Some of them are associated with alkalic centers mainly emplaced during the Mesozoic and the Cenozoic along the major dislocation lines of the shield areas. The most important uranium concentrations are found in the last differentiation products of hyperalkalic syenites.

Epigenetic uranium deposits may occur in interbedded continental sediments deposited in Mesozoic or Cenozoic basins and grabens formed generally by dislocations of the Precambrian basement. The most favourable basins are those containing volcanics or characterized by hydrothermal activity.

The choice of the shield areas to be prospected might be aided by better knowledge of the paleogeographical evolution of the Precambrian basins, of the distribution of the different geological units based on the interpretation of age data and of the sedimentary and magmatic cycles. Methods of prospecting based on geophysical methods and radon emanation will be necessary to find concealed deposits, especially of the sedimentary type.

From the geological data concerning the distribution of uranium deposits in the Precambrian shields, I shall try to point out several criteria that may be useful for the search of new mineralized districts.

II. GEOLOGICAL CRITERIA AS A GUIDE FOR URANIUM-BEARING CONGLOMERATES

Conglomeratic ore bodies form the main bulk of the world's uranium reserves, and the outlook for finding new deposits in the extension of the known mineralized belds and in other new areas is good. The origin of this important type of deposit always remains a subject of controversy between geologists (36) (37) (38) (39) (40) (41) (42) (43) (9) (15) (16). However, these conglomerates exhibit a similar lithological and depositional environment which could be used for the search of new favourable areas. All the deposits are located near the margin of a basin characterized by frequent interfingerings of marine and continental sediments. Banket formations occur after a break in sedimentation, and the richest beds lie close to the main unconformities near the contact with an older basement, but not all apparently favourable beds are mineralized. The Dominion reef, which overlies the granitic basement, has a mean uranium content in excess of that in the other main uraniferous reefs of the Witwatersrand, but its gold content is lower. In the Blind River area, the richest conglomeratic ore bodies occur in the Matinenda Formation at the base of the Huronian System (14) (17) (43). Commonly the mineralized bankets pass laterally to uranium-bearing quartzites of lower grade. The uranium mineralizations appear to be confined to stream channels which are quite similar to those of the Colorado Plateau. The structure of the mineralized basins is simple. The sediments are flat lying, or folded into large anticlines and synclines. Vertical faults and faulted blocks are common in some areas. The conglomeratic deposits always contain pyrite and traces of metallic elements such as Cu, Co and Pb and detrital minerals such as monazite, zircon and ilmenite. The metamorphism of the sediments is of low- to medium-grade intensity and intrusions are limited to veins and dikes.

The distribution of the uranium mineralization at Paukkajanvaara in Finland is mainly controlled by diabase dikes cutting the Jatulian conglomerates of Proterozoic age (44). At Serra de Jacobina in Brazil, hydrothermal activity probably related to the Caledonian orogeny, may have altered the primary lithological control of the gold and uranium. M.G. WHITE considers the mineralization to be hydrothermal (45) (46) (47). At Mounana in Gabon, there is uranium and vanadium mineralization in intraformational conglomerates and, despite a different mineral assemblage the geological environment is very similar to the other conglomeratic deposits (48) (49). The uranium occurrences of conglomeratic type are thus restricted to platform areas at the boundary of two geological units. They are characterized by episodic continental sedimentation anda lack of younger granitic intrusions. The presence of pyrite indicates a reducing environment. Pebble conglomerates and other permeable arenaceous sediments constitute the most favourable host rocks for uranium.

Although the origin of the conglomeratic uranium deposits of Precambrian age remains controversial the geological environment for this type of occurrence is similar throughout the world. However, the mineralizations, which are generally more frequent near the base of the stratigraphic unit in a marginal basin, may be entirely concealed under barren marine transgressive sediments of the same series.

Therefore, they could not be detected by surface prospecting. Geophysical methods are very useful in obtaining knowledge of the depth and the structure of the basin lying on the basement. Such knowledge helps to choose the most favourable sites for possible concealed uranium ore bodies. In the Huronian province of southern Ontario, the outcrops of the mineralized banket conglomerates are limited but important new deposits will certainly be discovered in the same stratigraphical position and also probably in other levels in the bordering zone of the basin between Sault Ste Marie and Cobalt (43) (50).

The hypotheses advanced to explain the source of uranium may be divided in three main groups: accumulation of detrital uraninite; leaching of uranium from the basement or from rocks belonging to the uraniferous sequence and magmatic or hydrothermal solutions derived from acid or basic differentiation (9) (36) (39) (40) (41) (42) (51)*. Among the conditions favouring the circulation of uraniferous solutions and the precipitation of uranium in the margin of both intracratonic basins and geosynclines are: (1) dislocations of the basement, sometimes followed by magmatic activity mainly of volcanic origin; (2) change in the geothermal gradients and in the levels of the water table during the sedimentation; (3) presence of non-marine sediments and of a reducing environment. The source of uranium may differ from one site to another.

In a recent paper (9), C.F. DAVIDSON has drawn attention to the presence of acid/intermediate volcanic and pyroclastic rocks (Witwatersrand) and of granitic debris (Blind River) in the sequence as a possible source of uranium

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* see also the recent publications of M.Schidlowski on this subject (69).

for the conglomerates. He considers that uranium and gold in the conglomeratic beds of the Witwatersrand are derived from the leaching of the important series of acid/intermediate volicanic and pyroclastic rocks which are found especially in the Dominion Reef and Ventersdorp Systems but occur also locally in the Witwatersrand System (6).

Uranium mineralizations are common in acid/intermediate volcanics and pyroclastics and their associated sediments, but in many areas little attention was given to these rocks in the search of uranium. In the Hercynian provinces of western Europe, uranium deposits are connected with the late orogenic acid vulcanism such at Ellweiler, ore bodies were also found recently with intermediate volcanics of Tertiary age in Macedonia, southern Yugoslavia (55).

In North America uranium mineralization is associated with Tertiary vulcanism at Marysvale, Utah (rhyolites) and in British Columbia (andesites) (56) (57). In the Andean belt, several uranium occurrences are associated with acid/intermediate Tertiary volcanics and with their interbedded sediments. These facts indicate that uranium ore bodies of economic grade may be found in volcanic areas.

In the Precambrian shields, auriferous pitchblende veins and pockets are known in both South Alligator and Pandanus Creek areas, N. Territory, Australia (10) (20). These veins cut the Upper Proterozoic containing an important basal unit of unmetamorphized acid/intermediate volcanics and also the neighbouring basement in the South Alligator area. In this last area, the mineralization took place 500 m.y. ago (13) during a mild stage of metamorphism and, in the absence of any intrusions, must be derived from the leaching of the volcanics.

In the Pandanus Creek area, the veins also are located in the volcanics. In the composite geosyncline of Mount Isa-Cloncurry in N.W. Queensland are the main uranium occurrences in metasediments, such as Mary-Kathleen, Skal, Anderson's Lode, Surprise, Barrier. These lie along a N.S. trending tectonic welt that divided the region in two troughs during sedimentation and was characterized by intense acid and basic volcanism (13) (27) (see fig. 2). The volcanic activity may be the principal source of uranium which was deposited initially in a favourable geological environment in a platform area. Later granitic intrusions and orogenic movements appear to have caused a redistribution of the uranium (9).

The relationship in several areas between uranium mineralization and the presence of acid/intermediate volcanics, especially in the marginal zones of Precambrian basins, may be used as a valid criterion for the search of new mineralized districts of the conglomeratic type. In this favourable environment the uranium mineralization may or may not be associated with gold or other metals and inversely. For example, several gold reefs, stratigraphically correlated with the Dominion Reef or the Witwatersrand System and containing acid/intermediate volcanics, are known outside the Witwatersrand in South Africa but seem to be devoid of uranium (6). However, in many other uraniferous conglomerate districts, such as Blind River or Serra de Jacobina, the stratigraphic series either do not contain volcanics or contain only minor occurrences and therefore uranium is certainly not derived from these rocks.

Taking account of the geological distribution and the lithological environment, the choice of new favourable areas for conglomeratic ore bodies may be based on several geological criteria which could be summarized as follows:

- location of the uranium mineralization in coarse permeable arenaceous beds of continental facies, especially those filling depressions in the old basement,
- selective concentration of the uranium in a reducing environment (presence of pyrite and other sulfides),
- eventual presence of interbedded acid/intermediate volcanics in the stratigraphic series,
- low- to medium-grade metamorphism of the sediments,
- absence of granitic intrusions in the mineralized belt with the exception of minor veins or dikes,
- simple folding structure at the margin of the basins in open anticlines and synclines or in monoclines with sometimes intense faulting.

The geological criteria indicated above may serve as a primary guide to discover mineralized areas of the conglomeratic type. In intracratonic basins the most promising areas could be easily delineated at the contact zone with the basement, but some overlapping of upper strata may occur. Besides the possible occurrences of acid/intermediate volcanics in the sequence, attention must be especially focused on the basal arenaceous units and on minor unconformities with a change of facies affecting the stratigraphic series. In the second prospecting stage of a promising area, it should be important to know the structure of the basement in order to recognize eventually buried old valleys and subsiding basins that may contain uraniferous beds.

In geosynclines the pattern is practically the same but tectonic unconformities must be not confused with stratigraphic unconformities along the contact with an older basement.

On the basis of the geological criteria, I shall try to give some examples of Precambrian basins which could contain uraniferous conglomeratic ore bodies.

II.1. SOME EXAMPLES OF APPARENTLY FAVOURABLE PRECAMBRIAN BASINS CONTAINING INTERBEDDED ACID/INTERMEDIATE VOLCANICS FOR OCCURRENCES OF URANIFEROUS BANKET ORE BODIES

Australia

As an example of a possibly favourable Precambrian marginal basin characterized by acid volcanics and low-grade metamorphic sediments for conglomeratic uranium deposits, I must point out the Upper Proterozoic in the South Alligator region and its northern and southern extension along the contact with the Lower Proterozoic basement in the Northern Territory, Australia. In this area several pitchblende veins containing some gold were mined for uranium some years ago. The volcanics were the source of uranium which was partially redistributed during a mild phase of metamorphism and concentrated in the tectonic fractures along the contact zone in both Proterozoic formations. The Upper Proterozoic consists of a basal acid volcanic unit up to 1.000 m thick admixed with coarse arenites in place and is overlain by arenites mixed with intermediate and basic flows (12). There is widespread uranium mineralization and acid volcanics have locally filled old valleys in the basement. Faulting in places is contemporaneous with volcanism and sedimentation and the sediments have been subjected to low-grade metamorphism. Only minor folding has occurred in subbasins localized at the boundary of both Precambrian units. All these features are favourable factors for possible uranium mineralization in some of the more permeable arenites, especially those filling old stream channels.

Australia

In the Kimberley basin in the northern part of Western Australia, 500 to 1000 m of undifferentiated Proterozoic rocks (probably lower Upper Proterozoic) overlay the Lower Proterozoic granitic and faulted basement. They consist mainly of sandstones, minor conglomerates and acid to intermediate volcanics locally intruded by large basic sills. Until now, only secondary uranium minerals have been found in volcanics at four localities of the Denham River area (10). Although these mineralizations are insignificant, they indicate that higher uranium concentrations may be found in this basin. The contact zone between both Proterozoic formations seems to be a favourable environment not only for uranium mineralizations in permeable sedimentary rocks, such as conglomerates or coarse sandstones but also in volcanics or in veins. The best areas for conglomeratic-type deposits appear to be the undifferentiated Proterozoic subbasins overlying the Lower Proterozoic granitic basement in the Margaret River area and the contact zone east of Durack and Boyd ranges, as well as minor inliers of undifferentiated Proterozoic sediments of the Leopold range.

Canada

Conglomeratic uranium orebodies may be also found in the Great Bear Lake Proterozoic province, especially near the contact with the Yellowknife Archean province in Canada. The basal Proterozoic sediments belong to the Echo Bay Group, presumably correlative with the Snare Group, and consist of coarse arkoses and quartzites with lenses of conglomerates and intermediate volcanics (59). Several uranium veins characterized by a Ni-Co-U-Ag mineral assemblage (Eldorado and Contact Lake mines) or by U only (Rayrock Mine), were mined in this province (17). In the largest deposit, the Eldorado mine, the mineralization was almost confined to the Echo Bay Group. The close association of the mineralization with the Echo Bay Group seems to indicate a redistribution and concentration of the dispersed metals of the volcanics in the fractures when the acid intrusions took place. Along the Yellowknife Archean province at the margin of the basin, the Proterozoic sediments and volcanics were partially preserved from intense metamorphism and granitization. The frequency of the intermediate volcanics in the basal arenaceous unit as well as the paleogeographic conditions favour the formation of conglomeratic uranium deposits between the north arm of Great Slave and Point lakes and probably also further north.

II.2. SOME EXAMPLES OF APPARENTLY FAVOURABLE PRECAMBRIAN BASINS WITHOUT ACID/INTERMEDIATE VOLCANICS OR ONLY MINOR OCCURRENCES FOR URANIFEROUS BANKET ORE BODIES

Banket ore bodies are also found in Precambrian series which do not contain acid/intermediate volcanics or have only minor occurrences. The uranium may be derived from the basement, its overlying stratigraphic unit, or hydrothermal activity. Favourable geological conditions for precipitation of uranium are confined to permeable arenaceous beds of continental facies located near the major and minor unconformities and often filling old stream channels.

Brazil

An example of an unprospected intracratonic basin favourable for uraniferous conglomerates is the Minas series of Proterozoic age in the Araguaia-Tocantins hydrographic basin, Brazil. In Para and Goias states, the Minas series overlie the Archean crystalline basement forming an elongated belt over 1000 km long. This Proterozoic area is still poorly known geologically but the strata which contain important quartzitic beds are characterized by low-grade metamorphism, by minor folding and a lack of granitic intrusions (58). Geological conditions are favourable for local occurrences of banket ore bodies, especially near the base of the sequence.

Brazil

The Minas series form also a belt surrounding the São Francisco hydrographic basin (58) (61). The sediments were deposited in a composite geosyncline and are partially covered by younger formations. They were affected by several orogenies: Huronian (1100 m.y.), Penokean (750 m.y.) and Taconian-Caledonian (450-375 m.y.). The basal unit of the Minas series is represented by the Caraça formation consisting mainly of quartzites with minor conglomerates. In the central part of Minas Gerais this formation is intruded by granites. The metamorphic grade of the sediments and the orogenic intensity decrease approximately from SW to NE in this area, and there is little probability of finding uraniferous conglomerates. In Bahia between the Sâo Francisco and Ireçẹ basins, the Minas series is characterized by open anticlines and synclines and the metamorphism is of low- to medium-grade. The sediments were deposited mainly on a platform area on the Archean basement and banket ore bodies are much more likely than in central Minas Gerais. In Goias with the same geological features the western margin zone of the geo-syncline which overlies the Archean basement, may be a favourable area for uraniferous conglomerates.

The Itacolomi series, deposited after the Minas series (58), consists of a basal quartzitic unit with conglo-meratic beds overlying locally the granitic Archean base-ment. To that unit belong several occurrences of gold-bearing conglomerates of the Serra de Espinhaço and probably also the uranium-gold reefs of the Serra de Jacobina in Bahia. The frequence of ripple marks and crossbedding in the basal unit indicates deposition in shallow water near the shore. The metamorphism is of the epizonal facies. This basal unit, especially along its contact with the Archean basement from the northern part of the Serra de Espinhaço to the Ireçe basin, shows favourable geological and paleogeo-graphical conditions for the occurrence of uraniferous conglomerate ore bodies.

Congo

The conglomeratic quartzites at the base of the Kibali group in the northeast Congo Republic overlie, with stratigraphic unconformity, the crystalline basement of the West Nolian Formation (62) (3). They also may be considered as a possible favourable area for uraniferous banket ore bodies.

Australia

Several intracratonic Proterozoic basins formed by dislocations and warping of the Archean basement are found in Central Australia and also may contain uraniferous conglomeratic beds along the contact zone.

In summary, if the origin of the uraniferous conglomerates is still a matter of controversy, the distribution of such occurrences is confined mainly to intraformational beds deposited in depressions and channels of an older basement. A reducing environment prevailed. Therefore the favourable areas for such deposits may be delimited to the platform of the Precambrian basins which have not been affected by high regional metamorphism and granitization. The presence of acid/intermediate volcanics in a stratigraphic unit of a basin serves only as a first indication for choosing the best areas to be prospected. A preliminary knowledge of the paleogeographical and geological evolution as well as of the main structural features in a Precambrian basin becomes an important factor for the location of the most interesting areas for uraniferous conglomerates. The outlook to find new mineralized districts in the Precambrian shields seems good in some of the unprospected Precambrian basins as well as in the extension of known mineralized districts such as Blind River.

III. GEOLOGICAL CRITERIA AS A GUIDE FOR OTHER URANIUM DEPOSITS IN THE PRECAMBRIAN SHIELDS

Outside the conglomeratic ore bodies, it is more difficult to predict apparently favourable areas for other uranium deposits in the Precambrian shields. Nevertheless, some general criteria based on the distribution of the world's Precambrian uranium occurrences provide a rough delineation of the areas to be prospected:

- The probability to find recoverable uranium deposits in the crystalline areas, characterized by metasediments of the catazone, is rather limited. However, later intrusions or renewal of hydrothermal activity may lead to uranium mineralizations.

- The old marginal zones of geosynclines may have been affected by intrusions, hydrothermal activity, alkali metasomatism, etc. with possible redistribution of the primary uranium minerals. In many cases, a relation is observed between the presence of uraniferous beds and of veins or even pyrometasomatic deposits. Therefore, in geosynclines the occurrences of uraniferous strata, even of low grade, may be used as a first criterion concerning the probable interest of an area for uranium deposits.

- The distribution of uranium occurrences in intracratonic basins is mainly restricted to marginal zones, and a relation is found in many cases between uranium mineralizations and the presence of acid/intermediate volcanics in the stratigraphic series.

Taking account of the preferential location of the uranium occurrences near the contact zone between two Precambrian provinces, these geological criteria must be kept in mind for the choice of the most favourable areas to be prospected, either in geosynclines or in intracratonic basins.

III.1. GEOLOGICAL CRITERIA IN INTRACRATONIC BASINS

The intracratonic basins, formed by dislocations or warping of the basement, contain basic and ultrabasic intrusions but the acid/intermediate igneous activity is of volcanic origin. Uranium occurs in sediments, volcanics or in veins, but its distribution is mostly confined to the margin of the intracratonic basin, thus near the contact with an older basement. If the source of the uranium varies, this marginal distribution of the main occurrences may be explained on the basis of paleogeographical and geological arguments:

- The dislocations of the basement during and sometimes after the sedimentation gave rise to local channelways for igneous activity, for hydrothermal solutions or even mineralized percolating ground-water. Statistically, these dislocations are more frequent in the unstable bordering zone of the basin.

- Continental interfingerings, favourable host rocks for uranium, may occur in the stratigraphic series, but are also mostly restricted to marginal zones and subsiding-basins.

- The relation observed in several areas between the presence of interbedded acid/intermediate volcanics and uranium deposits and the preferential distribution of the latter along the margin of the basins.

These considerations obviously limit the choice of the areas to be prospected in the intracratonic basins. Nevertheless, occurrences of acid/intermediate volcanics in the interior of a basin also must be examined because basic intrusions, metamorphism and other processes may lead to an eventual redistribution and concentration of the uranium dispersed in the volcanics.

Outside conglomeratic ore bodies, pitchblende veins are found in the fractures and shear zones affecting the margin of intracratonic basins characterized by acid/intermediate volcanics, such as in the South Alligator and Pandanus Creek areas in Australia (20), where uranium is associated with a weak gold mineralization. The veins in these areas cut both the upper Proterozoic strata and the lower Proterozoic basement. Similar veins may occur in intracratonic basins, such as along the contact zone between the undifferentiated Proterozoic and the lower Proterozoic basement of the Kimberley region of Western Australia. The Proterozoic rocks also contain interbedded acid/intermediate volcanics (12).

Favourable paleogeographical conditions may prevail during sedimentation for the deposition of uraniferous beds rich in carbonaceous matter although mineable deposits of uranium are not too likely to accumulate in geosynclines. However, local enrichment may be observed in relation to exhalative volcanic activity or, sometimes, by ground-water. Therefore, attention must be focused on carbonaceous-rich strata interbedded in a volcanic series or deposited during the final stage of volcanic activity. In the intracratonic basins, the main source of uranium is derived from acid/ intermediate volcanics or from the basement.

III.2. GEOLOGICAL CRITERIA IN GEOSYNCLINAL BASINS

The distribution of uranium occurrences in Precambrian geosynclines appear to be more erratic but nevertheless several basic criteria may be used for a preliminary delineation of the areas to be prospected. These basic criteria are the following:

- Presence in the stratigraphic series of uraniferous beds, even of low-grade. especially carbonaceous and continental sediments deposited in old marginal zones during the sedimentation.
- Presence of acid/intermediate volcanic and pyroclastic rocks in the sequence.
- Preferential distribution of pitchblende veins in fractures affecting low-grade metamorphic sediments located in the marginal zones of a geosyncline.
- Location of pyrometasomatic deposits around old marginal zones.
- Existence of alkali metasomatic processes.

The formation of vein and pyrometasomatic deposits in many geosynclines appears to be linked to the preexistence of uraniferous beds, with later redistribution and often concentration of the uranium by granitic intrusions, alkali metasomatism or hydrothermal activity. Therefore, a knowledge of the paleogeographic evolution of geosynclines becomes an important factor in selecting the areas to be prospected.

The discovery of quite extensive radioactive anomalies related to low-grade uraniferous strata constitutes a good indication for the possible existence of recoverable uranium deposits in an area, especially when the old marginal zones containing uranium are cut by granitic intrusions or are affected by hydrothermal activity.

I shall try hereunder to point out several criteria which may be helpful for the search of new mineralized areas.

Outside the conglomeratic ore bodies, disseminated uranium mineralizations occur in carbonaceous sediments, especially shales and quartzitic rocks. Uraniferous shales, sometimes quartzitic, are known in the Rum Jungle area (19) (20), in the Katanga-Zambia belt and in central Rajasthan, India. This type of occurrence is generally of low-grade, and uranium may be associated with other metals such as Cu and, sometimes, Co and Ni. These uraniferous beds were deposited during sedimentation near the margin of a geosyncline and often in subsiding basins characterized by reducing conditions favourable for the precipitation of uranium and other metals. From the shore, a zonal distribution U-Cu (Co)-Fe (Zn-Pb) is frequently observed within a mineralized strata (18). Therefore the paleogeographical conditions and the lithological environment are important factors for the formation of such mineralizations. In geosynclines, reworking and redistribution of the primary stratiform mineralization, either by magmatic or hydrothermal activity or by other processes, gave rise to veins and replacement deposits whose mineral assemblage and geochemistry is very similar to the primary mineralized beds.

In the Katanga-Zambia belt, the mineral composition of the veins and pockets reflects that of the uranium-copper rich graphitic schists and quartzitic schists of the Roan series.

Uranium-copper-lead anomalies are widespread, especially in the carbonaceous or graphitic shales of the Brocks Creek Group (19) (20) of lower Proterozoic age in the Rum Jungle area, Australia. Granitic intrusions and orogenic movements have led to local reconcentration of the mineralization in the carbonaceous beds or in the fractures. Two main types of uranium ore deposits are known: the copper-rich and copper-poor types.

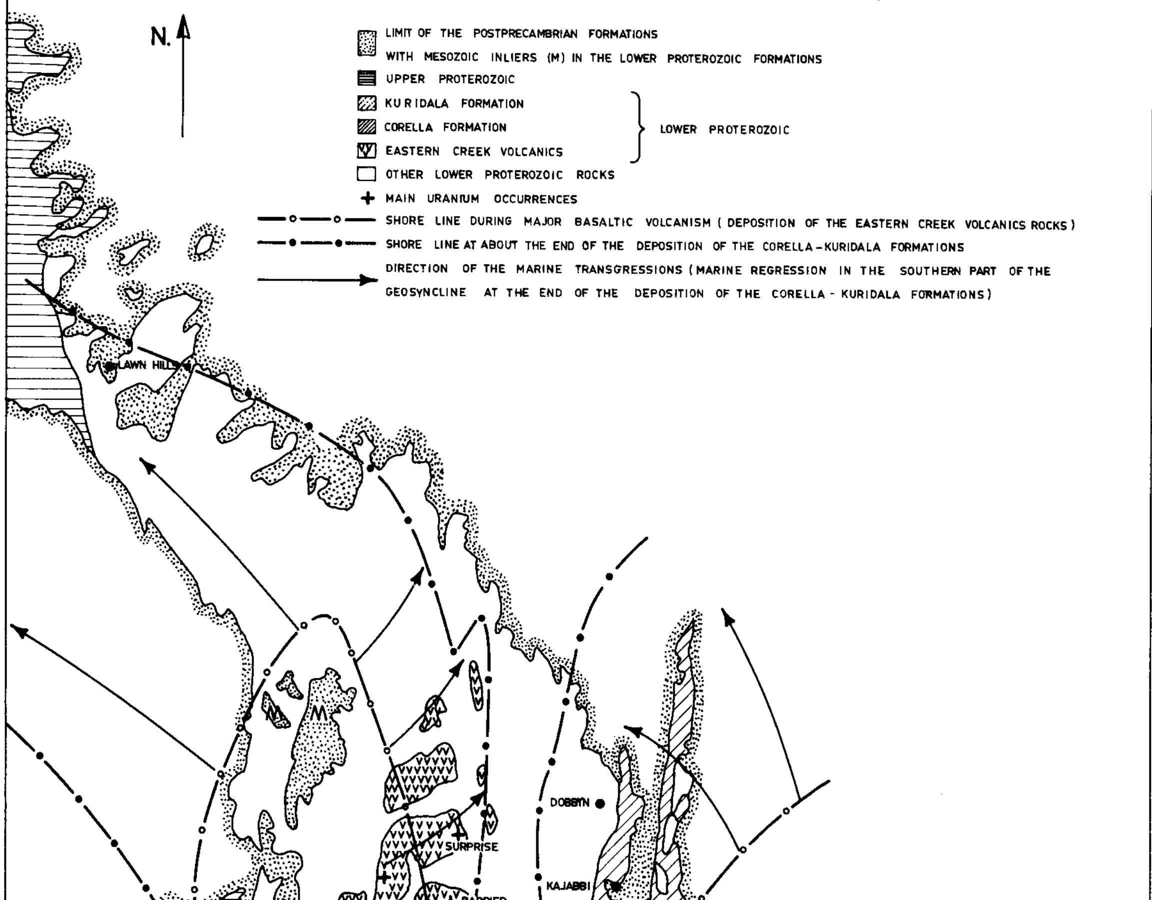
In central Rajasthan (7) (63), the uranium mineralization is widely distributed in chloritic or carbonaceous phyllites containing several uranium-rich lenses. Moreover, uranium veins and stringers occur in the shear zones and faults trough the neighbouring country rocks. Old copper workings are known in or away from the zone of uranium mineralizations. The uranium and also the copper deposits are believed to be genetically linked with intrusions of sodic and acid granites. However, the close association of the mineralization with carbonaceous phyllites and the extension of the radioactive anomalies related to these beds suggest a primary deposition of the uranium in a favourable lithological environment with later redistribution and reconcentration by the intrusions.

Therefore, in geosynclines attention must be focused on the eventual presence in the stratigraphic series of uraniferous carbonaceous sediments even of low-grade, which constitute a valuable criterion for the possible existence of veins and replacement deposits. When cropping out over large areas, these uraniferous beds give extensive radioactive anomalies but generally of low intensity. Moreover as uranium is often associated with copper in this type of mineralization, widespread occurrences of secondary copper minerals in the weathering zone may in some cases indicate a new uranium district.

Australia

The Kuridala formation of Lower Proterozoic age (see fig. 2) (27) which extends to the southern part of the Cloncurry geosyncline in Queensland, Australia, may be a promising area for uranium. As a matter of fact, the stratigraphic series contains copper-rich carbonaceous slates that show locally abnormal radioactivity (Mount Dore) (11) (26). This series is cut by granitic intrusions. There are numerous occurrences of generally weak copper mineralizations in slates or in shear zones, an old cobalt mine and abnormal radioactivity in several points in the area between N. of Kuridala and S. of Selwyn. These features call to mind other known uranium districts characterized by copper-uranium-rich carbonaceous sediments such as for example Rum Jungle. Taking

FIG. 2 MARGINAL DISTRIBUTION OF THE URANIUM OCCURRENCES ALONG THE TECTONIC WELT IN THE MOUNT ISA-CLONCURRY GEOSYNCLINE, AUSTRALIA



account of the general zonal distribution of the mineralization in a stratigraphic horizon and of the paleogeographical conditions and environment during the deposition of the Kuridala formation, uranium veins or replacement deposits, associated or not with other metals, may be found especially in the western part of this geological formation which corresponds to the most marginal zones of the basin (27).

Besides conglomeratic and carbonaceous sediments, uranium is found in various rocks, especially of the arenaceous type. Such occurrences are also widespread in the lower Proterozoic Mount Isa - Cloncurry composite geosyncline (26) (27). In the western belt, nearly all the uranium deposits are confined to the Eastern Creek volcanics belonging to the lower unit and are mainly in arenaceous sediments and sometimes in metabasalts. The uranium mineralizations in the eastern belt occur in several types of metamorphic rocks, but most of the deposits, including Mary Kathleen, are in the Corella formation of the middle unit. The uranium occurrences are mostly related to well-defined stratigraphic units and may also be controlled by lithology, such as at Andersons Lode. Moreover, all important uranium deposits are spatially related to old margin zones along a tectonic welt and to a subsiding basin located north of Mount Isa during the deposition of the Eastern Creek volcanics and the Corella formation (see fig. 2). Outside these marginal zones only minor uranium occurrences were found in the same geological formation. The spatial distribution of the main uranium mineralizations suggests the preexistence of uraniferous beds along the tectonic welt and in the subsiding basins of this composite geosyncline with later redistribution of the uranium by granitic intrusions, orogenic movements, or hydrothermal activity.

Here also the paleogeographical conditions appear to have played an important role in the formation of uranium deposits in sediments during the lower and the middle lower Proterozoic. Moreover, the deposition of uranium has followed a period of intense acid volcanism (Argylla formation) and of granitic intrusions (Kalkadoon and Ewen granites) which were principally emplaced in the tectonic welt. Taking account of the paleogeographical and geological evolution of this composite geosyncline and of the rather selective stratigraphical distribution of the uranium occurrences, the most promising area for uranium deposits in the Cloncurry geosyncline is mainly represented by the Corella formation and other contemporaneous units deposited near or in an old marginal zone which corresponds to a N-S line going from NE of Kajabbi to Duchess. In the western geosyncline, attention must be focused on the Eastern Creek volcanics and equivalent units located not only in a subbasin north of Mount Isa but also between this town and the country south of Dajarra. The probability of finding new uranium deposits in the Mount Isa - Cloncurry geosyncline seems good and moreover many uranium prospects discovered were only superficially studied. Reconstitution of the paleogeographical conditions during the different stages of sedimentation, of intrusions and of volcanism may be helpful for the choice of new areas and geological formations to be prospected for uranium in the Mount Isa - Cloncurry geosynclines and elsewhere.

The uranium-thorium mineralizations of the Västervik area, Sweden, also occur in partially granitized quartzitic rocks belonging to the Västervik series of old Gothian age (Proterozoic). These sediments, which show crossbedding and sometimes ripple-marks, were deposited in a subsiding basin.

The pitchblende-tucholite disseminated mineralizations is confined to the least transformed parts of the quartzites, whereas the thorium paragenesis (davidite-thorite) is located in the granitized sediments (64) (65). Here again, we find a spatial relation between the U-Th mineralization and the sediments deposited in the marginal zones of a geosyncline granitized by the Småland granite. It is also noteworthy that the elements of the thorium paragenesis are present in the accessory minerals such as titanite, rutile and zircon of the quartzites.

The pitchblende veins of the Canadian shield *

(a brief review of the unexplored uranium and thorium resources of Canada was given recently by S.M. Roscoe (68)), (17) were formed during the **Proterozoic** but later reworking occurred in several deposits. The mineralized belts are mostly confined to low and moderate metamorphized sedimentary basins but the veins also extend into the neighbouring basement. Outside the contact zones, the granitic-gneiss basement is generally devoid of any recoverable mineralization with the exception of uraniferous pegmatites and more rarely pyrometasomatic deposits. The most important vein district of the Canadian shield is the Beaverlodge-Athabasca area. Pitchblende occurs in fault and shear zones cutting the granitized sediments of the Tazin group and the flat-lying Athabasca series respectively belonging to the lower and middle Proterozoic. The Tazin group was affected by the Hudsonian orogeny, whereas the Athabasca series was deposited in an intracratonic basin formed by dislocation of the Hudsonian basement of the Churchill province (59). The uranium mineralization is found on the north side of Lake Athabasca near the margin of two geological provinces. During at least the beginning of the deposition of the Athabasca series,

* a brief review of the unexplored uranium and thorium resources of Canada was given recently by S.M. Roscoe (68).

the basement has undergone dislocations and was also intruded by late orogenic Hudsonian granites which have also affected the basal arenaceous unit of the Athabasca series. It is well known that the pitchblende veins in the Hercynian provinces of Europe are associated with late orogenic granites. In the Athabasca area such intrusions may be also responsible for the widespread uranium occurrences which took place at the end of the Hudsonian orogeny. However, here redistribution of the primary pitchblende mineralization is frequent. The dislocations of the basement during the first stages of sedimentation of the Athabasca series seem to have favoured both late magmatic and hydrothermal activities related to the end of the Hudsonian orogeny. Similar favourable geological conditions for uranium mineralizations may also exist in the Keewatin district, Northwest Territory, especially along the contact zone between the Dubawnt series of middle Proterozoic age deposited in an intracratonic basin and the Hudsonian basement of the Churchill province. Until now this area was poorly prospected for uranium. Aerial photographs probably may be used in this region to point out the eventual major dislocations of the contact zone between both geological formations which can be mineralized in uranium.

Outside the Great Bear Lake province, the pitchblende occurrences of the <u>Great Slave Lake, Sault Sainte Marie and Makkovik areas</u> (17) (43) are also found in the marginal zones of Proterozoic basins near the contact with the Archean basement which may be also mineralized. These pitchblende veins may originate only from magmatic hydrothermal activity. However, it is possible that some of these mineralizations arise from the redistribution of hidden uraniferous beds. Similar pitchblende occurrences may also exist in the Port-Arthur-Nipigon area, Ontario. In the Northwest Territory, a possible promising area is represented mainly by the sedimentary inliers of the Churchill province near the contact with the Archean Yellowknife province. The Hudsonian magmatic activity in this favourable marginal zone for uranium occurrences of the sedimentary type may have led to pitchblende veins in the fractured areas.

In the Great Bear Lake Proterozoic province, the pitchblende veins are characterized by a complex mineral assemblage of Ag-Ni-Co or by U alone. They are related to shallow granitic intrusions which cut the Echo Bay and Snare Groups (17) (59). Both series comprise important lavas and pyroclastics of andesitic and dacitic composition that locally contain disseminated mineralizations. Such volcanics in other countries gave rise to ore deposits of silver and other metals. Also uranium is sometimes associated with these volcanics such as in Yugoslavia, in British Columbia, Canada, Mexico and the Peruvian Andes. The widespread distribution of silver and uranium mineralization in the Great Bear Lake province suggests that these metals may derive from the important series of intermediate volcanics intruded by granites. A study of the geochemistry of these rocks could probably not only resolve the problem of the origin of the uranium and of other metals but also may help to select new areas to be prospected. Moreover both principal mineral assemblages of the pitchblende veins, the earliest mineral formed, could be explained in terms of temperature-pressure gradients of ore deposition.

Therefore the association of silver and other metals with even low radioactivity at the surface may indicate more extensive uranium mineralization at depth. Considering the mineral paragenesis and the distribution of the pitchblende veins, the best areas for uranium prospecting in the Great Bear Lake province appear to be the sedimentary remnants and their neighbouring granitic and porphyritic intrusions.

The granitic-gneissic basement could also be affected later by metamorphism that may be accompanied by granitic intrusions (67) (68). Pitchblende veins may occur in this case especially with shallow depth intrusions. In the northern part of the Yellowknife province (Archean), in the Cross Lake sub-province (Archean) belonging to the Superior province as well as in the Eastern Nain sub-province in Labrador, several granites were intruded during the Hudsonian orogeny of Proterozoic age and later. Until now only one pitchblende occurrence was found at Contwoyto lake (Yellowknife) but these areas of younger granitic intrusions merit more attention.

Outside Canada, similar younger granitic intrusions in the basement are observed in the Brazilian shield in relation to the Caledonian orogeny (58) (61) and along the Darling fault in the Archean province of Kalgoorlie in Western Australia (12). Renewal of magmatic activity may lead locally to pitchblende veins and perhaps also to other types of deposits. As the pitchblende veins are frequently characterized by hematitization of the country rocks, such alteration may serve as a guide for uranium in many areas.

Uraniferous pegmatites are widespread in the granitic areas of the Precambrian shields but generally the reserves are small and the mean uranium content too low. Only granite or syenite pegmatitic belts, characterized by uraninite or uranothorite and having a high ratio U/Nb+Ta+Zr, may possibly be considered as interesting for eventual production of uranium at a price of \$ 8,- per pound of U_3O_8. However, in these belts, the pegmatites must be of large size with sufficient grade and reserves, which was only the case for the Bancroft area, Canada. New pegmatitic productive areas may be perhaps found in the southern part of the Grenville province or in the south western part of the Churchill and Superior provinces in Canada where uraninite or uranothorite-rich pegmatites are frequent.

In the Gondwana shields of Brazil central and South Africa, Australia, India, most of the uraniferous pegmatitic districts contain complex uranium minerals and have a low ratio U/Nb+Ta+Zr; therefore the probability of finding economic ore deposits seems to be small.

In conclusion, the distribution of uranium occurrences in Precambrian shields may be explained in most cases on the basis of the geological and paleogeographical evolution of sedimentary basins and the choice of new favourable areas for prospecting may be based on several geological criteria.

In intracratonic basins, uranium occurs in sediments especially conglomerates and other arenaceous rocks, in acid/intermediate volcanics, and in veins. The mineralization is located mainly in the marginal zones of a basin and in the neighbouring basement (for pitchblende veins). In the basins without granitic intrusions, new favourable areas for uranium deposits are thus mostly restricted to the boundary of two geological units. Attention must be especially focused on intracratonic basins containing interbedded acid/intermediate volcanics and/or formed by intense fracturing of the basement.

The distribution pattern of the uranium occurrences in geosynclines is more complicated but several criteria may be used to find new mineralized districts. In granitized or ultrametamorphized areas, the probability of finding uranium deposits outside pegmatites is scant but later renewal of magmatic or hydrothermal activity may lead to local uranium concentrations. Uranium occurrences in conglomerates or other arenaceous or carbonaceous-rich rocks show a paleogeographical environment and marginal distribution similar to those in intracratonic bains. Prospecting of such ore bodies may be delineated to weakly moderately metamorphized sedimentary series deposited in marginal zones or in subsiding basins during the development of geosynclines.

The preferential location of pitchblende veins and even pyrometasomatic deposits along old marginal zones of Precambrian basins suggests in many cases a redistribution of the uranium contained in sediments or in acid/intermediate volcanics by magmatic, hydrothermal or other processes. Therefore, the presence of even low-grade beds and volcanics in geosynclinal zones characterized by igneous or by hydrothermal activities constitutes a good indication for the search of new promising areas for uranium deposits. Uranium mineralizations related to differentiation of granites may also be found especially with shallow to medium depth intrusions closing an orogenic cycle.

Important uranium deposits will be certainly found in future in the Precambrian shields either in the extension of the known mineralized districts or in poorly and unprospected areas. Taking account of favourable geological and paleogeographical conditions in several Precambrian basins for large and smaller uranium deposits and of the extension of the shield areas, at least 600.000 metric tons of uranium metal recoverable at a price of $ 8,- per pound may be discovered by using not only classical methods of prospecting but also new ones for the search of concealed uranium mineralization. Besides the large potential recoverable uranium reserves of the Huronian province of Southern Ontario, Canada, evaluated at about 180.000 metric tons of U metal, new uranium districts may be found in almost all shield areas. Application of geologic concepts will become helpful for the choice of the most promising areas to be prospected with some probability of success.

This publication is derived from a detailed study of the uranium outlook of several countries outside the European community, made for the Supply Agency of Euratom.

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Alfred Nobel

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