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GEOLOGY OF THE FISSIONABLE MATERIALS.[1]

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CONTENTS.

[1] This article was prepared in 1946 for presentation in abstract at the 75th Anniversary Meeting of the A.I.M.E. and was withdrawn from the program pending clarification of government policy on publication of uranium information. This paper has been reviewed by the Atomic Energy Commission for security.

ABSTRACT.

Deposits of uranium and thorium have characteristics of mineralogy and geologic occurrence with geographic distribution pattern that facilitates estimating the resources in each type. Positions for known geographic occurrences are shown on maps and the geologic control over the distribution for each type is reviewed in the text. Aggregate abundance in the earth is about that for tin and theoretical difficulty of recovery from large deposits would appear to be slightly less than for silver. Amount and expense incurred in recovery would seem to place uranium and thorium along with the high priced industrial metals rather than the rare or precious elements.

Occurrences are classified under primary or hypogene types, sedimentary or bedded deposits, and oxidized bodies. At present the primary deposits are the principal source of supply and currently only mesothermal lodes seem to have productive value. For the future, all varieties of sedimentary occurrences give promise of large sustained production at reasonable cost.

Geographically the southern parts of the land hemisphere seem better provided with concentrations of these elements than the northern land mass.

Primary uranium deposits are either in massifs or close to the margin of Shields. The center of Shields has no known or indicated concentrations. Furthermore, economical lode deposits are unknown in a uraniferous pegmatite province. Thorium in significant amounts comes almost exclusively from monazite and has a more varied structural distribution than uranium. Uranium and thorium are more abundant than gold in most alluvial deposits and the ratio is large in many instances. Marine beds, which accumulated very slowly at high pH (hydrocarbon and phosphorite bearing strata which interrupt the organic food cycle) have above average uranium. Some of these marine deposits and many lake beds and soil layers of steppe climate have the contained uranium reconcentrated slightly when concretion-forming processes affect them.

Concentrations of oxidized uranium mineral occur in the pedalfer type soil areas where acidity declines at depth; it appears in the pedocal type soil areas at the surface or at the watertable in the special instance where acidity is sustained by oxidation of sulphide masses. Source of uranium can be in either primary hypogene minerals or in sedimentary deposits. Known deposits of oxidized uranium ores have less than 50 tons of U_3O_8. General indications are that such occurrences will not contribute significantly to world supply.

INTRODUCTION.

THE geology of fissionable materials penetrates to the very heart of the atomic energy problem. If uranium and thorium are available only in limited amounts to be guarded jealously, they may continue to be only a material of war, suitable for dealing death; should they exist in that abundance, expected of industrial metals, they might be produced for prosperity and be used in launching a new era of life. My hope and faith is in the latter and this assessment of the world occurrence for these elements should be our hope for prosperity, not an end to human progress. Geology of the fissionable materials includes their general abundance in the earth as well as the degree of concentration in specific deposits, the probable cost of production, and some potential methods of recovery from rock. The types of deposits, their characteristic distribution in relation to the broader geological structures, and the ore pattern within specific occurrences is treated in detail. The capacity of some geographic occurrences to yield uranium and thorium supplies is outlined.

General Statement of Resources.—Consumption of hundreds of tons of uranium and thorium annually would soon exhaust present sources and make these expensive metals. Demand for thousands of tons annually should see the cost stabilized at about that of silver, with the supply in the earth somewhere near that for tin. So it is to deposits than can yield thousands of tons that interest should turn and one ton producers can be dismissed now as essentially inconsequential.

The basic ideas on production assume a uranium value of about \$5.00 to \$10.00 per pound of U_3O_8 in a simple salt of reasonably high purity. This may be achieved about as easily by a large scale operation on low grade rock as by a small scale operation on high grade rock; the former is definitely the more dependable source. Achievement of this goal is no more established now than was cyanidation of low grade gold ores in 1885 or successful recovery of porphyry coppers a reality in 1910 yet the general concentration principles for uranium extraction are about as set now as in either of the above examples at the dates mentioned.

The grouped ideas concerning uranium and thorium resources and their utilization are like a cable. Each of the three strands has many threads. The threads make the cable but it is hard to realize the cable is in the making until it is finished; so it is in this case. For this reason the full theme is presented before its individual components are described. First, fissionable materials need to be produced in thousands of tons annually for industrial use. Second, the supply may be expected to come principally from large low-grade deposits. Third, the deposits should be susceptible to operation at low cost and with minimum supervision. Each of these principal strands needs exposition before entering upon details of world resources and mapping out the distribution pattern.

Uranium resources are measured in millions of tons if large regular deposits containing upwards of ⅓ pound per ton are considered workable. At $10.00 per pound of U_3O_8, the value of contained uranium exceeds that of porphyry coppers and a few large gold operations. Thus, enough metal appears available to assure supplies that might be required to take advantage of research discoveries. On the other hand developments seem to assure a definite use for uranium produced at say $10.00 per pound.

Further study of the long history for iron shows almost immediate need for transfer of fissionable material from military to industrial use, from sword to ploughshare as a defense measure. While iron was used for swords and was available in amounts adequate only for swords, raiding armies swept back and forth over the cultured world. Under the Romans, iron was produced for nails to build houses, straps to bind wheels of vehicles, chains that were not all used for bondage, and the world prospered for almost a ¾ of a millennium. Uranium for power is in its way, and for this day, what iron was in that yesteryear. Industrial uranium is necessary soon if man's decision is for peace and progress, not war and waste again in this generation.

General Types of Occurrence and Content.—Thorium and uranium are distributed widely. Only monazite is known to have thorium in significant total amount; it is known as rich concentrations of large size only in alluvial deposits. Uranium has now principal attention and greatest variety in known types of occurrences; heretofore pegmatites, mineral veins and carnotite-bearing sandstones or surface oxidation products from these have been considered as the principal uranium carriers; but other modes of occurrence will certainly outstrip these in future production.

Pegmatites are small and content rarely reaches ⅕ pound per ton; by-product yield, limited as it is by need for feldspar, quartz, lithium and mica, is inconsequential. A lode deposit which will produce 10 tons of U_3O_8 per meter of depth is unique and even 1 ton per meter of depth is exceptional; vein deposits, for good reason, rarely have a depth range of 500 meters so that large supplies for a long period are not expected from such a source.

Very large deposits containing ⅓ pound upwards of U_3O_8 per ton of rock occur in such bituminous strata as the Cambro-Ordovician age shales of southern Sweden and Russia, and with some alluvial gold and tin deposits. Only slightly less rich, are certain zones in late Devonian age shale of Kentucky and adjacent states. The phosphatic shale deposits of Permian age in the northwestern states are another important source. These deposits have great size and regularity. The carnotite-bearing sandstone type of deposit in the Colorado plateau and in the Ferghana region of Russia is very irregular and to date no geophysical method has been devised to discover the ore shoots beneath even a few feet of overburden. Monazite averages about 1 part of U_3O_8 for each 50 parts of ThO_2 and some monazite alluvials have other refractory uranium minerals; therefore monazite-bearing placer deposits of Brazil, India and all southeast and eastern Asia are a not inconsequential source for uranium.

The enriched oxidized ores have been singularly disappointing sources; they occur principally where extremely sparse uranium is leached from rock by acid surface water and is precipitated at low hydrogen ion concentration by limestone, alkaline groundwater, or phosphatic rock. They are known in Bulgaria, Portugal, the Ferghana region of Russia and in New Mexico. Characteristically the deposits have about 0.25% U_3O_8.

Capacity of Some Geographic Occurrences.—Pegmatites are nowhere large producers of low cost fissionable materials. This characteristic discourages interest in Ontario, Karelia, Madagascar, Southwest Africa and northeastern Asia, except for possible alluvial concentrations from them. Furthermore vein deposits, mentioned below, never occur in any ore province with numerous uraniferous pegmatites. Katanga has the only known lode deposits that can begin to meet presumptive industrial requirements; the combined output of all other lodes could not be significant. Thus so long as pegmatites and lodes are uppermost in the mind of man, military use of fissionable material will remain paramount. However the above geologic sources should soon give way to larger ones.

The Swedish Cambro-Ordovician age shales with ⅓ pound per ton [2] have 1,800 metric tons of U_3O_8 per square kilometer under at least 400 square kilometers. Likewise impressive is the indirect evidence from the green diamonds of the Rand Banket, that, unwittingly the mills may have been passing many tons of U_3O_8 to the dumps.[3] Most bituminous shales are uraniferous and extensive deposits are reported both in the Leningrad district of Russia and in the United States and may be expected in many other places, particularly the petroleum areas of the world. All of these deposits are regular and susceptible

[2] Since this article was written, a statement has appeared stating that some portion of the Swedish shales have been reported to contain as much as 0.5 percent uranium. This statement is partly true but altogether misleading, since it applies only to nodules of hydrocarbon called kolm, distributed as widely separated and concretionlike masses through the *Peltura scaraboides* zone of the alum shales. No authoritative report of shale with mineable thickness indicates a content above 0.05 percent U_3O_8.

[3] A high uraninite content in the heavy mineral fraction of the Witwatersrand ores was identified during the author's study of gold ores collected from the Kimberley Reefs in 1941. Previously Cooper had identified insignificant amounts in 1926. One discovery specimen was returned to the Transvaal Museum in 1945 and the others were kept at Amherst College. Simpson announced recently, what the mineralogical study had revealed, that "Uranium is a more common constituent of the Witwatersrand System than gold," and published a series of radioactivity logs and data from which the actual uranium content can be calculated.

Simpson, D. J., and Bouwer, R. F., Radioactivity logging: Geol. Soc. South Africa Trans., vol. 53, March 1950 (preprint).

of mining at low cost with minimum supervision. The main problem is production of an enriched product. German metallurgists attempted froth flotation of the metal content of oil shales during the war but were unsuccessful and it appears that some leaching technique would be essential as at least one stage in the extraction of uranium. Separation of a uranium-bearing leach liquor from the argillaceous slime will be difficult and expensive, particularly in cold northern climates; but it is not impossible. Thus the low-grade bituminous deposits appear as one likely supply for industrial requirements. The inimitable mineral wealth of the Union of South Africa and its Witwatersrand almost certainly is another.

The oxidized ores are limited mostly to surface leached zones; few extend to over twenty meters depth. In a majority of instances the uranium came from overlying bituminous shales and the ores cease altogether at shallow depth. Grade rarely exceeds 0.25% U_3O_8; some hand dressing is usually practised. Only the unusual deposit at Bukhovo, in Bulgaria, gives promise of yielding even 30,000 tons of mineralized rock. At even 80 percent recovery only 60 tons of U_3O_8 would be expected and this could have no great influence upon world supply.

GEOLOGICAL ASSOCIATIONS OF URANIUM.

The geological aspect of uranium occurrence covers the probable ways that the element may occur in nature. The mineral carriers, the geographic distribution pattern for all carriers, and the geologic influence upon local concentration are considered. From this statistical and background data, a statement is prepared to set forth not only the known supplies but the expectable resources for the future. Thus, this account presents the world state both now and as it is expected to develop in the years immediately ahead. The errors of the explorer become obvious as he looks upon his journeys in retrospect and by the fool he is criticized for them. All "charts," even though poor, are necessary to assess the relatively unknown; every engineer must realize that present information does not encompass all knowledge and dependence must be placed upon the expectable as well as allowance made for the unexpected. Some of that unknown holds great possibilities; some of it is a mineral desert. In making this assessment, I use all "charts" that my geological experience, mining training and ore dressing instruction offers, with the full realization of their individual shortcomings and the hope that their combined information is nearly adequate. But even as early estimates for petroleum have been modified, so change in this evaluation of this new power source, uranium and thorium, is anticipated; but may the error be less. And as in the case for petroleum, it is very doubtful whether entirely new regions—as distinct from deposits—or new types of holding structures are apt to be listed.

Identification of Uranium and Thorium.

Most uranyl salts and minerals fluoresce, subject to the quenching effect of other heavy metals. A solution of uranium minerals in sulphuric acid, evaporated to dryness fluoresces. Likewise a uranium-bearing mineral decomposed by fusion in a lithium or sodium fluoride bead will usually cause the bead to fluoresce in ultraviolet light. Heavy rare earths, tungsten and molybdenum interfere with this test. The particles emitted by radioactive decomposition will discharge an electroscope, activate a Geiger-Muller tube or induce phosphorescence on specially prepared zinc sulphide. The above methods are adapted to field use and a wide variety of other methods may be used in the laboratory. Thorium is obtained almost exclusively from monazite and it is identified by the carrying mineral or by radioactivity.

Proximity of uranium and thorium in amounts over 0.01% equivalent U_3O_8 is indicated by unusual colors in certain neighboring minerals; radioactive minerals do not cause these effects always but do so in enough cases to make them useful. Near uranium minerals quartz is turned smoky, diamond becomes green, coarse calcite assumes a pink color and fluorite turns deep purple. Green monazite is highly uraniferous although uraniferous monazite is not always green. Near thorium minerals, quartz becomes rose colored. Feldspar has a strained halo of reddish color around primary uranium or thorium minerals. Primary uranium and thorium minerals have high specific gravity and usually remain in the pan concentrate along with magnetite, ilmenite, zircon and other heavies familiar to the placer miner. Magnetic attraction is so weak that even a powerful hand magnet fails to remove the uranium and thorium varieties.

The Uranium and Thorium Minerals.

Most field geologists are familiar with about ten uranium- and thorium-bearing minerals. Actually over one hundred minerals are recognized and attempts have been made to recover these at one place or another. A few are primary minerals including the black oxides—usually referred to as uraninite and pitchblende—and a brownish to black group of minerals—referred to as the refractory columbotantalates. The largest number of species are secondary uranyl salts including the bright yellow vanadates—referred to as carnotite—and the so-called bright oxides which are principally yellow and green phosphates, silicates and sulphates. Most uranium minerals have over 5% U_3O_8 but thorium-bearing monazite, zircon and allanite have hundredths to tenths of a percent.

Hypogene uranium deposits include both veins and pegmatites but verified metasomatic replacements and disseminations are a curiosity. Only one mineral, namely uraninite or the botryoidal form pitchblende, is known from veins.[4] Pegmatites have at least four ordinary oxide minerals and twenty-six additional refractory sorts. The ordinary ones are all simple oxides and include broggerite, cleveite, uraninite, uranothorianite. The refractory minerals include the columbotantalates, the titanoniobates and the complex titanates. Examples of columbotantalates include samarskite, the fergusonite series, the pyrochlore-microlite series, yttrotantalite and ishikawite. The titanoniobates, columbotantalates and complex titanates list the euxenite-polycrase series, the eschynite-

[4] Vein uraninite has less than 0.25 percent ThO_2; pegmatite uraninite, from over ¾ths of the reported localities, has 2 percent or more ThO_2. This is a useful characteristic in identifying origin of specimens from casual collections. The refractory minerals are exclusively from pegmatites or pegmatite-like deposits.

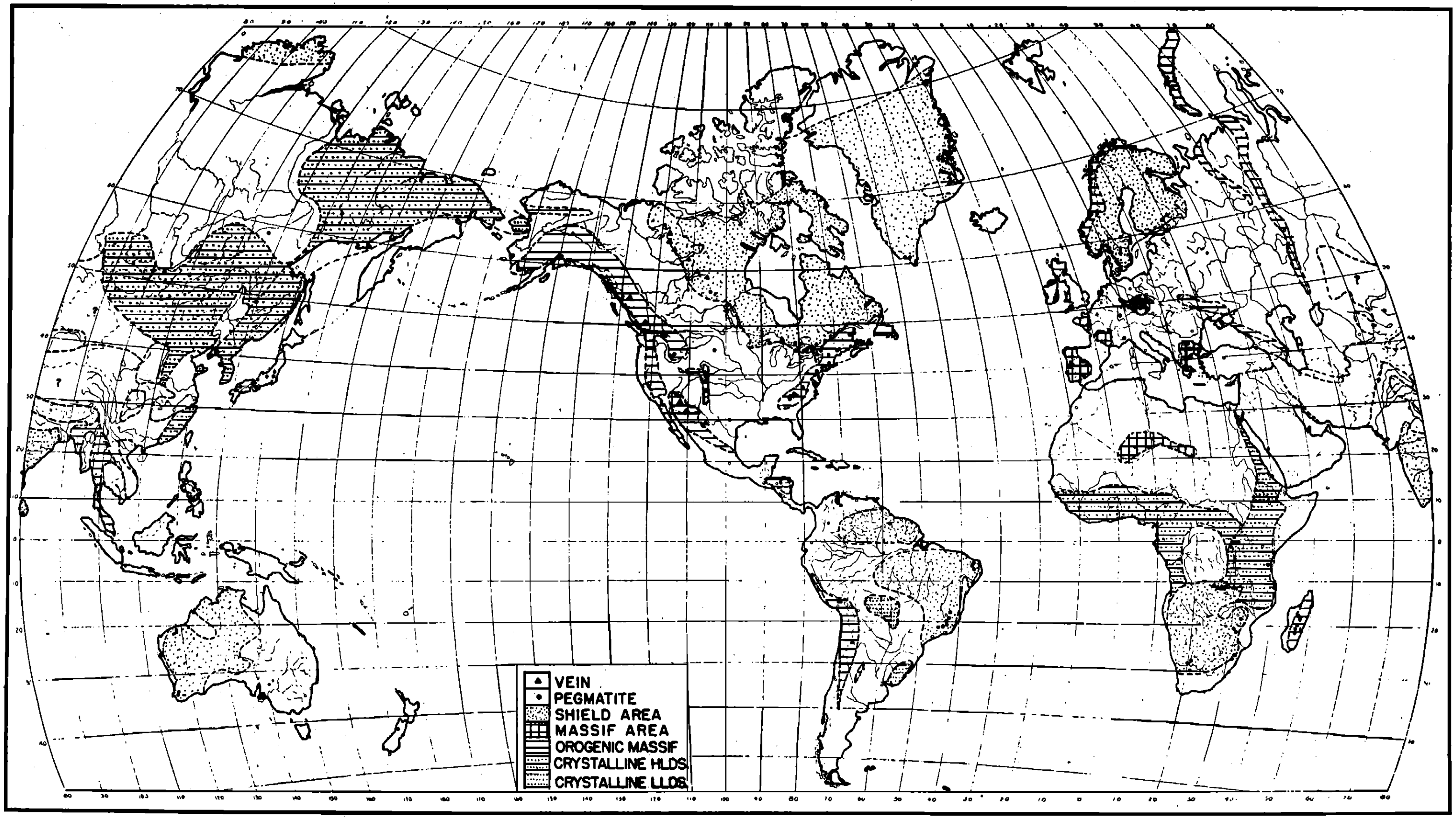
priorite series and betafite series. Every hypogene mineral has been recognized in some alluvial deposit and the very refractory titanoniobates and complex titanates appear with greatest frequency. Monazite is a hypogene rare earth phosphate which carries thorium and generally significant uranium; it is sufficiently refractory to appear in most alluvial deposits derived from pegmatite areas.

Uranium appears in a wide variety of supergene minerals including hydrous oxides, carbonates, sulphates, phosphates, arsenates, vanadates, and silicates, in fact combined with almost any negatively charged ion appearing in groundwater. Uranium separates from solution, at pH 5 to 6 which is encountered in the parent material zone of most mature soils, and combines with whatever negative ion happens to be available. Reduction of ionization by H_2S derived from bituminous shale and sulphide ores introduces a special case; no natural uranium sulphide has been recognized; the uranium separates out under these circumstances as a sooty black oxide, usually earthy but occasionally in firm botryoidal pitchblende. Most supergene uranium minerals are yellow, orange or emerald green. Well known hydrous oxides (8)* are becquerelite and curite. Schroeckingerite and sharpite are the most frequent carbonates (4). Zippeite and uraconite are typical sulphates (8). Practically every collection has the phosphates (14) autunite and torbernite, the arsenate (4) trogerite, and zeunerite, and the vanadates (4) tyuyamunite and carnotite. The silicates (10) soddyite, sklodowskite and uranophane are widely distributed. Thucolite, kolm and a variety of other asphaltic compounds seem to be black oxide of uranium dispersed through the hydrocarbon.

Distribution of Uranium and Thorium.

Uranium has wide geographic distribution yet each type of deposit is restricted in areal occurrence. Primary deposits are confined to favorable metallographic provinces and are not dispersed beyond the province limits by any metallogenetic episode of dissimilar pattern; distribution appears to be controlled by inherent original differences in components of the earth. All secondary deposits owe their position to genetic factors and their uranium was diverted into one restricted area by chemical or structural controls related to surficial agencies; solution and movement is enhanced by acidity; precipitation is almost certain at pH 5.2. Diversion into some secondary deposits was due to depression of hydrogen ion concentration; locally this functioned due to oxygen deficiency in the presence of hydrocarbons or sulphides and elsewhere was caused by strong positively ionized substances like alkali carbonates or even excess lime; in places a precipitant like vanadium or phosphorus unstabilized a solution already near saturation. Bituminous shales by adsorption gather uranium, vanadium, and other metals during sedimentation as in the alum shales of Sweden. Abundant calcium neutralized acid sulphate solutions from a bituminous shale at Tyuya Muyun. Vanadium and phosphorus precipitated the uranium in some bedded carnotite and autunite deposits and in the phosphorites. Lastly signifi-

* The number in parenthesis indicates the number of mineral species of this type occurring with high frequency in deposits.



Map 1. Reported locations for primary uranium minerals.

FIG. 1.

cant mechanical concentration of thorium-bearing monazite, and less commonly of uranium minerals, occurs from diffuse primary deposits into rich alluvials; tropical zone and beach placers have lost less uranium than those formed in the more acid northern rivers.

The search for uranium in primary and alluvial deposits ought to be guided by the metallographic province pattern. Bedded deposits are in formations rich in bituminous matter or associated with vanadium and phosphorus precipitants. The oxidized ores are almost exclusively phosphates or vanadates and may be expected either to follow the distribution of the vanadiferous and phosphatic rocks, or to be in the alkaline soil horizons.

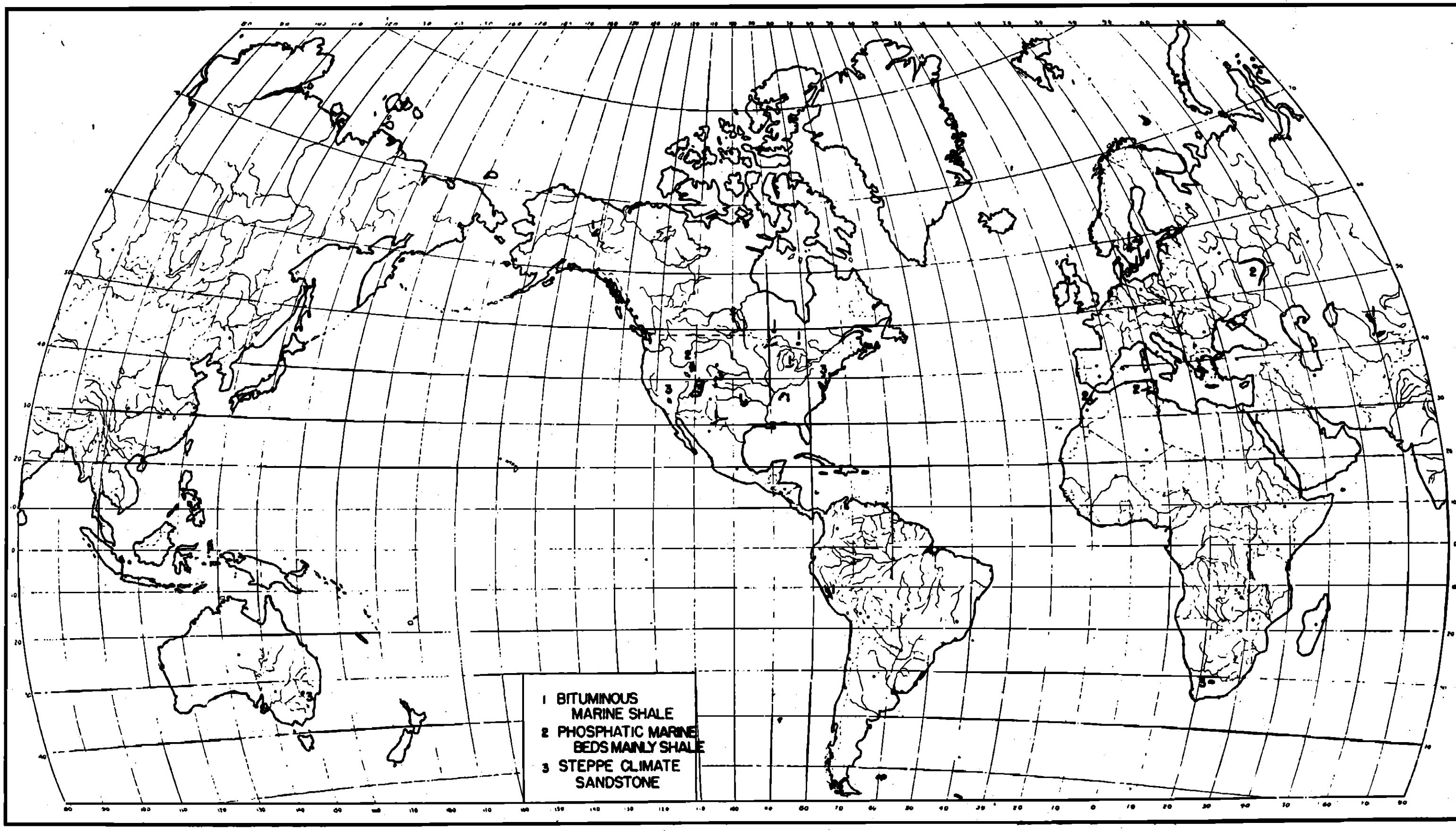
The Primary Mineral Distribution Pattern.—The occurrences of primary uranium minerals recorded in the literature [5] are plotted on the world map (Fig. 1). This distribution is considered under pattern, grade, and regions favorable for uranium. Low content minerals are distinguished from the significant content ones and for all practical purposes the low varieties may be disregarded.

Three features of the distribution pattern are outstanding. First refractory minerals are distributed rather generally through most crystalline rocks except those in the center of shields. Second, the center of shields is generally free from uranium minerals. Third, the principal uranium metalliferous provinces are on the periphery of shields or in large persistent massifs.

The massifs and shield borders locally possess concentrated mineralization but generally exhibit diffuse mineralization. Pegmatites represent diffuse mineralization supplying many museums but no mills, and such parts of a shield border are not known to have rich lodes. The Karelian S. S. R., Trans-Baikal regions, southern Norway, Ontario, Brazil, Southwest Africa, and the Central Massif of France represent such places. Conversely, shield borders or massifs with rich lode deposits almost everywhere lack uraniferous pegmatites. Great Bear Lake, the Katanga, the Bohemian massif, the Cornwall area, and the mid-western part of the Spanish Meseta are outstanding examples. Clearly those parts of shield borders and massifs which lack uraniferous pegmatites are more auspicious sites to search for rich lodes than are the places with abundant uranium localities. Pegmatite-type mineralization seems to scatter the uranium, whereas the lodes gather it into a very small space.

In accord with the above, the absence of uraniferous localities within shields might suggest that the occurrences are concentrated and undiscovered, and that these are indeed good sites for lode deposits. Evidence does not support this possibility. The great mining districts of the Canadian Shield and the most intensively explored areas of it, lie in the interior; the periphery with all the known localities, has received least geological study. The same statement applies to the Scandinavian Shield, the Australian Shield and the Rhodesian Shield. In addition, each of the shields has a locality which is generally favorable for concentration of any uranium that might exist there. The Canadian Shield has the Cobalt district with a type of mineralization most favorable for pitchblende deposition; none is there although the similar deposit on Silver Islet on the shield border has some radioactivity. Broken Hill (Northern Rhodesia) and Tsumeb (S.W. Africa) have vanadium and phosphate ores which would pre-

[5] See list of references on primary mineral occurrences.



Map 2. Locations for uranium in sedimentary deposits exclusive of alluvials.

FIG. 2.

cipitate any uranium in the groundwater of their basins but not one uranium specimen is reported in the lists from these much studied localities. The phosphatic iron ore bands at Kirunavaara and the phosphate minerals at Varutrask should have secondary deposits if any uranium was in the region yet only 4 rare specimens came from Varutrask and none from Kirunavaara.

Elongate orogenic massifs like the Appalachian Mountains, most of the Rocky Mountain ranges in the United States, the Ilmen Mountains and the ranges of the Trans-Baikal region in Russia, the Japan arc, the Tenasserim and Malay ranges in southeast Asia and the Antsirabe Massif in Madagascar have furnished only pegmatite deposits, with a predominance of refractory minerals. The record from such regions is distinctly unfavorable for significant uranium supplies but may be a place for important alluvial concentrations, particularly of thorium minerals.

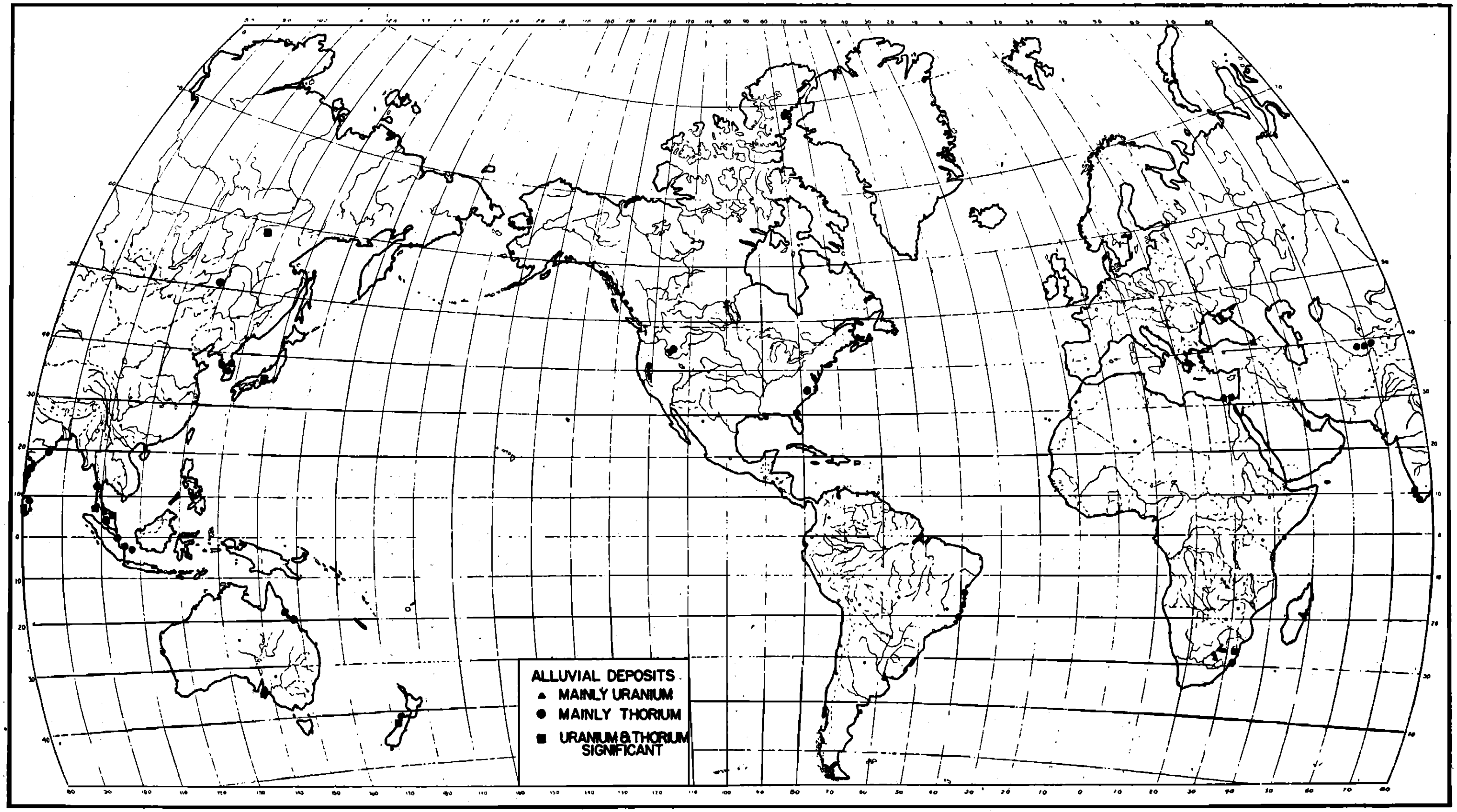
From the point of view of distribution of uranium provinces, no primary deposits of consequence can be expected in a large part of Canada, Greenland, Scandinavia, Siberia, Australia, Brazil, and the Guianas. Short strips on the edge of some of the shields, and one or two massifs are inadequately known. Furthermore the great areas of plains country in South America, North America, Siberia, and the European Russia are not places to find primary uranium mineral deposits. Equally unfruitful will be any search of the elongate orogenic strips of most of the Andes, the Western Cordillera, the Alpine chains and the ranges of east Asia. Other types of deposit may exist in some of these places, and will be considered later, but not the sort of deposit known at Great Bear Lake, Katanga, Joachimsthal, Cornwall or Portugal. In making an assessment of these possible but unexplored areas or areas not yet reported on in the literature, resources should be allotted proportional to that equal area of productive territory.

The Secondary Sedimentary Deposits.—The sedimentary secondary deposits have diverse origins and distribution control. Bituminous and phosphatic shales, alluvial deposits, and carnotite-bearing sandstones represent the outstanding types. All have low uranium content and great areal extent (Figs. 2 and 3). It is to these that industry must turn for principal future supplies.

The source rocks for petroleum are highly radioactive due partly to thorium but principally to uranium and the daughter elements.[6] This uranium is a part of the original organic rich mud laid in brackish or salt water and adsorbed from it at pH 6 to 7.5. The uranium content is generally greater in strata that accumulated very slowly rather than in those which were built up rapidly; however within formations that accumulated very slowly, highest content is generally associated with greatest organic content without regard to thickness. The highest U_3O_8 content is in the Cambro-Ordovician strata of southern Sweden[7] where 17 m represents the total accumulation during all upper Cambrian time and in southern Ferghana where less than 10 m represents the deposit for most

[6] Russell, W. L., Relation of radioactivity, organic content and sedimentation: Am. Assoc. Petroleum Geologists Bull., vol. 29, pp. 1470–94, 1945. See list of references on sedimentary occurrences.

[7] Westergard, A. H., Borrningar genom alunskifferlagret pa Oland och i Ostergotland 1943; Sveriges geol. undersökning, ser. C., no. 463, p. 18, 1944. Borrningar genom Skanes alunskiffer 1941–42; Sveriges geol. undersökning, ser. C., no. 459, p. 13, 1944.



Map 3. Location for uranium and thorium in alluvial deposits.

FIG. 3.

of the Silurian period.[8] These deposits accumulated on a foul-water, oxygen-deficient bottom where uranium solubility was far below that in ordinary oxygenated sea-water; uranium was adsorbed on the clay as phosphate and vanadate crystallites along with other metals. The precipitation would seem to have been extremely slow and significant amounts accumulated only where it was sustained for extremely long periods. Thus, it is the thin petroleum source rocks that are the most probable sources for extensive low-grade deposits of uranium and to a lesser extent for thorium and several incidental metals including copper, molybdenum, nickel, cobalt and vanadium. The thick source rocks of the California oil fields are not an auspicious site for uranium but the thin source strata of the Midcontinent, Illinois-Indiana, and western Appalachian fields are. All the oil field and oil shale areas are suspect but only the thin shales hold much hope of yielding supplies of uranium.

Alluvial deposits derived from pegmatite areas should and usually do have uranium minerals particularly of the refractory type. Xenotime and euxenite are recognized in considerable amount in the cassiterite concentrates of southeast Asia.[9] Fergusonite and samarskite have been identified in the alluvials of Korea, Manchuria and Japan.[10] Brannerite is a constituent of the Boise Basin placers in Idaho.[11] Aeschynite is reported in the Fairbanks region of Alaska. The green diamonds in the Witwatersrand banket indicate that these ancient alluvials contain not less than 0.01 per cent U_3O_8.[12] All alluvials which are derived from areas where primary uranium or thorium minerals exist, or are expected, should have these minerals in the placer concentrates. A usual ratio for monazite is about 100 times that of gold and about equal to that of cassiterite. Since uraninite, fergusonite, euxenite and other minerals are less abundant, a ratio of about 1/10 to 1/100 that of monazite is near average. The great alluvial deposits of gold, cassiterite, and ilmenite which are derived from crystalline rock (not volcanic) areas are a potential source for uranium and thorium.

The carnotite bearing sandstones have carnotite in a limited stratigraphic horizon in the Colorado Plateau [13] and in Ferghana [14] where they have been studied. Within the favorable stratigraphic horizon in the Colorado Plateau, the rich deposits are concentrated on certain favorable structures called rolls. These rolls have the general internal structural characteristics of concretions and this mode of occurrence suggests a groundwater concentration of a diffuse mineral distribution through the host stratum. The carnotite sandstone occur-

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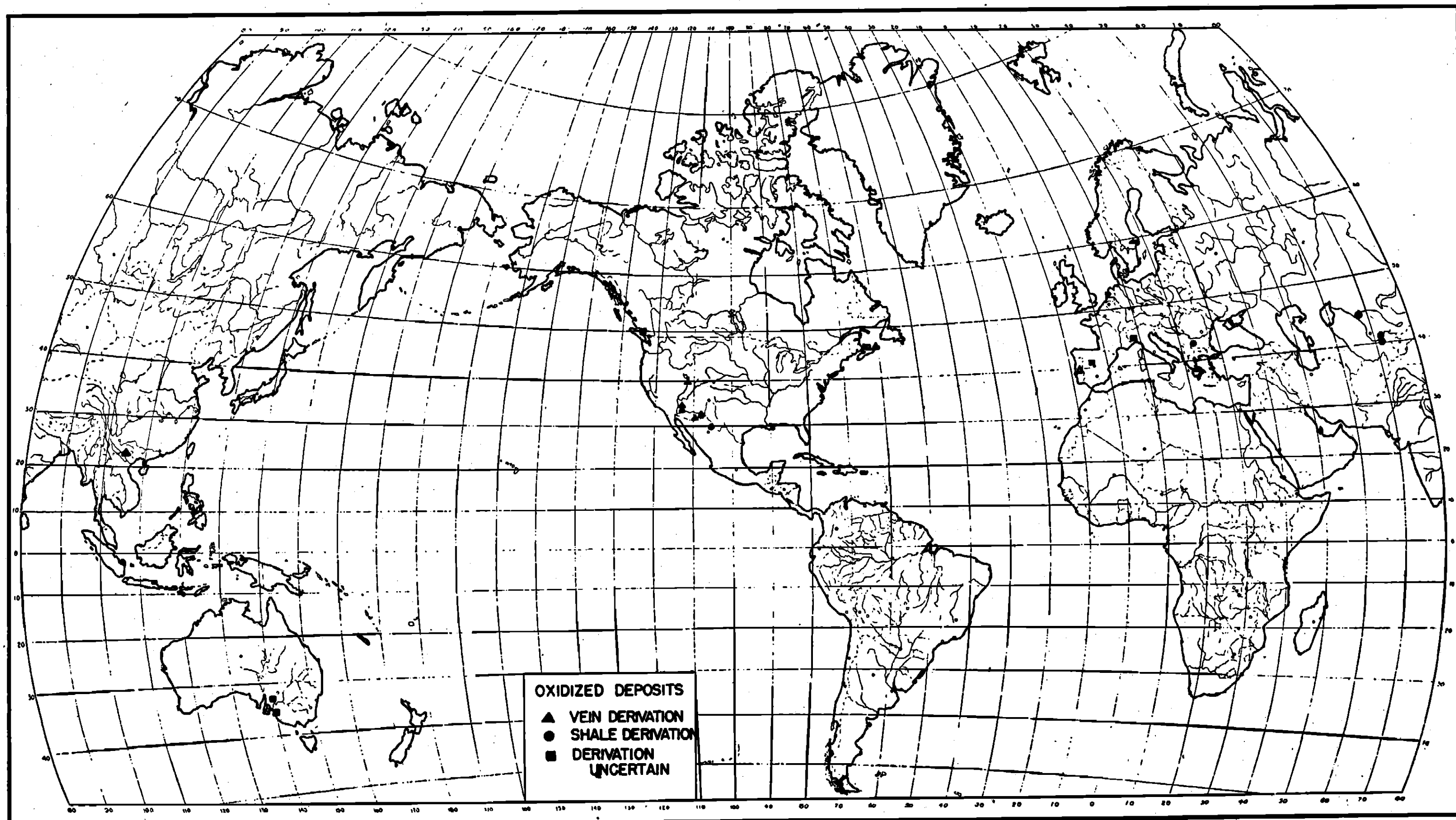

Map 4. Location of oxidized uranium deposits of some size.

FIG. 4.

rences had their strata accumulate under an "irrigated" steppe climatic condition which would cause the uranium and vanadium to be retained in the alkaline soil instead of going to the sea in the runoff discharge. However uranium has been identified in only a few steppe climate sediments. As yet no way of identifying potential carnotite areas has been recognized except by finding carnotite. But any group of sediments accumulated slowly under conditions of steppe climate is suspect.

The Oxidized Secondary Deposits.—The geographic distribution of oxidized secondary deposits (Fig. 4) is controlled by the pattern of source materials which may be primary pegmatites and lodes or sedimentary secondary deposits. Further the oxidized deposits can differ to only minor degree in distribution and richness from their source. Generally they are on fracture zones where groundwater movement is concentrated; fixation is due to presence of phosphate or vanadate precipitants or to lime which lowers the acidity and reduces solubility of phosphate and vanadate compounds. The greatest known series of these deposits is in southeastern Turkestan in Russia. Here they appear in the Kara Tau, Kara Mazar and Alai Ranges. The ores are in limestone or are associated with lead and copper ores. All occurrences are near the uraniferous, black Cambrian and Silurian shales, slates and schists, which are regarded as the source for the uranium and possibly vanadium. Distribution is controlled by the groundwater circulation and indirectly by the fracture pattern in the rocks. The Bukhovo, Bulgaria, deposit is in a fault breccia through sandstone; no source is obvious but a denuded shale seems more probable than any other. High phosphorous lamprophyre dikes localize the autunite distribution in a number of instances.

In Portugal and Spain, secondary black oxides and autunite with torbernite occur in films and rich concentration in narrow veins in the Vizeu and Guarda districts and in the phosphorite veins farther south. The ores are associated with open fractures receptive to percolating waters. The uranium may have come from scattered veins in the Hercynian granite but in view of the wide distribution and the shallow depth of most occurrences (20 m), it is by no means beyond expectation that most of the uranium may have migrated downward in an acid solution from a covering stratum or soil that is now denuded; the minerals were precipitated by reduction of pH in the deeper fractures. This same condition is encountered in all known occurrences of supergene black oxide.

No generalized geographic pattern for the oxidized ores is recognized other than the pattern of rich primary or extensive sedimentary deposits. The lack of characteristic pattern is due partly to the multitudinous sources for the uranium in them and to the high mobility of uranium in slightly acid sulphate waters. The immediate occurrence is almost always in a fracture zone which controls the groundwater movement. However the deposits as a class are relatively insignificant and only three are known which have or can yield 25 tons or more of contained U_3O_8.

TYPES OF URANIUM DEPOSITS.

Metallogenetic processes working within the larger geographic areas where uranium is known or expected, and under some special structural guidance, have gathered the uranium into small local masses or deposits. Three principal classes of control, responsible for formation of deposits, are recognized each with specific characteristic minerals, metal content, and size. These are:

1. Primary deposits	Pegmatites. High temperature fissure veins. Mesothermal fissure veins.
2. Sedimentary deposits	Bituminous and phosphatic shales. Alluvial or placer deposits. Carnotite-bearing sandstones.
3. Oxidized deposits	Precipitated almost in situ. Precipitated by an alkaline rock or soil. Precipitated in playa or playa-like deposits.

Each type of deposit has characteristics of distribution, size, and grade so limited that the accuracy and completeness of reports concerning most occurrences can be assessed easily. Actually evaluation of the world uranium situation, blanketed as it is by secrecy, depends upon criteria developed from characteristics of known deposits. This is not unlike practices guiding acceptance or rejection of clandestine reports on the varied types of gold deposits and many sorts of copper occurrences. The method does not give a summation of proven reserves or assays to 0.1 percent content but it does afford an assessment indicating that order of magnitude of tonnage and grade to be expected.

Primary Deposits.

Pegmatites have been a source of uraninite specimens but have produced only inconsequential amounts from very low content rock. High temperature veins have yielded up to 20 tons U_3O_8 but have lacked sustained production.[15] Mesothermal veins have been the principal producers and are well known at three great localities. The distribution of primary occurrences is shown on Figure 1.

General Features.—The principal primary uraninite occurrences are disposed around the periphery of almost equidimensional, strongly positive elements of the earth, called shields where they are large, or massifs where they are smaller. Very minor uraninite and refractory minerals appear also in elongate or orogenic crystalline rock masses. But no economic primary deposit is known to occur on the latter structure even where such places have produced large quantities of refractory columbate and tantalate minerals and have abundant alluvial deposits. Vein deposits have been very partial to a specific wall rock or formation.[16] Fissures become narrow, and uraninite or pitchblende diminish per cubic meter of ore where the veins pass out of the favorable formation at Joachimsthal and Shinkolobwe; similar behavior may be inferred at all

[15] Beyschlag, F., Krusch, P., and Vogt, J. H. L., The deposits of the useful minerals and rocks, MacMillan and Co., London, p. 713, 1916.

[16] Kraus, M., Das staatliche uranpecherz-Bergbaurevier bei St. Joachimsthal in Bohmen: Bergbau und Hutte, Wien, vol. 1, pp. 3–30, 45–63, 93–112, 128–148, 168–183, 1915.

other occurrences. High-temperature fissure veins generally have erratic grade and are short, ending in a series of horsetails.

Pegmatites.—Pegmatites almost never have 0.01% U_3O_8 in the entire mass and rarely have this amount even in the high content bands. Most uranium-bearing pegmatites are banded and the greatest concentration is near the quartz core. Content is estimated easily by the volumetric abundance of autunite and uraninite.

High Temperature Fissure Veins.—High temperature quartz veins have been known to have two inches width of uraninite for fifty feet. Thereafter, even specimens have been hard to find.

Mesothermal Fissure Veins.—The uraniferous mesothermal veins belong to a cobaltite-niccolite type and to a fluorite type. The cobalt-bearing type generally exhibits some banding or comb structure such as is found in epithermal veins. Recurrent fracturing, such as appears in hypothermal veins is rather common. The walls of the fissure have a crust of quartz generally with some hematite over the crystals. Uraninite cubes or even botryoidal pitchblende forms the next zone and the center is filled with cobalt and nickel sulphides, arsenides, sulpharsenides and various carbonates.[17] The vein matter at Joachimsthal specifically, and in other deposits generally, averages about 1% U_3O_8 where the space between walls or breccia fragments is about a foot; content increases to 12 percent for veins two or more feet wide and diminishes to tenths of a percent where the veins are only two inches wide.[18] A district with a system of veins about one foot wide averages about one metric ton of U_3O_8 per meter of depth; since the grade content of the veins generally varies with the width, 100 tons per meter of depth may be expected from a district with two foot veins; only 0.1 tons per meter of depth can be anticipated where two inches represents the average width.

Any fissure vein which shows great preference for a specific wall rock rarely attains great depth. This has been amply demonstrated for mesothermal deposits generally. The Joachimsthal mines are about 500 m deep and anywhere else low content would have decreed closing many years ago. It will be very unusual if any other uraninite lodes can be operated to this depth. The fluorite vein type has yielded specimens at a number of places and about 100 tons of ore at Wolsendorf in Bavaria.[19] This kind of deposit seems to have insignificant content and is worthy of only passing consideration.

Sedimentary Secondary Deposits.

The Kolm-bearing alum shales of Sweden were considered unique in having uranium. However studies on source rocks for petroleum discloses that all such strata are uraniferous and even the origin of the petroleum may be due to this

[17] Kidd, D. F., and Haycock, M. H., Mineragraphy of the ores of Great Bear Lake: Geol. Soc. America Bull., vol. 46, pp. 879–960, 1935. Bastin, E. S., The nickel-cobalt-native silver ore type: Econ. Geol., vol. 34, pp. 1–40, 1939.

[18] Kraus, M., op. cit. (Kraus compares the yield of wide veins with narrow ones.)

[19] Kohl, E., Grossdeutschlands Vorkommen naturlich-radioactiver Stoffe und der Bedeutung fur die Versorgung mit radioactiven Substanzen: Zeitschr. Berg-, Hütten u. Salinenwesen in Deutschen Reich, Band 90, pp. 153–179, 1942. Die Mineralfuhrung der Wolsendorfer Fluorspatgange: Zeitschr. prakt. Geologie, Band 42, pp. 69–79, 1934.

radioactive material.[20] Two other sorts of deposits with stratigraphic control of deposition are recognized. The high specific gravity of primary uranium minerals causes them to be concentrated into placers and they have been found in Alaska, Armenia, Brazil, Ceylon, India, Burma, Malaya, Mozambique, Siberia, South Africa and Swaziland to mention a few instances. The concentrate from alluvial gold, gem, and tin deposits generally has uranium minerals. Also more than a few deposits of uranyl salt minerals have such stratigraphic regularity of distribution, if not of continuity, as to suggest some bedded feature as the principal control. Carnotite, tyuyamunite and at least one autunite occurrence in sandstone come in this category.

The Bituminous Shales.—The uraniferous bituminous source rocks for petroleum are marine deposits that accumulated very slowly. Generally only marine shales yielding over 10 percent of oil by distillation have significant uranium. However, a few slates and schists of this derivation, but which have been so metamorphosed as to lose most of their volatile hydrocarbons, still retain their uranium. The uranium content of 0.02% U_3O_8 or more has been confirmed rarely. Some typical shales are the Antrim and Chattanooga with about 0.01% U_3O_8,[21] the Cambrian age alum shale of Narke (Sweden) with 0.023% U_3O_8,[22] the Cambro-Ordovician shales of the Leningrad district, Russia, with 0.008 to 0.03% U_3O_8,[23] and the black siliceous Cambro-Silurian schist (?) of the Ferghana region, Russia, with 0.03 to 0.08% U_3O_8.[24] (High values in the latter case seem to be due to surface enrichment.) The ThO_2 content is almost equal to the U_3O_8 in a few places but averages only about 25 percent abundance.

Uraniferous shales are from 1 to 17 m thick and underlie hundreds of square kilometers. Each square kilometer has about 225 metric tons of U_3O_8 for each meter of thickness of 0.01 percent content. The Ferghana occurrences are highly folded and show great surface enrichment but soon pass under such heavy overburden as to make mining expensive. The Swedish, Leningrad, and United States occurrences are not enriched, have great regularity, and each has over 100 square kilometers amenable to open pit mining.

This type of deposit is formed only in marine shales and then only where accumulation was slow and the bottom water was oxygen deficient. All fresh water carbonaceous shales and glacial clays lack even 0.001% U_3O_8. The same discouraging situation holds for oxygenated marine sediments including all conglomerates, sandstones and limestones. Thus, potential stratigraphic position and areal distribution is very limited. The uranium is relatively immobile in a reduced state and in ordinary alkaline water, and remains with the formation through all metamorphism short of intense injection.

20 Sheppard, C. W., and Whitehead, W. L., Formation of hydrocarbons from fatty acids by alpha particle bombardment: Am. Assoc. Petroleum Geologists Bull., vol. 30, pp. 32–51, 1946.

21 Russell, W. L., Relation of radioactivity, organic content and sedimentation: Am. Assoc. Petroleum Geologists Bull., vol. 29, pp. 1479–1480, 1945.

22 Westergard, A. H., Borrningar genom alunskifferlagret pa Oland och i Ostergotland 1943: Sveriges geol. undersökning, ser. C., no. 463, pp. 18, 1944.

23 Orlov, N. A., and Kurbatov, L. M., The radioactivity of bituminous shale: Khimiya Tverdogo Topliva, vol. 5, pp. 525–527, 1934; vol. 6, pp. 228–291, 1935; vol. 7, pp. 94–98, 1936.

24 Fersman, A., Geochemische migration der Elemente, Pt 2. Die Uran-Vanadium grube Tuja Mujun in Turkestan; Abh. prakt. Geologie und Bergwirtschaftslehre, Halle, vol. 19, 1930.

The phosphatic shales accumulated where recycling of the phosphatic waste of organisms was inhibited. This is in oxygen-deficient water of near neutral pH. Chemically, the conditions resemble those of the bituminous shales; grade and distribution are closely comparable.

The Alluvial Deposits.—The alluvial or placer deposits of monazite and thorianite have been the principal source for thorium and a minor one for uranium. Only beach alluvials have been worked successfully for monazite but the heavy concentrate from gold washing,[25] and cassiterite mining[26] have as much monazite as any beach sand. Therefore, this heavy concentrate should be considered a definite source for thorium although previously it was saved only in the Netherlands East Indies. In addition, river alluvials in places contain euxenite and xenotime with significant U_3O_8.[27] The principal known beach placers are found in Travancore, India,[28] and the coast of Brazil from Cape Frio northward.[29] The alluvials are generally in crescent-shaped beaches and have richest surface concentration just before the on-shore storm season.[30] This is due to greatest removal of low specific weight sand from the bays at this time. The headlands undergo greatest erosion during the on-shore storms and presumably their concentration during the opposite season is due to this factor.

Monazite is a heavy, decay resistant, but relatively soft mineral, especially if we accept F. L. Hess's test for it. Excessive wear by the poorly decayed detritus of temperate climate streams reduces much of it below recoverable size. Tropical decay separates monazite from its matrix rock with minimum disintegration. For this reason principal rich alluvial occurrences are in the tropics; temperate climate alluvials are distinctly poor. The beach detritus from any region of crystalline rocks, known to contain monazite, particularly in the tropics, may be expected to have monazite where conditions are favorable for separation of quartz from the heavy minerals. The stream alluvials of poleward areas may have deposits of poorer quality.

Monazite content of cassiterite placers is almost equal to that of cassiterite but, due to greater difficulty of separation, probably only 10 percent can be recovered. The monazite content of many brown-sand, gold alluvials is almost 100 times that of gold. Thus, the productivity from such by-product sources is linked to the main metal production and may be assessed as a certain ratio to it; usually this may be taken as about 10 percent of the tin and 50 to 100 times the gold.

25 Houk, L. G., Monazite sand: U. S. Bur. Mines, Inf. Circ. 7233, p. 9, 1943. Reed, J. C., Geology and ore deposits of the Warren Mining District, Idaho County, Idaho: Idaho Bur. Mines and Geol. Pamph. 45, 1937.

26 Houk, L. G., op. cit. Anonymous, Occurrence of monazite in the tin-bearing alluvium of the Malay Peninsula: Bull. Imp. Inst., vol. 4, pp. 301–309, 1906. Amang from the Federated Malay States: Bull. Imp. Inst., vol. 9, pp. 99–102, 1911. Johnstone, S. J., Monazite from some new localities: Chem. Ind. Jour., vol. 33, pp. 55–59, 1914.

27 Anonymous, Monazite in the Federated Malay States: Bull. Imp. Inst., vol. 4, pp. 301–309, 1906. Johnstone, S. J., op. cit.

28 Tripper, G. H., The monazite sands of Travancore: India Geol. Survey Rec., vol. 44, pp. 186–196, 1914. Krusch, P., Die metallischen Rohstoffe, ihre lagerungsverhaltnisse und ihre Wirtschaftliche Bedeutung, Heft 2, pp. 65–87, Ferdinand Enke, Stuttgart, 1938.

29 Leonardos, O. H., Monazito no Estado da Bahia: Mineracao e Metallurgia, no. 8, 1937. Borges, D. B., Areias monaziticas do Espirito Santo: Mineracao e Metallurgia, II, vol. 7, pp. 66–67, Rio de Janeiro, 1937.

30 Tripper, G. H., op. cit.

The resources of the beach placers may be assessed from the area of the placer, the thickness of the concentrate layer, and the average content of monazite in the enriched sand. A concentrate of 1 percent content, one centimeter thick of one square kilometer area, contains 200 metric tons of monazite. Concentrations of 3 percent monazite are rare or are for small areas only. Thickness of half a meter are likewise unusual. From this it is evident that 1,500 tons of ThO_2 represents a very excellent and unusual beach. Hess points out that monazite usually has about 0.2% U_3O_8 [31] and is a source for both radioactive elements.

The Carnotite-Bearing Sandstones.—The carnotite-bearing sandstone type of deposit has a variety of uranium-bearing minerals in which vanadates predominate. Autunite,[32] carnotite,[33] tyuyamunite,[34] and dakeite or schroeckingerite [35] have been recognized. As a group the deposits are in permeable quartz sandstones and are not known in highly feldspathic sandstones or graywackes. They appear generally only slightly above a clay or bentonite zone which has a restraining influence on groundwater movement. The rocks are mostly alkaline or nearly alkaline and have calcite or siderite cement; less commonly gypsum is present. Occurrences are confined mostly to a very limited stratum in any region so that favorable structures in higher or lower strata rarely contain deposits. Nearby but structurally separate regions may have deposits in a higher or lower stratum. Traces of uranium and vanadium minerals appear throughout much of the propitious geological stratum but rich concentrations occur only on and near rolls. These are concretionlike structures, in places over 100 feet long and 10 feet thickness and sustain economic production.

The carnotite-bearing sandstone type of deposit is known only in strata formed in a steppe climate. The most probable source, for uranium gathered to the "concretions" by groundwater, seems to be low grade caliche accumulations. Such a carnotite type region probably has only 10 to 20 metric tons of U_3O_8 per square mile. No assessment of the proportion which may be concentrated into rolls, and is recoverable, has been made but it is unlikely from present evidence that over 10 percent or 2 tons per square mile is so concentrated.

The assessment of carnotite possibilities is based upon the distribution of sandstone strata deposited in a steppe climate. Furthermore, these strata require some clays to confine the groundwater circulation and some structures to guide the water into channels. These conditions are encountered at a number of places where carnotite is unknown and at all places where it has been recognized. On the average, 2 tons of concentrated U_3O_8 per square mile of a carnotite province is as close as can be guessed now. The type is known in the Colorado River Plateau, the Ferghana Basin, a small stratigraphic level in the

[31] Hess, F. L., Industrial minerals and rocks, pp. 524, Am. Inst. Min. Met. Engs., New York, 1937.

[32] Lacroix, A., Acad. Sci. Paris Comptes rendus, vol. 152, p. 559, 1911, quoted in Min. Jour., p. 430, London, May 4, 1912.

[33] Stokes, W. L., Morrison formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., vol. 55, pp. 974–975, 1944.

[34] Popov, V. I., On the discovery of analogies of the carnotite sandstones: Sovietskaya Geologiya, vol. 9, nos. 4–5, pp. 32–39, Moscow, 1939.

[35] Larsen, E. S. Jr., and Gonyer, F. A., Dakeite, a new uranium mineral from Wyoming: Am. Mineralogist, vol. 22, pp. 561–563, 1937.

Australian geosyncline, a thin zone in the Karroo beds of South Africa, and in a small part of the Mauch Chunk series in Pennsylvania.

The Oxidized Secondary Deposits.

The oxidized secondary deposits are conspicuous because of the bright, almost gaudy color of their minerals. Yellow, orange, and brown are the prevailing colors but a few are bright green. Generally these minerals form a film, which is thinner than a coat of paint, and the deposits always look higher grade than they assay. The minerals are mostly phosphates but the list includes also silicates, vanadates, oxides and hydrated oxides. A few oxidized deposits are produced in situ; enrichment is inconsequential and equally good primary ores may be expected at depth. Most oxidized ores have moved in solution some distance away from their source, generally downward, and have been precipitated where they encountered an alkaline rock or soil zone. Less often the solutions migrated far afield to a playa or a caliche slope before encountering an alkaline environment which removed their uranium.

The deposits rarely contain over 0.25% U_3O_8 where they are removed from their source and in these, phosphates and vanadates predominate. Deposits formed almost in situ may have phosphates and vanadates but mostly are oxides, hydroxides, hydrated oxides and silicates and may be higher grade due to high content in the protore. Highest content is generally near the surface where leaching has been moderate; where leaching has been intense and oxidation deep, highest content is expected near the watertable or even below it.

Oxidation in Situ.—The great variety of minerals from the Shinkolobwe open pit represent oxidized deposits with the uranium fixed almost at its point of origin. Many high grade oxidized minerals from this deposit have enough of the outline of the primary source minerals left to indicate little loss on the one hand or enrichment on the other. This zone extends down to below the 50-meter level where primary minerals appear and to about where the watertable stands at the end of the dry season. Specimens of autunite and uranocircite are plentiful along joints in most pegmatites of the New England (U. S. A.) region and these minerals are believed to have formed from local materials. Pegmatites containing them have only the usual 0.01% U_3O_8 and show no enrichment. Climate seems to have very little effect upon formation of these minerals in this type of deposit. The primary ore exerts the entire control over extent and grade of the deposit.

Concentrations in Adjacent Rocks.—The uranium of most oxidized minerals has moved some distance away from its source. The source rock can be identified in many places but in a few origin is implied only by similarity with recognized occurrences; the host structures are clear but the source is gone.

Uranium in the numerous deposits of the Ferghana region seems to have come from a Cambrian or a Silurian black shale, to have moved slight but variable distance, and to have been precipitated in a variety of ways to acquire its present position. The Karatau deposit follows a 10- to 14-m siliceous black shale zone for 25 to 35 kilometers.[36] The tyuyamunite and metatorbernite are

36 Tyurin, B. A., Karatausskoye mestorozhdenie urano-vanadisvikh Rud: Izvestiya Acad. Nauk, S.S.S.R., Seriya Geologicheskaya, no. 2, pp. 99–106, 1944.

in fissure zones localized by fold structures in the formation. Dolomite and marble are interstratified with the black shale and the ores are confined fairly close to the source stratum. Tyuya Muyun lies 600 km to southeastward and is in a limestone karst with the cavern pattern determined by a systematic fracture system in the limestone. The secondary ores were deposited in this karst and are still being deposited by percolating water.[37] The karst deposits end at 170 meters depth. Fersman considered the uranium and vanadium to be leached from the older "schist" (?) formation. The other vanadium deposits of the range are strung out parallel to the strike of the rocks in the range and support derivation from a single parent formation. Whether this is the Cambrian shale of the Karatau or the upper Silurian graptolite shale of the Alai Range is indeterminate from the literature. Only a thin film of ore marble coats the joints below the karst zone and even it disappears at 20 m greater depth or is not obvious. This would give the general impression that, except under unusual conditions favoring deep penetration of groundwater, 20 m depth range for oxidized ore is all that can be expected. The ore marble of the karst, which is all that is considered ore, constitutes about 15 percent of the deposit and averages 1.6% U_3O_8 to give the entire mass about 0.25% U_3O_8.

The Urgeirica deposit in Portugal [38] is in a quartz vein; it has the usual 20 m oxidized zone but below this the fractured quartz is coated with films of a black oxide and some yellow autunite and green torbernite. Some ore is said to assay 2.4 percent but it is uncertain whether this is run-of-mine or hand-dressed ore. However, as at Tyuya Muyun, enrichment by torbernite and black oxide films extends to considerable depth and the uranium seems to have originated in denuded parts of the quartz lode as well as in the part remaining. No obvious source for the uranium appears at most Guarda and Belmonte deposits which are films of autunite and torbernite extending along joints to the depth of 20 m or less. Content of a deposit rarely is 0.25% U_3O_8 and tonnage produced at the height of the radium business was only a few tons. In most instances the source rock for these oxidized deposits, except at Urgeirica and Rosmaneira has been denuded completely. Not even specimens can be expected below the present oxidized zone where the openings close up.

The Bukhova, Bulgaria, deposit [39] represents a stage once removed from the above. Autunite and metatorbernite occur with limonite in a breccia zone through quartzite (?). Hand-dressing of the ore raises the average content from about 0.2 to 2 percent U_3O_8. The origin of the uranium is not recognized but the general mode of occurrence suggests downward leaching from bituminous shale.

Caliche Type of Deposit.—The schroeckingerite or dakeite locality at Wamsutter in Wyoming has very little of the mineral sparsely distributed through a gypsiferous and calcareous sand. The percent content in a thin bed probably

[37] Fersman, A., op. cit.

[38] Segaud and Humery, Gisements d'uranium du Portugal: Annales des mines, Paris, 11th ser., vol. 3, pp. 111–118, 1913.

Lepierre, C. and Leite, A. P., L'industrie du radium au Portugal: Chimie et ing., vol. 29, pp. 797–804, 1933.

[39] Konjarov, G., Die uranerzlagerstatte auf dem Gipfel Goten: Podz bogat i min. industr., pp. 236–244, Bulgaria, Sofia. Trudy 8, 1938. Kostov, I., Metallization of the Balkan Peninsula: Mining Mag., vol. 68, pp. 261–274, London, 1943.

does not average over 0.001 percent (20 tons per mile foot). This deposit formed in a region of steppe climate and where highly alkaline soils would precipitate the uranium from groundwater.[40] It will be extraordinary, if other such occurrences containing schroeckingerite, tyuyamunite or autunite, are not discovered in regions of steppe and desert climate because of the close proximity of the above content to that of the average sandstone.[41] Such types of occurrence may be the direct source for the carnotite in the carnotite-bearing sandstones.[42] This is the lowest content type of deposit and it may have no economic significance; however it probably has a very important bearing upon the origin of carnotite-bearing sandstones and upon the evaluation of carnotite deposits.

Summary of Deposit Characteristics.

Deposits are not evaluated directly by geographic areas. To obtain an assessment of an area, the potential resources for each type of deposit possible in it must be assessed separately. This can be done with some assurance of dependability on the basis of geologic characteristics. But rules of amount that apply to one type of deposit do not fit another and assessment by geographic areas, without regard for geologic controls, causes almost infinite confusion of results. The assessment for a geographic area becomes the sum of the potential of all geologic types of deposits.

Primary Deposits.—Significant primary deposits are confined to those crystalline, structural elements of the earth having strongly positive character and equidimensional form. Less than one percent of the land area where metalliferous lodes might be expected, conforms to this requirement. Here over 95 percent of the favorable potential area has pegmatite-type mineralization which is antipathetic to rich lode deposits. Thus, only 0.05 percent of the mineralized areas of the world deserve organized investigation for lodes with uranium. Furthermore such regions have little hope of producing from other than vein deposits, except as a by-product. Pegmatites at best average only 0.01% U_3O_8; by-product from mining 200,000 tons of pegmatite, which is a large amount for any country, would be less than 20 tons U_3O_8. For this reason pegmatites are no longer considered a source for industrial uranium. Lode districts yield about 1 ton of U_3O_8 per meter of depth from ore averaging about 1% U_3O_8; but these values are tied to width of lode and are for one foot veins or breccias with one foot openings at least locally. Two-foot or wider openings may have 12% U_3O_8 and the deposits may yield 25 tons upwards per meter of depth whereas 2-inch veins commonly have only tenths of a percent U_3O_8 and the systems carry only hundredths of a ton per meter of depth.

Up to the present only four parts of the margin of the Canadian Shield have exhibited favorable mineralization features and only one part of the Rhodesian Shield seems suited to mesothermal lodes. No part of the Scandinavian Shield

40 Larsen, E. S., and Gonyer, F. A., Dakeite, a new uranium mineral from Wyoming: Am. Mineralogist, vol. 22, pp. 1004–1005, 1937.

41 Goodman, C., and Evans, R. D., Radioactivity of rocks: Geol. Soc. America Bull., vol. 52, pp. 459–490, 1941.

42 Stokes, W. L., Morrison formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., vol. 55, pp. 974–975, 1944.

is known to be auspicious. Lode possibilities are recognized in four massifs (Fig. 1). The total supply from these favorable areas is probably under 30,000 tons of U_3O_8 of which between 5,000 and 10,000 tons has been produced already.

Sedimentary Secondary Deposits.—The sedimentary secondary deposits are evaluated principally on the basis of area. Placers are assessed upon the basis of gold and tin production from alluvial deposits and are given as a definite ratio to those other metals.

The bituminous shales average about 0.01% U_3O_8 for 5 m thickness; a few are 15 m thick and have 0.025% U_3O_8 but they are unusual. The average shales have 1,125 metric tons per square kilometer. Sweden, Russia, and the United States have about 2,000 square kilometers or more which may be assessed at 2,250,000 metric tons of contained U_3O_8. Petroleum source rocks elsewhere may double this value and the phosphorite shales increase it by an equal amount.

The protore of the carnotites is estimated at about 20 tons of U_3O_8 per square mile of area. Assuming that under favorable conditions 10 percent of this material is concentrated into structures where it is recoverable, each square mile of carnotite province can be expected to yield about 2 tons of U_3O_8. The United States and Russia have over 20,000 square miles of potential carnotite area so that 40,000 tons of U_3O_8 would not be too much to expect if the concentrating structures can be located.

The placer deposits of uranium and thorium are partly from the well known beaches where the monazite is about 1/10th as abundant as ilmenite, and mainly from precious metal and cassiterite placers. The beach deposits can be assessed easily. The gold placers have about 100 times the monazite that they have gold, and the cassiterite and monazite are about equally abundant. However only about 10 percent of this monazite is believed to be recoverable and production can be guessed at fairly closely. Tin production at 180,000 tons could yield at least 18,000 tons of monazite with 50 tons of U_3O_8 and 1,000 tons ThO_2. Alluvial gold including the Witwatersrand, could be expected to contribute at least 4,000 tons of U_3O_8 and 200 tons of ThO_2. This yield would be a sustained annual by-product and is exclusive of the direct output from beach sand and lode deposits. Principal alluvial deposits are in the tropics where rock decay exceeds rock granulation as a disintegration process.

Oxidized Secondary Deposits.—The only economically significant ore deposits of this sort are limited in size by the extent of the source rock that has been worked over. Except in the case of the lode deposits this is usually an inconsequential total amount. Depth rarely exceeds 20 meters. Furthermore grade does not seem to be raised above 0.25% U_3O_8. Where the original material was above this content, the grade change is negligible and generally downward.

Oxidized ores are known in France, Portugal, Bulgaria, Ferghana, Australia, and the United States. In view of the low grade and characteristic shallow depth, it is improbable that these deposits can furnish 1,000 tons of U_3O_8 which is relatively insignificant.

RESOURCES OF PRODUCING COUNTRIES.

Major attention and almost the sole interest has been in capacity of the past producers of uranium including the Belgian Congo, Canada, United States, Czechoslovakia, England (Cornwall), Portugal, Russia and Madagascar. These countries obviously have uranium; however the outstanding features of distribution and continuity to deposits obviously suggest that the well known ones have limitations and will be unable to satisfy industrial requirements. Their diminishing supply must be augmented by production from other types which have been mentioned but about which little has been done. Such occurrences range from the extensive sediments in Sweden to the small oxidized deposits in Bulgaria. In the even less known class are the many oil shale source rocks and phosphorites throughout the world, the green alluvial diamond occurrences indicating radiation from ore with more than 0.01% U_3O_8 content, and gold, gem, and cassiterite alluvials which have been reported to contain uranium minerals.

TABLE 1

PRODUCTION IN METRIC TONS

Country	U_3O_8	Monazite	U_3O_8*
Congo Belge	4,442	?	25,000
Canada	1,440	—	2,100
U. S. A.	1,200	5,443	28,100
U. S. S. R.	72 (?)	—	900
England	300	—	?
Portugal	250	—	400
Madagascar	18	?	1,250
Australia	5	?	50
Brazil	?	72,000	?
India	?	45,000	200
Ceylon	?	852	—
Neth. E. Indies	—	1,570	—
Malaya	—	?	—
Other S. E. Asia	?	?	—
Bulgaria	?	—	60
Un. S. Afr.	—	—	?
Sweden	?	—	?

* Probable and possible ore of the approximate type and grade which has been mined previous to the present time.

Monazite, containing thorium, has been produced from the ilmenite beach sands of Brazil, India, Ceylon and Australia and the cassiterite alluvials of the Netherlands East Indies. It has been reported in considerable amount in the preliminary cassiterite concentrate in Malaya, the gold concentrates of Idaho and far eastern Russia, and is known in lower proportions at many other places. Almost all gold dredging operations, which have been studied mineralogically, report some monazite and these deserve serious consideration wherever the detritus comes from crystalline rock areas. Of lesser immediate significance are those regions where monazite is reported from the crystalline rocks, but has not been listed in large amount in the detritus from them. These latter include placer mining communities in Madagascar,[43] Tanganyika,[44] Kenya,[45] the entire Nile drainage,[46] the Belgian Congo, southwest Africa,[47] the Guianas, and Colombia in the tropics, and Japan, Korea, Alaska, California and New Zealand in extratropical regions.[48]

Production.

Previous to 1940, the world is known to have produced slightly more than 7,500 tons of uranium or its equivalent, indicated directly, or by radium statistics. Production is distributed as listed in Table I. Where radium statistics are available but data on uranium is lacking, calculations assume 75 percent recovery of radium from the uranium delivered at the plant. Joachimsthal was the earliest contributor; the Belgian Congo was the largest.

The Belgian Congo.

The writer visited Katanga during a pre-war geological excursion through Africa and enjoyed the privilege of studying mineralization of this interesting region. The regional geology has been outlined [49] and the principal features around Shinkolobwe have been described.[50] The ores are limited to the predominantly dolomitic Mines Series and appear in zones of prominent fissuring. Even the copper mineralization of the Rhodesia-Congo border is itself profoundly, but not critically, influenced by fractures. Thoreau indicates great diminution in grade wherever the veins pass laterally or downward into less favorable members of the Mines Series. Such a condition is anticipated from experience elsewhere and barren levels may be expected within the possible 500-m depth range or maximum usually expectable for this type of deposit. Production previous to 1940 was slightly over 75 metric tons per meter of depth for the block mined out.

The mesothermal type of mineralization having uraninite appears in Katanga along an east-west zone from Luiswishi to Kalongwe.[51] Museum collections list minerals from at least thirteen other localities but only Kalongwe and Shinkolobwe have veins of significant width.[52] Some occurrences may be to Shinkolobwe what Johanngeorgenstadt in the Erzgebirge is to Joachimsthal.

43 Besairie, H., La géologie du Nord-Ouest (Madagascar): Mem. Acad. Malgache, vol. 21, 259 pp., 1936.

44 Krenkel, E., Geologie Africas, Pt. 1, p. 413, Berlin, 1928.

45 Anonymous, Min. Jour., vol. 179, p. 826, London, 1932.

46 Anonymous, Minerals Yearbook for 1944, U. S. Bur. Mines, p. 866, 1945.

47 Hintze, C., Handbuch der Mineralogie, vol. 1, pt. 4, p. 344, 1933.

48 The Rupununi district: British Guiana Geol. Survey Bull. 13, 1937 (1939). Hintze, C., Handbuch der Mineralogie, vol. 1, pt. 4, p. 344, Berlin, 1933.

49 Robert, M., and du Trieu de Terdonck, R., Le bassin cuprifère du Katanga méridional: Copper resources of the world, pp. 703–715, XVI, Inter. Geol. Cong., Washington, 1935.

50 Thoreau, J., and du Trieu de Terdonck, R., Concentrations uranifères du Katanga (Congo Belge), XVI Inter. Geol. Cong. Rept., pp. 1099–1101, 1933. Le gîte d'uranium de Shinkolobwe-Kasolo (Katanga): Inst. Colonial Belge, Sec. sci. nat. et méd. Mém., tome 1, fasc. 8, 1933.

51 Mineral Industry in 1932, p. 464, McGraw-Hill Book Co., New York, 1933.

52 The author would acknowledge the rare privileges, the thought, and the courtesy extended by the officials of the Union Minière du haut Katanga which made the study inclusive and enjoyable. Drs. Schuiling and Vaes spared no effort to present the geological features of this interesting region; however the views here expressed are not necessarily theirs and are merely the author's interpretation of the evidence as he saw it.

Considering the record for all deposits of this type and their characteristics, it appears likely that Shinkolobwe is the "big master" and will have 5/8ths of the U_3O_8 for the district.[53]

Pegmatites with refractory uranium minerals are known at Kiambi and also in the Uganda Highlands just outside the Congo. Lode deposits with uranium should not be expected among the pegmatites of these northern massifs and this outside area is not a potential source for significant U_3O_8.

No marine bituminous shales are known in the Congo and steppe climate deposits, even in the Karroo beds, are not recognized and carnotite deposits are not expected. Modern placers are worked for gold in the Butembo Highlands and for cassiterite at Mitwaba west of Lake Tanganyika. Ancient placers in the Kasai have diamonds; monazite is recognized but no uranium minerals have been identified with them.

The surrounding regions of Portuguese West Africa and Northern Rhodesia have fracture filling mineralization and lie close enough to the Shinkolobwe zone to be interesting for speculation. But most of Northern Rhodesia is too far inside the Rhodesian Shield to be potential ground. Portuguese West Africa has a small area of Katanga type mineralization near the Rhodesia-Congo border and also a coastal sandstone strip suitable for carnotite sandstone type mineralization. However descriptions of both locations fail to mention at least one essential feature for that type of deposit which might occur there.

Canada.

Canada has all three classes of ore occurrence. Primary ores appear on the Shield rim in lodes in the Great Bear Lake and Lake Athabaska districts, and in pegmatites in the Ontario-Quebec section.[54] Sedimentary occurrences are represented by the anthraxolite of the Onwatin slate and possibly some petroleum source rocks. Even the monazite-bearing gold placers of the Yukon have possible although uncertain value. Oxidized ores are represented by a single locality on Quadra Island, B. C.[55] Great Bear Lake has been the only significant producer although an attempt was made to operate a fluorite-bearing pegmatite at Wilberforce, Ontario. Estimates based upon scattered data suggest that ore shipped from the Eldorado Mine up to the end of 1939 produced about 310 grams of radium. Applying the data given by Lord [56] for a specific period to the general production and shipments, the deposit may be expected to have yielded by 1940 about 347 grams of radium at 75 percent recovery. This is equivalent to about 1,400 tons U_3O_8 in concentrates arriving at Port Hope.

53 See data on Joachimsthal and the general quantitative zonal diminution of uranium mineralization away from the main center. Less data is available on Great Bear Lake but there too the abundance seems to be distinctly concentrated at the main center.

54 Ellsworth, H. V., Rare element minerals of Canada: Canada Geol. Survey, Econ. Geol. Ser. no. 11, 1932. For a recent summary see: James. W. F., Lang, A. H., Murphy, R., and Kesten, S. N., Canadian deposits of uranium and thorium: A. I. M. E., Mining Engineering, vol. 187, pp. 239–255, 1950.

55 Mineral Industry for 1932, p. 465, McGraw-Hill Book Co., New York, 1933. Ellsworth, H. V., op. cit., p. 139.

56 Lord, C. S., Mineral Industry of the Northwest Territories: Canada Geol. Survey Mem. 230, pp. 38–47, 1941. Minerals Yearbook for 1940, U. S. Bur. Mines, p. 765, 1941. Minerals Yearbook for 1941, U. S. Bur. Mines, 1942. Mineral Industry for 1941, p. 487, McGraw-Hill Book Co., New York, 1942.

The four Eldorado veins are in shear zones cutting through an ancient series of sediments and volcanics which are intruded by diabase, feldspar porphyry and granite. The veins cut across the older diabase and the feldspar porphyry but the relations to the granite are not clear. The porphyry follows below the sediments and above the volcanics and has a synclinal shape; the bottom of the trough was expected to be near the 650 level.[57] Most of the ore shoots end where the strike of the lode zone carries it laterally out of the syncline of sediments, and almost the same change is expected to occur at depth. The ore shoots in No. 2 vein, and principal producer, appear to have been influenced by the character of the wallrock or by the change in strike of the shear zone or both. The wallrock influence is in complete accord with the behavior of this type of deposit everywhere else.

Bodies of pitchblende in No. 2 vein are up to 20 inches wide and 40 feet long but most occurrences are much smaller. The entire shear zone is 2,100 feet long and 1 to 30 feet wide (average 5 feet) and is a stockwork. Pitchblende appeared over 1,200 feet length on the surface but was mined over only 500 feet at the adit level and 220 feet on the 500-foot level. The shoots pitch 60° westward. Another shoot appears at about 1,000 feet eastward and extends down to the 800-foot level.

No. 1 vein is at least 1,500 feet long and may be over 3,000 feet; it is 5 to 30 feet wide (average 8 feet). An ore shoot 80 to 150 feet long pitches 65° westward through to the 500-foot level.

No. 3 vein is 700 feet long and is 1 to 12 feet wide (average 3 feet). It has one recognized ore shoot.

If the Eldorado Mine is likened to Joachimsthal, then the BEAR at Contact Lake is like Johanngeorgenstadt. At BEAR three stockwork veins are in granodiorite. The veinlets in the stockworks are usually one-half inch wide but a few are up to two feet. The pitchblende shoots were up to six inches and may have averaged 1.5 inches and the shoots were definitely where the fractures were widest.[58] Nine shoots were mined and their length—only 25 to 75 feet—exceeded their depth.

Pitchblende occurrences are listed by Joliffe [59] at Beaverlodge and Hardisty Lakes on the overland route from Great Slave Lake to Great Bear Lake.

A small area near Goldfields on the north shore of Lake Athabaska has two narrow mesothermal pitchblende veins.[60] The limited width gives the known occurrences inconsequential productivity.

The only other areas are at Silver Islet and near Batchewana Bay in Lake Superior and a possibility on theoretical grounds in the Baffin Strait area on the other side of the Shield. Elsewhere pegmatites or hypothermal lodes characterize mineralization on the Shield perimeter and these are incompatible with important uranium producers.

57 Lord, C. S., op. cit., p. 45.

58 Furnival, G. M., A silver-pitchblende deposit at Contact Lake, Great Bear Lake area, Canada: Econ. Geol., vol. 34, p. 764, 1939.

59 Joliffe, A. W., The Northwest Territories: Canadian Inst. Min. Metallurgy Bull., vol. 40, pp. 663–677, 1937.

60 Alcock, F. J., Geology of the Lake Athabaska Region: Canada Geol. Survey Mem. 196, pp. 36–37, 1936.

Canada has a number of important petroleum source rocks but the uranium content of these does not appear in the literature. Yagoda reports anthraxolite in the same category as kolm.[61] Anthraxolite is known in the 8 by 29 mile Onwatin Slate area (600 square kilometers) of the Sudbury basin, Ontario [62] and in the Animikie strata in the area northwest of Lake Superior. Some Onwatin slate zones have up to 10 percent carbon and on theoretical grounds there is reason to believe that some part may be equal to the alum shales of Sweden.

No data are available on the amount of monazite present in the Yukon alluvials.

The only record of oxidized ores is in Quadra Island and the amount seems to be altogether inconsequential.

An assessment of the Canadian lode resources indicates that new deposits, comparable in size and richness to those which have been worked, should not be expected on the west or south side of the Shield. Some may be found on the little explored northeastern edge. The Onwatin slate certainly has uraniferous anthraxolite and it seems very probable that the carbon rich groups of beds will have over 0.01% U_3O_8. It is perhaps too early to speculate upon the importance of this occurrence but it may become Canada's principal future supply. It is assessed at possibly 10,000 tons U_3O_8.

Czechoslovakia and the Erzgebirge.

Pitchblende and its decay products were recognized in the Erzgebirge early in the past century and they were mined for industrial consumption after 1850. Czechoslovakia celebrated the production of the 100th gram [63] of radium in 1936 and at 75 percent recovery this would represent 400 tons of U_3O_8. Production was then at the rate of about 15 metric tons U_3O_8 annually so that total production up to 1940 may have been almost 450 tons U_3O_8. Saxony produced about 120 tons of U_3O_8 from all operations and Bavaria and other parts of Bohemia may have yielded another 120 tons.

Geographically the Erzgebirge localities lie along two zones which intersect at Joachimsthal. One zone extends approximately N-S from Freiberg through Marienberg, Annaberg, Niederschlag, Joachimsthal, Schlaggenwald, St. Viti and Hagendorf to Wolsendorf. The northwestern end of the other is Schneeberg and it extends through Johanngeorgenstadt to beyond Joachimsthal. Generally the ore veins are in the Precambrian schists and Cambrian phyllites and cease to be mineralized where they enter the granite; however they have pitchblende even through the granite in the Weisser-Hirsch mine at Schneeberg.[64] The principal mineralization is in the major fractures and di-

[61] Yagoda, H., The localization of uranium and thorium minerals in polished section. Pt. 1, The alpha ray emission pattern: Am. Mineralogist, vol. 31, p. 120, 1946.

[62] Coleman, A. P., The anthraxolite of Sudbury: Am. Jour. Sci., ser. 5, vol. 15, pp. 25–27, 1928.

[63] Presumably this was only the theoretical 100th gram because radium was not saved until a very late date in the history of this region. Production since radium was discovered has been adequate to yield only about 40 grams and all older uranium was dissipated and with it the contained radium.

[64] Beyschlag, F., Vogt, J. H. L., and Krusch, P., Ore Deposits, vol. 2, pp. 680–681, MacMillan and Co., London, 1916.

minishes as the fractures become narrower; some pitchblende follows microfractures in the schists of the Weisser-Hirsch Mine in Schneeberg, at Johanngeorgenstadt and also at Joachimsthal; the granite walls of the fluorite veins at Wolsendorf carry pitchblende. According to Babanek[65] the scapolite schist wallrock in the eastern part of the Joachimsthal district averages 0.265% U_3O_8. While Krusch estimates the average uranium content of the veins at about 1% U_3O_8,[66] records show only the Schweizer vein has ore of 1 percent grade and that the average is about 0.2 percent.

Joachimsthal.—The favorable host rock for the Joachimsthal lodes is a series of schistose Precambrian age sediments. A late Paleozoic age granite stock forms their southern border. Schist in the immediate environs of the Ur limestone seems to be the most favorable area for pitchblende. Trends to veins have been mentioned. The E-W or Morning veins are narrow, rarely one foot thick, and only in recent years have yielded any pitchblende. The N-S or Midnight veins are up to a meter wide (mostly 0.1 to 0.5 m) and have yielded almost the entire mineral production. A thin layer of quartz covers the walls at some places. This is followed by successive depositions of dolomite and lenses of pitchblende, with dolomite and arsenides occupying the central section. The calcite and dolomite are reddish brown near the uraninite. The principal Midnight veins from west to east are the Geister, Schweizer, Johann Evangelistas, Hillebrande, Prokopi, and Goldene Rose in the Joachimsthal group and the Gluckauf and Francisci in the Edelleutstollen group. The mine plans of Kraus[67] show pitchblende mineralization predominant in the zone between the thick limestone and the top of the Ur limestone zone. The detailed cross sections on the plane of the Johann Evangelistas vein and the Hillebrande vein show silver and cobalt minerals in greater relative abundance where the veins on each individual level pass northward out of the Ur limestone zone. Since schists overhang the Ur limestone, the silver-cobalt mineralization appears above the pitchblende in any vertical section. This latter spatial arrangement has been attributed to thermal or depth zoning. Actually careful scrutiny of Kraus's sections shows that the depth association is inapplicable and any mineral appears at any depth but uranium exhibits strong wallrock preference which is in turn related to width of openings. Kohl[68] states that the veins in the Edelleut Mine pass into granite at 200 m depth at its eastern end which is about the greatest depth attained in this particular part of the mining district. This is considered to indicate that the granite was unfavorable wallrock.

Kraus[69] gives the average yield of the mine stopes between the years 1897–1913 as follows:

[65] Babanek, F., Beschreibung der geologisch-bergmannischen Verhaltnisse der Joachimsthaler Erzlagerstatten in geologisch-bergmannische Karte mit profilen von Joachimsthal: U. S. W., Vienna, 1891. Die uranhaltigen skapolith-glimmerschiefer von Joachimsthal: Oesterr. Zeitschr. Berg- u. Hüttenwessen, vol. 37, pp. 343–345, 1889.

[66] Krusch, P., Die metallischen Rohstoffe, ihre Lager Verhaltnisse, vol. 1, pp. 104–108, Ferdinand Enke, Stuttgart, 1937.

[67] Kraus, M., Das staatliche Uranpecherz-Bergbaurevier bei St. Joachimsthal in Bohmen: Bergbau und Hutte, vol. 1, pp. 3–30, 45–63, 93–112, 128–148, 168–183, Vienna, 1915.

[68] Kohl, E., Grossdeutschlands Vorkommen naturlich-radioaktiver Stoffe und deren Bedeutung fur die Versorgung mit radioactiven substanzen: Zeitschr. Berg-, Hütten- u. Salinenwesen in Deutschen Reich, vol. 90, pp. 153–178, Berlin, 1942.

[69] Kraus, M., op. cit.

TABLE 2

YIELD FROM VARIOUS VEINS

Vein	Kgs/sq. meter	Kgs/cu. meter	% appr.	Mining width
Schweizer	53.42	40.33	1.61	1.33
Jungschweizer	2.23	1.67	.07	1.33
Bergkittler	4.73	3.48	.14	1.37
Geister	19.16	14.82	.60	1.29
Geister-hangingwall split	19.26	14.82	.60	1.30
Geister-footwall split	11.75	9.15	.37	1.28
Widersinniger	0.42	0.30	.012	1.33
Roter, S. of Kuh vein	4.16	2.87	.115	1.45
Radium	5.83	4.14	.165	1.40
Western mines (1926)	0.40	3.2	.128	.125*

Only the amount hoisted is included.
* Apparently hand dressing was practised underground.

The percent grade, except in the rich Schweizer and Geister veins, seems to be about 0.2% U_3O_8. The scapolite wallrocks of the Edelleut Mine are estimated to contain 0.265% U_3O_8 or 6.6 kgs per cubic meter. Kraus states that the pitchblende content of vein matter broken in the Edelleut Mine was as follows:

TABLE 3

KILOGRAMS PER CUBIC METER

Year	Gluckauf vein	Francisci vein	Zeidler vein	Parallel vein	New vein
1912	12.25	4.30	146.18	—	55.51
1913	79.10	60.60	2.60	270.3	82.60

Schneeberg.—Schneeberg occupies a major structural position very similar to Joachimsthal. Production has been about 80 tons of pitchblende. Cambrian micaceous phyllite lies along the northeast side of the Eibenstock granite at Schneeberg and Neustadtel. Intrusive granite is encountered at depth in all of the mines and according to Becke [70] the veins usually become poor or unmineralized where they pass into it. Muller [71] indicates that the mineralized area extends over 10 square kilometers. The veins generally strike W.N.W. or N.N.W. and dip steeply. However they are so numerous that they may be described as a stockwork. Width varies between 0.5 and 3 meters. A few are up to 3 km long and extend to 300 m depth. Only the strong cobalt bearing veins in the Weisser-Hirsch Mine, that also have uranium ore, persist down into the granite. These strong veins, particularly the Katerina-Flacen lode, had minor mineralization on microfractures in the wallrock.

Johanngeorgenstadt.—Johanngeorgenstadt is midway between Schneeberg and Joachimsthal. The general geological features are identical with those at Schneeberg. Production has been about 12 tons. The strongest uraninite vein

70 Becke, F., and Step, J., Das Vorkommen des Uranpecherzes zu St. Joachimsthal: Akad Wiss Wien, vol. 103, pt. 1, 1904.

71 Muller, H., Der erzdistrict von Schneeberg in Ergebirge, *in* B. von Cotta, Gangstudien, vol. 3, 1860.

is in the Vereinigt Mine in the Fastenberg. Maximum yield in any one year was 2.7 metric tons in 1905.

Durrnaul.—Another occurrence is at Durrnaul near Marienbad far to the south of Joachimsthal. One vein in the St. Viti Mine is reported to have had a shoot with 100 to 150 tons of pitchblende. The uranium mineralization of the veins is concentrated into the contact zone between the Konigswart-Kuttenplaner granite and the crystalline schists.

Other Occurrences.—Freiberg is said to have produced 10 tons of U_3O_8. The pitchblende occurs in association with silver ores in cobalt-bearing fissure veins through metamorphosed sediments overlying a granite and gneiss dome. The Schmideberg occurrences are where the younger ore veins intersect massive magnetite deposits along the contact between sediments and intrusive granite. The magnetite is changed to martite adjacent to the veins. The Przibram veins cut the Ordovician sediments at or near the contact between graywacke with an overlying slate and occur particularly along the margin of intrusive dikes through the graywacke-sandstone. The Johanni lode has a 2 to 5 cm zone with kidney and hazelnut shaped masses of pitchblende at the footwall.

General Resources of the Erzgebirge.—The entire Erzgebirge region had about 1,000 tons of recoverable U_3O_8 of industrial grade at the start of mining. Exploitation without regard to cost might raise the amount by 50 percent. At least 680 tons had been removed before 1940 and the disposition of the remainder is uncertain. As of 1940, about 50 tons was in tailings, 120 tons was in low grade veins and wallrock at Joachimsthal and 100 tons was in the fluorite veins at Marienbad and Wolsendorf. An additional 70 tons may be in lodes at Schmideberg, Przibram, and other outlying districts. Originally the central area had 5/8ths of the total known uranium and it is expected that, in conformity with other similarities, Shinkolobwe and Eldorado will have similar proportions for their respective districts. Production and reserves amount to 1.2 metric tons per meter depth. The two principal satellite areas furnish only 1/8th the amount of the leading district and the others dropped to 2 percent of the leader. The record for lode deposits suggests, in no uncertain manner, high concentration in a single district.

Czechoslovakia has only minor uraniferous sediments. The possible occurrence in the Cambrian shales is realized but presence in significant amounts is unlikely. Oxidized secondary deposits of size are unknown and almost beyond possibility.

Cornwall, England.

The high temperature lodes around the granites of Cornwall contain small rich shoots of pitchblende. However, like these shoots everywhere, they are short and irregular, spectacular and disappointing. Although the Cornwall ore is believed to have been mined out almost completely, the record is presented to indicate the low significance of other similar deposits that are reported from time to time in the Central Massif of France,[72] the Schwartzwald,[73] in Korea, in Portugal and in other parts of the world where tin and tungsten are associates.

[72] New York Times, January 12, 1947. (Near Limoges.)
[73] Kohl, E., op. cit., p. 157.

MacAllister [74] indicates that the uraniferous veins commonly have some cobalt and nickel and generally are later than the tin-tungsten lodes. The South Terras mine near St. Austell has a lode 2 to 4 feet wide with a uranium stringer from a mere film up to a foot thick along one side. The deposit was about 200 feet deep and 500 feet long and produced about 50 tons of U_3O_8 if the ore value stated is accepted. This is only 0.8 tons per meter of depth and the depth was very limited.

Other mines have contributed to the general production in less amount. Total production from Cornwall is estimated as follows:

1890–1901	287 tons ore	grade about 30% U_3O_8*	86.1 tons
1901–1912	654 tons ore	grade about 30% U_3O_8*	196.2
1914–1917	308 tons ore	grade about 1.06% U_3O_8	3.3
1917–1926	677 tons ore	grade about 2.00% U_3O_8	13.6
			299.2

* Estimated from the sterling value.

Portugal.

The uranium deposits of Portugal are in the triangular area including Vizeu, Guarda and Belmonte and lie within but near the southern edge of the Hercynian granite batholith.[75] The mines produced over 18,000 tons of ore assaying from 1.0 to 1.8% U_3O_8 in the period 1908 to 1940.[76] The major production was from the Urgeirica Mine which attained 150 m depth by 1936. Lepierre [77] recognized autunite to at least 95 m depth and this indicates unusually deep oxidized ore. Duparc [78] indicates that most ore ceases at a relatively barren zone at 20 m below the surface and apparently was impressed by the many autunite deposits along joints in granite at Guarda, Bemdada and Belmonte more than by the large quartz veins like Urgeirica and Rosmaneira. Undoubtedly most production is from oxidized ores but the source for some uranium may have been in denuded lodes and may be present in lesser amount in their deeper parts. However, it is also quite possible that a considerable amount of uranium may have been carried down from denuded strata.

About 10,000 tons of the 18,000 tons listed for Portugal must be attributed to Urgeirica production before 1938. Lepierre showed that the thoroughly decomposed parts of the vein were depleted in sulphides and U_3O_8 in black oxides, but were enriched in autunite. The magnitude of the change decreased with depth and the general tenor of the undecomposed ore (still carrying autunite at 95 m depth) was better. The black oxides were partly soluble in acid (uranic uranium) and partly soluble in alkali (uranous uranium); even the undecom-

74 Hill and MacAllister, The geology of the country around Bodmin and St. Austell: Geol. Survey England and Wales Mem., p. 134, London, 1909. Mineral resources of the United States in 1912: U. S. Bur. Mines, pp. 1023–1026, 1913. Collins, J. H., Observations on some English Mining Regions, pp. 241–244, Plymouth, 1912.

75 Mineral resources of the United States in 1912: U. S. Bur. Mines, pp. 1029–1031, 1913.

76 Compiled from Mineral Industry, Minerals Yearbook, Mineral resources of the U. S., Eng. and Min. Jour., Min. Jour. (London), Statesman's Yearbook.

77 Lepierre, C., and Leite, A. P., L'industrie du radium au Portugal: Chimie et industrie, vol. 29, num. spec. 12, pp. 797–804, June 1933.

78 Duparc, L., Sur les filons et les minéraux radioactifs d'urane du Portugal: Archives Sci. Phys., vol. 5, pp. 79–82, 599, 1923.

posed ore seems to be partly oxidized and enriched by secondary autunite. It is almost certain that all autunite and much of the uranic black oxide will be lacking in depth and the ore grade will decline proportionately.

Segaud and Humery [79] describe the Guarda-Bemdada area. The Rosmaneira Mine employed 600 men in 1912 and developed a quartz vein up to 8 m wide. Ore with 2% U_3O_8 is high grade and 0.3 percent is considered the lower working limit. Total production was 1,900 tons containing 11 tons U_3O_8. The Rosmaneira vein averaged about 0.25% U_3O_8 through barren quartz and ore shoot. Operations stopped at the water table. Rosmaneira may be enriched below the water table after the manner described for Urgeirica by Duparc and in the most optimistic view it cannot be expected to yield more than 150 tons U_3O_8.

All other occurrences described yielded a ton or so of U_3O_8 in low grade autunite ore. Assuming that each of the 90 odd concessions listed furnished on the average one ton of U_3O_8, yield would be only 90 tons and most of this would be expected from a few.

The total production from Portugal is a rather inconsequential amount from the viewpoint of industrial needs or world supply as it appears in the sedimentary occurrences.

United States.

No primary deposits of consequence are known in the United States although veins and by-products from pegmatites have swelled the supply at times. Bituminous and phosphorite shales are known and the alluvial deposits of California, Oregon, Washington, Idaho, Colorado, Florida and the Carolinas all have monazite. Carnotite-bearing sandstones have been the principal source of the United States supply of uranium and radium. Oxidized ores are known in both Arizona and New Mexico but are considered to be inconsequential in the world supply.

United States production of radium is said to be slightly under 300 grams previous to 1934.[80] Between 1934 and 1940, 15,888 tons of carnotite ore yielded about 116 short tons of U_3O_8 and 29.5 grams of radium.[81] From the above it may be inferred that uranium ores mined up to 1940 contained about 1,200 tons of U_3O_8.

Primary Deposits.—Pegmatites and the Cornwall type lodes are recognized in the United States but the content and yield is low. Pegmatites of Mid-Paleozoic age occur in the Appalachian crystallines at least from Newry (Me.) to Mitchell (S.C.). No pegmatite has yielded one ton and the great majority have furnished only museum specimens. Samarskite is the usual mineral. Uraninite-bearing pegmatites are reported from the northwestern Adirondacks [82] but the content is inconsequential. Microlite and other refractory min-

[79] Segaud and Humery, Gisements d'uranium du Portugal: Annales des mines, 11th ser., vol. 3, pp. 111–118, Paris, 1913.

[80] Minerals Yearbook for 1940: U. S. Bur. Mines, p. 766, 1941.

[81] Mineral Industry for 1941, p. 490, Mc-Graw-Hill Book Co., New York, 1942.

[82] Shaub, B. M., Age of the uraninite from the McLear pegmatite near Richville Station, St. Lawrence Co., New York: Am. Mineralogist, vol. 25, pp. 480–487, 1940.

erals are found in the Southern Rocky Mountain Massif as far south as New Mexico.[83]

Vein deposits have yielded only about 20 tons of ore from the mines near Central City and Black Hawk, Colorado.[84] The general occurrence suggests the Cornwall type of lode, with all its attendant irregularities.

The primary deposits cannot be counted upon for any production of consequence. However there is little doubt but that the Southern Rocky Mountains will continue to be the center of inflated rumors like those originating in the Central Massif of France. Other massifs within the Cordilleran Region will add their share, but the total output should not be expected to surpass a few hundred tons.

Sedimentary Secondary Deposits.—The Antrim black shale and the Chattanooga black shale (Woodford shale in Oklahoma) are radioactive everywhere and locally have about 0.01 percent equivalent U_3O_8.[85] Well logs indicate that the radioactive zone is several feet thick but do not show the thickness range of the high U_3O_8 zone. Areal distribution of the radioactive zone is not given but the uniformity for a given stratum in Sweden and Russia suggests that continuity for ten miles radius may be expected. Although study of this type of radioactive rock had been pursued assiduously in Russia and Sweden, American interest in it appeared only in 1940. Consequently, little actual information is available but, both by analogy and by indication, 300 square miles may be expected to be underlain by such strata in the Chattanooga shale area, and at the average content of 1,125 metric tons per square kilometer, it is not unreasonable to expect up to 810,000 tons U_3O_8 in this sort of occurrence; 10 percent of this amount is almost certain to exist.

Monazite is the only radioactive mineral reported in abundance in the alluvial deposits of the United States. The ilmenite sands of Florida contain 0.09 percent monazite.[86] North Carolina produced 5,443 tons of monazite in the early days but production costs were high and ThO_2 content averaged below 6 percent. A crude beach sand at Crescent City, California, yielded 56 pounds of monazite per ton and 0.4×10^{-4} percent gold. Some placers in San Luis Valley, Colorado, had 3 pounds monazite per ton but the gold content is negligible; the concentrates from nearby Routt County are ¼ monazite.[87] All Boise Basin Idaho sands have monazite and content in the crude sand is about 0.08 percent.[87] A natural sand from the Columbia River bed at Astoria, Oregon, had

[83] Jahns, R. H., Lithium tantalum pegmatites in Moro Co., N. Mex.: Geol. Soc. America Bull., vol. 57, p. 1208, 1946. Mica-bearing pegmatites of the Pataca district, northern New Mexico: Geol. Soc. America Bull., vol. 57, p. 1254, 1946.

Uranium lodes were known in the Front Range of the Colorado Rockies, along the N.W.-S.E. diagonal of Arizona, and have been reported recently from the Kellogg Mining district of Idaho and its extension through British Columbia, but none give promise of yield adequate to sustain industrial use.

[84] Mineral resources of the United States for 1912: U. S. Bur. Mines, pp. 1013–1015, 1913. Bastin, E. S., and Hill, J. M., Economic geology of Gilpin and adjacent parts of Clear Creek and Boulder Counties, Colo.: U. S. Geol. Survey Prof. Pap. 94, pp. 121–125, 1917.

[85] Russell, W. L., Relation of radioactivity, organic content and sedimentation: Am. Assoc. Petroleum Geologists Bull., vol. 29, pp. 1471 and 1479, 1945.

[86] Hess, F. L., Industrial Minerals and Rocks, p. 524, Am. Inst. Min. Met. Engs., New York, 1937.

[87] Mineral resources of the U. S. in 1905: U. S. Bur. Mines, pp. 1180–1223, 1906.

131 pounds of monazite per ton but others here and at Hammond and Warrenton had 1 pound or less; no Columbia River mouth sand tested lacked monazite. A Washington State beach at Gray's Harbor yielded 71.5 pounds of monazite per ton. One sample from the Bighorn Mountains had 1.7 percent monazite. Also it is reported from alluvium near Topock in the western part of Arizona.[88] Monazite obviously occurs in the dredge concentrates from many Pacific slope alluvials, particularly in Idaho, the mouth of the Columbia River and at coastal sites both north and south from it. Less attractive amounts appear in many Great Valley and Sierra Nevada alluvials. Five contiguous counties in Idaho, which receive drainage from crystalline rocks, average 1 pound of monazite per pennyweight of gold (relative abundance 300 to 1) for all samples wherein 95 percent of the sample was classified. Relative abundance is 1,800 of monazite to 1 of gold downstream at the Columbia River mouth and indicates the greater mobility of monazite.

The principal U. S. source for radioactive materials is in the carnotite-bearing sandstones. The deposits are confined principally to the Salt Wash Member of the Morrison Formation; however a 1946 midsummer news report from Durango (Colorado) lists carnotite with roscoelite type ore from the Entrada Formation near Rico. The roscoelite ores at nearby Placerville had been reported previously to contain 0.05% U_3O_8,[89] so that these occurrences, if confirmed, extend the area of the carnotite province beyond its previously recognized borders. The Salt Wash member is known throughout most of an area 150 miles square near where the four states meet. The region had saved only about 1,200 tons of U_3O_8 previous to 1940. Without being too critical of past procedures, the writer would point out that in most other areas the first step in the search for ore is to learn what structures favor its localization and then to learn how to find them even where they are not obvious. When that procedure is followed on the Plateau this writer believes that the resources in recoverable concentration will be very close to the 2 tons per square mile indicated for sandstones. The prolonged and recurrent steppe climatic conditions affecting the Morrison Formation would certainly convert all uranium to the uranyl state in which condition concentration into deposits is possible.

Oxidized Secondary Deposits.—Oxidized deposits with autunite or torbernite are reported near Tyrone (N. Mex.) [90] and carnotite is found in volcanic tuffs near Aguila (Ariz.).[91] Oxidized rock in a prospect tunnel in Round Mountain (Nev.) had uranocircite or autunite. The occurrences appear to be without economic consequence and to indicate the occurrence of undisclosed primary deposits; the Tyrone occurrences may have up to 50 tons U_3O_8 in very low grade rock. Carnotite was reported in sandstone (?) near Lusk, Wyoming, but the occurrence in fissures indicates that it is an oxidized mineral. Oxidized minerals have been reported repeatedly in small amount from the

88 Heineman, R. E. S., A note on the occurrence of monazite in W. Arizona: Am. Mineralogist, vol. 15, p. 536–537, 1930.

89 Lindgren, W., Mineral Deposits, p. 457, McGraw-Hill Book Co., New York, 1919.

90 Mineral Industry for 1923, pp. 593, 596–597, McGraw-Hill Book Co., New York, 1924. Mineral Industry for 1932, p. 466, McGraw-Hill Book Co., New York, 1933.

91 Hewett, D. F., Carnotite discovered near Aguila, Arizona: Eng. and Min. Jour. Press, vol. 120, p. 19, New York, 1925.

Nevada-California border region. Numerous other localities have been listed in the western desert areas but all of them might load one good burro.

Russia.

Russia has all three types of ore but each type is the low-grade variant. The primary deposits are represented by pegmatites and only wishful thinking could expect anything better. Bituminous shales, placers, and carnotite-bearing sandstones are all recognized in the sedimentary class. Oxidized ores which have moved only a short distance from their source are abundantly developed. Russia had hoped in 1938 to be self-sufficient for radium. To that end, three extraction plants were operating; the Radium Institute of the Academy of Sciences in Leningrad may have produced 0.75 grams annually and is believed to have used uraninite selected from pegmatites in Karelia; the Uchta plant, using radioactive waters, had about 1 gram capacity; the Redelen plant of the Rare Metal Trust in Moscow had a capacity of 2 grams per year and used principally the uranyl salts from Ferghana and other Asiatic occurrences.[92] Only the Leningrad and Moscow plants used uranium ores, and assuming that they operated to their 2.75 gram capacity, they could not have had more than 10 metric tons of U_3O_8 annually. Therefore the indications are that at the outbreak of war only small productive uranium resources were known within Russia. Production from 1922 to 1940 probably did not average over 1 gram of radium annually, equivalent to 72 tons U_3O_8 in all, at 75 percent recovery of radium. The situation relative to high-grade ores probably has not improved significantly and is not likely to improve. However low U_3O_8 rocks of 0.01 to 0.05% U_3O_8 are relatively abundant and can change the supply situation materially; unfortunately for Russia those low-grade deposits occur either in deserts where water is scarce or in microthermal climates where the ground is frozen for 7 months of the year so that beneficiation is technologically difficult.

Primary Deposits.—All known primary deposits and all areas where primary deposits of consequence might occur have pegmatites in such abundance that lodes are extremely improbable. The periphery of the Scandinavian Shield has numerous uraninite pegmatites from Helsinki in Finland to the Arctic; here lode mineralization possibility is almost nil. The Urals are an elongate massif and, in conformity with such structures, the known uranium occurrences are refractory minerals in pegmatites chiefly at Miask [93] and oxidized minerals from Beresovsk. The Taimyr Peninsula has an extremely low-lying crystalline rock area concerning which little data is available but absence of strongly positive structural characteristics suggest that it can be considered of no importance even although nearby mines at Norilsk supply some nickel and cobalt. Far eastern Russia is replete with pegmatite occurrences of refractory minerals and even thorianite.[94] The north border of the Mongolian Shield contains only occurrences of samarskite, chlopinite, mendeleffite and refractory minerals re-

[92] Anonymous, Vorkommen und ausbeutung von radiummineralien in der U. S. S. R.: Die Chem. Ind., vol. 65, no. 27–28, pp. 283–284, Berlin, 1942.

[93] Zavaritsky, A. N., Ilmen State Mineralogical Reservation, XVII Inter. Geol. Cong., Guidebook to Uralian Excursion, pp. 5–17, Moscow, 1937.

[94] Bespalov, M. M., On the discovery of a new mineral of the thorianite group: Soviet Geol. no. 6, pp. 105–107, 1941.

ported from Kansk, past Slyudyanka to Chita, and into the Zeya Basin. The edge of the Tibetan Shield in the Uzbek S. S. R. has pegmatites with monazite and uraninite but uraninite or cobalt-bearing veins are not reported. The Caucasus Mountains have no known primary occurrences and only refractory minerals appear in the gold alluvials of ancient Colchis or Armenia. The Podolian Upland of the Ukraine represents the last of the Shields or massifs in Russia and all listed occurrences are euxenite. Thus, the record for the crystalline rock areas of Russia is fairly complete except perhaps in the Kolyma region where structure is like the Appalachian Mountains and favors refractory minerals in inconsequential pegmatites. These records consistently show no significant lodes, abundance of pegmatites everywhere, and no real opportunity for rich deposits anywhere.

Sedimentary Secondary Deposits.—Uraniferous shales are known in the Leningrad region, along the Kara Tau and on the south margin of the Ferghana. The high radium content of oil field waters around both the Caspian Sea and the Timan Range suggests that the source rocks carry an unusual amount of uranium. But the great area of Siberia between the Urals and Lake Baikal and Kazakstan to the Arctic, has only continental sediments which are not host to this type of deposit.

The Popovka River region near Leningrad is reported to have up to 0.21% U_3O_8—by radiometric measurement—but the chemical assays give only a tenth this amount. Considering the average thickness of the Dictyonema shales, their areal extent in this region, and the U_3O_8 content, 100,000 tons U_3O_8 would not be an exorbitant amount to anticipate here. However treatment of the 5,000 to 10,000 tons of rock to yield 1 ton of U_3O_8 would present more than ordinary difficulties in this climate.

Fersman held the opinion that the radium in Ukhta salt water and petroleum came from the pre-Devonian crystallines of the Timan Range. It seems much more probable that the radium came from uranium in the petroleum source rocks and left them not more than a millennium ago. Treatment of 30,000 tons of water annually to obtain 1 gram of radium was considered a memorable attainment. Milling 10,000 tons of rock for a ton of U_3O_8 would be a greater one and most impractical where the climate was as cold as the latitude of Leningrad.

The other localities have more favorable temperatures but the water supply for large mill operations in Ferghana, Kara Tau, or the Caspian Sea leaves much to be desired. The Kara Tau deposit occurs 90 km northeast from Chiili and is in Cambrian age shale interstratified with dolomite.[95] The ore horizon is 8 to 14 m thick under an area 40 to 50 sq km and has roscoelite and carnotite. The occurrence in a marine series indicates that the deposit is not the Colorado Plateau type but a surface enrichment of the bituminous shale type. A description of a deposit from nearby Suleytan Say appears to have the uranium leached from the shale and precipitated by a lead ore as a uraniferous vanadinite. It is not unlikely that this deposit may have 600 tons in surface enriched ore of grade 0.05% U_3O_8 along some ten kilometers of outcrop and 10,000 tons of U_3O_8 in rock of grade 0.01 to 0.02% U_3O_8.

[95] Tyurin, B. A., Karatausskoya mestorozhdenie urano-vanadievikh: Rud. Izvestiya Akad. Nauk. S.S.S.R., Ser. Geologicheskaya, no. 2, pp. 99–106, 1944.

The Alai Range south of Ferghana has thick black slates and shales of Silurian age. According to Fersman these are said to contain up to 0.05% U_3O_8, but again this is almost certainly due to surface enrichment in the desert climate. A series of secondary oxidized deposits occur for 100 km along a line following the margin of the Alai Range and their uranium almost certainly comes from that black slate and shale series. The bedded occurrences may be expected to have the usual 0.01% U_3O_8 and if ½ kilometer from the outcrop is considered accessible, the rock may be expected to have 25,000 to 30,000 tons of U_3O_8. Water deficiency would make milling this rock almost impossible.

No uraniferous shales are known around the Caspian Sea but the high radium content of salt water on Cheleken Island and of petroleum elsewhere in the region, indicates recent association with uranium.

Placer occurrences of radioactive minerals are recorded in the foothills of the Pamirs, in the Tchoruk River near Batum, in the gold alluvials east of the Yenesei River and in a conglomerate in the north slope of the Timan Range.[96] The Tchoruk River[97] has monazite, samarskite, orangeite and several other minerals with gold. Occurrence of monazite in abundance with relatively coarse gold indicates that significant monazite is on the delta in the Black Sea near Batum. Monazite occurs in the crystalline rocks at the head of the Selenga and Argun rivers in eastern Siberia and is a general constituent of these alluvials.[98] Since alluvial deposits account for at least 2,000,000 ounces of the annual Russian gold production, and all of the alluvials are in monazite areas, they could be capable of providing 600 tons of monazite annually if only 10 percent of the contained monazite was saved; careful operation might save 3,000 tons. Only one reference appears to radioactivity in a conglomerate on the north side of the Timan Range; whether monazite or uranium mineral is responsible is not stated.

Tyuyamunite or carnotite is listed from many localities from Ferghana to Minussinsk. The descriptions in all but one at Yuigur Sai show that the occurrences are oxidized ores concentrated from an overlying stratum. This overlying stratum is a black shale everywhere except at Potekhina and the Julia Mine northeast of Minussinsk. Here the source might have been a gray Devonian shale but more probably was sparse carnotite in the Devonian red sandstones. The Yuigur Sai deposit is in lenses and impregnations in a continental sandstone in the Papsk region of Northern Ferghana. The occurrences duplicate those in the Colorado Plateau even in minute detail. Only a small area has been explored but the favorable sandstone area extends under a section of 250 sq km area. At 2 metric tons per square mile, the region may be expected to furnish 200 metric tons. Uranium in traces is reported also in the copper bearing sandstone northwest of Molotov (Perm).

Secondary Oxidized Deposits.—Principal exploration and almost the entire Russian production has come from oxidized deposits. These appear in the

[96] Anonymous, Uranium in conglomerate of N. Timan: Soviet Sever., no. 4, pp. 40–51, 1938.

[97] Tschernik, G., Samarskite from monazite sand of Batum province: Phys. Chem. Jour. (Russ.) vol. 34, pp. 653–684, 1902.

[98] Kuznetsov, C. D., Acad. Sci. St. Petersburg Bull., ser. 6, vol. 6, p. 361, 1912. Zemel, V. K,. Analyses of monazite from gold alluvials of Aldan and S. Yenesei rivers: App. Chem. Jour. (U.S.S.R.) vol. 9, pp. 1969–1971, 1936.

desert country from Lake Balkash to the Afghanistan border. Principal source for the uranium in them has been the black shales and slates of Silurian and Cambrian age. The largest is the Tyuyamuyun deposit in a limestone karst. The deposit had originally about 5,000 tons of ore containing about 1% U_3O_8 in tyuyamunite or 50 tons U_3O_8 carrying 20 grams of radium.[99] Other deposits with lesser amounts are reported in the Kara Mazar, at Taboshar in the Alai Range [100] near Leninabad, and in the Kara Tau near Chiili. All have less than 10 tons of grade above 0.05% U_3O_8.

Secondary ores have been reported in the Podolian Upland and in the Tiblisi corridor. However these "Shinkolobwes" were demoted to museum specimen rank one to three years after discovery.

Russian Resources.—There exists no evidence that any high grade U_3O_8 ore is known in Russia and all geological evidence suggests that none of industrial size may be expected. In the medium-grade category, the carnotite deposits may furnish 200 tons of U_3O_8 and, following exhaustion of Tyuyamuyun, all the oxidized secondary deposits combined might produce 100 tons of U_3O_8 in addition to the 600 tons from the Chiili occurrence. Russia, like every other petroleum country, has large reserves of bituminous black shale and at least 45,000 tons of U_3O_8 can be expected in this sort of deposit. It should be realized that mill operations on Russian low-grade ores would have to be conducted under the most unfavorable climatic conditions possible and these might even render milling impractical. Alluvial gold deposits, properly supervised, could yield 3,000 tons of monazite annually.

Bulgaria.

Oxidized minerals are listed at Goten or Bukhovo [101] near Sofia and at Strelchna.[102] The Strelchna occurrence has autunite associated with pegmatite and has no significance. The Goten or Bukhovo occurrence is in a breccia zone through sandstone (?) and carries chalcolite (metatorbernite). The minerals seem to be entirely oxidized types deposited in a breccia zone by descending solutions. No primary ores or ore structures are mentioned so that it is presumed that the uranium was carried down from an overlying source now denuded; this might be the Jurassic oilshale still preserved at nearby Breznik.[103] Such a deposit would stop at or near the watertable possibly 20 m more or less below the surface. Kostov's report lists 25,000 tons of 2% U_3O_8 ore; however the original account indicates a lenticular deposit 4 to 15 m wide and 50 to 70 m long explored to about 10 m depth; hand dressing of 4 cubic meters of ore yielded a concentrate assaying 2% U_3O_8. The 25,000 tons estimate

99 Fersman, A., op. cit. Anonymous, Die Chem. Ind., pp. 283–284, 1942. Alexandrov, S. P., *in* "Gornyi Zhurnal," vol. 118, p. 415–416, Moscow, 1922. (Lists radium resources as equivalent to 80 tons U_3O_8.)

100 Nasledov, B. N., Kara Mazar No. 19, *in* "Material of the Tadjik-Pamir Expedition of 1933," 401 pp., Leningrad, 1935; Taboshar, pp. 275–276, Sarimsakhli, pp. 277–280, 381.

101 Konjarov, G., Die uranerzlagerstatte auf dem Gipfel Goten: Podz bogat i min. industr., pp. 236–244. Bulgaria, Sofia, Trudy 8, 1938. Kostov, I., Metallization of the Balkan Peninsula: Mining Mag., vol. 68, pp. 261–274, London, 1943.

102 Anonymous, Chem. Age, p. 367, London, Apr. 28, 1934.

103 Sundius, N., Oljeskiffaar och skifferoljeindustri: Sveriges geol. undersökning, ser. C, no. 441, p. 22, 1941.

uses the maximum dimensions of the deposit and assigns the 2 percent grade to the crude rock instead of to the hand dressed ore only. Considering all the evidence the earlier estimate suggests 6,000 cubic meters of ore which could be hand dressed to 1,500 tons assaying 2% U_3O_8 or a total content of 30 tons. If the deposit extends to 20 m depth at the same grade, its content might attain 60 metric tons of U_3O_8.

Madagascar.

Madagascar has primary uraniferous pegmatite, sedimentary secondary deposits and alluvial monazite, and oxidized secondary minerals. The source for all uranium is in pegmatites and these are distributed over so much of the central plateau that little ground favorable for lode type of mineralization exists. The crystallines have monazite everywhere and have been denuded extensively so that the alluvials have had an opportunity to accumulate this mineral in quantity.

The Madagascar pegmatites have banded structure. They occur principally on the lateritic grasslands of the central plateau and the central quartz band projects above the general topographic surface like an identification marker.[104] The uranium minerals are principally refractory titanoniobates and are found in the complex mineral band on either side of the quartz core. The pegmatites appear to have slightly higher content than is usual in this type, although higher value may be due to the large amount of the dike which was left undisturbed. About 12,000 cubic meters at Ambatofotsy yielded 20 metric tons of betafite (roughly 5 m t of U_3O_8) and 10 cubic meters at Andaombatotany supplied 280 kilograms of euxenite (roughly 28 kg of U_3O_8)[105]. The average content is about 0.02% U_3O_8 in the first instance and 0.13% U_3O_8 in the second which represents very high selection of material to be handled. Production may have yielded 15 tons of U_3O_8 in slightly over 100 tons of refractory minerals. All the ore was difficult to decompose and treat.

A small but interesting deposit of bedded autunite is known at Vinaninkarena at 10 km S.S.E. of Antsirabe. Alluvial gravel, sand and peaty clay about 20 m thick have two beds aggregating a meter thickness and containing autunite in worm holes, cracks, and as disseminated flakes. The layer underlies not more than a square kilometer and material sorted out from waste contains 0.5% U_3O_8. The material can be concentrated to 8 to 10 percent with rather heavy loss of mineral. About 37 metric tons of concentrate have been shipped.[106] If the grades and thickness apply to the limits of the deposit, it might have up to 2,500 tons U_3O_8 of which one-half might be recoverable.

Monazite is reported in the stream deposits of the plateau,[107] the long northwest flowing rivers [108] and the short eastward flowing streams.[109] Quantitative estimates are not available but all the monazite from the crystalline rocks eroded

104 Lacroix, A., Minéralogie de Madagascar, Vols. I, II, III, Paris, 1922–23.

105 Turner, H. W., Radioactive minerals of Madagascar: Econ. Geol., vol. 23, pp. 8–81, 1928.

106 Turner, H. W., op. cit., pp. 83–84.

107 Turner, H. W., op. cit., p. 82.

108 Besairie, H., La géologie du nord-ouest (Madagascar): Acad. Malgache Mem., vol. 21, pp. 259, Tananarive, 1936.

109 Hintze, C., Handbuch der Mineralogie, vol. 1, pt. 4, p. 345, Berlin, 1933.

to make the eastern coastal plain and the gorges of the western rivers must be somewhere. Some of the monazite concentrates have 10% ThO_2.[110] Production has been only a few metric tons.

Brazil.

The large area of the Brazilian Shield appears like a favorable locality for uraninite lodes but careful scrutiny of its geology shows a periphery with numerous pegmatites containing uraninite, samarskite, fergusonite and monazite.[111] A few tons of pegmatite mineral appear to have been saved, but the total amount is inconsequential. The monazite was washed down the streams and most of it is concentrated in the Cenozoic age sediments and recent beach bars. The monazite contains on the average about 6% ThO_2 and 0.15 to 0.25% UO_2.[112] Production is estimated at slightly over 72,000 tons of monazite.

The deposits occur on the beaches from Cape Frio to Recife, a linear distance of 1,800 km although most rich sands are in the southern 700 kilometers. Principally they avoid the forelands and are in the crescents. The rich deposits occur quite close to the strand line or on elevated bars but lower grade ones are recorded inland, in the recent river deltas, even in the elevated Cenozoic strata and some are along streams.[113] According to Krusch [114] the sands rarely have more than 6 percent monazite and most are even lower grade. This warning suggests that the grade quoted by most sources refers to the concentrate whereas the volume refers to the crude sand. Estimates need to be scaled down accordingly. The high content monazite sands rarely have more than 10 m lateral extent although they may be spread along a kilometer or more of beach and have a thickness of half a meter. Monazite is said to occur throughout very large areas of the beach sand in amounts up to 2 percent but this probably should be scaled down to about 1/10 in accordance with all other estimates.

The highest content deposits are at Comoxatiba, Guarapary and Macahe. The following beaches in Bahia are said to have supplied some monazite: Santa Cruz, Porto Seguro, Trancoso, Comoxatiba to Prado, Alcobaca to Caravelles and Vicosa, and Porto Alegre. In Espiritu Santo bars have monazite at Sao Matheus, Barra Nova, Praia do Diogo, Riacho, Santa Cruz, Carapebus, Meaipi, Maeba, Ouricos, Porto on Ponta do Caju and Barra do Itabapoana.[115] Comoxatiba and other Prado beaches are worked and are believed to be capable of supplying 1,200 tons of monazite annually and are so situated that erosion

110 Krenkel, E., Geologie Africas, pt. 1, p. 418, Berlin, 1925.

111 Friese, F., Mineralvorkommen der sudlichen Serra dos Oymores, staat Espirito Santo, Brasilien: Zeitschr. prakt. Geologie, p. 143, 1910. De Almeida *et al.*, The beryl-tantalite-cassiterite pegmatites of Paraiba and Rio Grande do Norte, N.E. Brazil: ECON. GEOL., vol. 39, p. 215, 1944.

112 Hess, F. L., Industrial minerals and rocks: p. 524, Am. Inst. Min. Met. Engs., New York, 1937.

113 Leonardos, O. H., Monazita no Estado da Bahai: Mineracao e Metallurgia, no. 8, Rio de Janeiro, 1937.

114 Krusch, P., Die metallischen Rohstoffe, ihre lagerungsverhaltnisse und ihre wirtschaftliche Bedeutung, pt. 2, pp. 65–87, Ferdinand Enke, Stuttgart, 1938.

115 Miranda, J., Areias ilmeniticas no Brazil: Mineracao e Metallurgia, vol. 7, pp. 195–198, Rio de Janeiro, 1943.

renews, out of the deeper sand, the heavy minerals armor-layer when it is removed. The Guarapary deposits are also high grade. High-grade deposits in Espiritu Santo are estimated to have 50,000 metric tons of monazite in high-grade sand and an indefinitely large amount in low-grade deposits.[116] These low-grade deposits furnish new monazite concentrates when the armor of surface heavy minerals is removed and at least two harvests can be made. No dependable estimate of the deposits in Bahia is available. Brazilian engineers suggest that the low-grade sands around Caravellas (Bahia) may have over 500,000 tons of monazite; even 1/10th of this is a lot of monazite. Nearly every bar at the mouth of the rivers from the interior has its monazite but these are always very low grade.

Miranda gives the resources for a number of beaches in Brazil as follows:

TABLE 4

EXPLORED MONAZITE BEACHES IN BRAZIL

Location	Tons of sand	% monazite	Tons of monazite
Carapebus	48,480	0.46	223
Barra do Itabapoana	229,000	rich (6%?)	13,740
Picuma	55,000	5.0	2,750
Meaipe	19,950	55.0#	10,950
Maeba	150,000	60.0#	90,000
Ouricos	166,000*	10 to 20#	23,500
Ponta do Caju	420,000*	10 to 12#	46,200
Diogo Coast	23,353	4.35	1,000
Total	1,110,783		188,363

* Calculated on basis of 1 cubic meter of sand weighing 1.75 metric tons.
# Content abnormally high and should be cut to 6 percent where estimate is in tons and to 1 percent where estimate was in cubic meters. Total then is 33,773 tons.

Several of the rivers have some monazite in the gold and diamond washings. The Pardo River has monazite with the diamond gravel.[117] The Paraguassu near Maracao and the Contas near Bom Jesus dos Meiras have monazite in the diamon-bearing gravels. The gold-bearing gravels of Rio Parahyba do Sul have monazite in tributaries from the northwest; the Rio Muriaba and Rio Pomba have 1.75 parts per million of gold and 5,000 parts of monazite (ratio 1 : 3,000) ; resources are not less than 100,000 tons of monazite of which 50 percent may be recoverable.

Assessment of Brazil's monazite resources is nearly impossible. Monazite contents of beach sands exceeding 50 percent obviously represent selected rather than representative samples. The best estimates indicate high content beach deposits to have 50,000 to 100,000 tons of proven reserves. The uncertainty rests in the importance to be attached to low-grade areas where content, recovery, and extent are unknown by direct measurement. Friese estimated

[116] Loren, O. G., Monazite: Mineral Trade Notes, vol. 4, no. 6, pp. 23–25, 1937. Borges, D. B., Areias monaziticas do Espiritu Santo: Mineracao e Metallurgia, vol. 7, Rio de Janeiro, 1937.

[117] Souza Carneiro, A. J., Requezas mineraes do Estado da Bahia, Bahia, 1900. Leonardos, O. H., op. cit.

that about half of the contained monazite in low content deposits can be recovered although this seems too optimistic. Leonardos quotes Souza e Silva as estimating the ore deposits between Alcobaca and Caravellas at 2.5 percent monazite in a volume of 1,300,000 cubic meters (70,000 tons of monazite). The content seems about 10 times too high for an extended deposit; nevertheless the local richness of the beaches, the unusual content of 0.5 percent monazite in the river alluvium of many streams from the precipitous Shield margin, and the relatively continuous extent of the monazite-bearing beach sands along 500 miles of coast are most impressive.

Uraniferous bituminous shales and carnotite bearing sandstones could occur in Brazil, the former in the Amazon Basin and the northern coastal plain and the latter in the Gondwana sediments of the Matto Grosso and the Parana Basin. All information now available on the soil and climate make the occurrence of economic deposits about as probable as in the Mauch Chunk beds of Pennsylvania. Absence of a source stratum makes occurrence of oxidized secondary ores very improbable.

India.

India has a shield area which embraces all the southern peninsula and Ceylon and in the northwest it has sediments that accumulated in a steppe climate. But the Shield border is ringed with pegmatites containing uranium minerals and presenting a set of conditions inimical to lodes. Likewise the northwest is unfavorable because its sediments accumulated so rapidly that even bones of animals, let alone uranium minerals, failed to be destroyed and pass into the groundwater circulation for preliminary surface concentration. Lode deposits and carnotite-bearing sandstones are improbable types of deposits for India. Bituminous shales are possible, but improbable, Indian sources of radioactive substances. The refractory minerals left as a residue from decay of the great mass of crystalline rock between the projected base of the Deccan lavas and the present land surface constitute the most significant source of radioactive minerals. Monazite is the most important of these and has been concentrated further in alluvials. Total amount of other uranium minerals probably does not exceed ten tons.

Monazite was discovered on the Travancore Coast and principal interest centered there.[118] The mineral is now known on the east coast as far north as the Mahanadi River,[119] and occurs in the Kistna River alluvium. Production up to 1940 was about 45,000 tons. Hess [120] indicates that the Travancore monazite has over 8.8% ThO_2 and considerable UO_2

Most monazite is brought to the coast by rivers and there the alongshore current carries it to the lee of the first headland, generally to southward on the Travancore coast. Shifting of river courses leaves many deposits seemingly

118 Tipper, G. H., The monazite sands of Travancore: India Geol. Survey Rec., vol. 44, pp. 186–192, 1914. Fermor, L. L., Monazite: India Geol. Survey Rec., vol. 70, pp. 260–263, 1935. Brown, J. C., India's Mineral Wealth, p. 271, Oxford Univ. Press, London, 1936. Anonymous, Monazite in India: Imp. Inst. London Bull., vol. 33, pp. 355–356, 1935.

119 Hess, F. L., Industrial minerals and rocks, p. 525, Am. Inst. Min. Met. Engs., New York, 1937. Anonymous, Mineral trade notes, vol. 22, no. 2.

120 Hess, F. L., op. cit., p. 525.

in incongruous places. As in Brazil, the Cenozoic age strata have some monazite streaks. On-shore storms aggrade the bays from May through September and replenish the parent sand; during the remainder of the year, gentler waves remove only the light quartz and leave a surface concentration of monazite, ilmenite, zircon and other heavy minerals. At a few places where replenishment is negligible, the principal deposits appear during the on-shore storm season.

The reserves of monazite present as 2 to 5 percent of the beach deposit in Travancore [121] probably do not exceed 100,000 tons and Krusch's [122] estimate of 1,760,000 tons of monazite in high-grade sands is far from fact. However, the low-grade deposits in beaches and in Cenozoic strata may reach the 1,000,000 ton mark.

The east coast deposits lie principally south of Madras. Proven reserves in deposits of 1 to 2 percent monazite are about 3,000 tons. Stream beds have deposits equally rich and fairly extensive. The east coast deposits are considered to have reserves almost as great as those for the west coast area but of decidedly lower content.

Ceylon.

The island of Ceylon is an outlier of the southern peninsula of India. It produced 852 tons of monazite and a small quantity of thorianite.[123] The principal deposits are near Galle. However, monazite occurs with the ilmenite sands all around the island and particularly on the east coast. These deposits are very low grade but it is believed that they contain not less than 1,000 tons on the dozen or more beaches where they are known. Mineralogical literature [124] lists monazite in most crystalline rocks of the island.

Southeast Asia Tinfields.

Monazite accompanies cassiterite in the alluvials throughout the southeast Asia tin fields.[125] It is rare in the lode deposits, uncommon in the eluvial deposits, and abundant only in dredging ground of the flat valleys. A large number of samples [126] from the principal states had, on the average, the ratio of monazite to one unit of cassiterite as follows: Kedah 2, Dindings 0.3, Trengganu 15 and Pahang 0.2. The lowest value indicates a ratio of one unit of monazite for five of cassiterite. The monazite averages about 6% ThO_2 and has significant UO_2 This tin belt continues northward into Thailand and Burma and southward and eastward into the Netherlands East Indies. To southward the Westkuste district of Sumatra [127] has abundant monazite and it

121 Houk, L. G., Monazite sand: U. S. Bur. Mines Inf. Circ. 7233, p. 8, 1943.
122 Krusch, P., op. cit., p. 76–79.
123 Houk, L. G., op. cit., p. 12.
124 Hintze, C., Handbuch der Mineralogie, vol. 1, pt. 4, p. 342, Berlin, 1933.
125 Krusch, P., op. cit., pp. 78–80. Houk, L. G., op. cit., p. 9.
126 Anonymous, Occurrence of monazite in the tin-bearing alluvium of the Malay Peninsula: Imp. Inst. London Bull., vol. 4, pp. 301–309, 1906. Amang from the Federated Malay States: Imp. Inst. London Bull., vol. 9, pp. 99–102, 1911. Johnstone, S. J., Monazite from some new localities: Chem. Ind. Jour., vol. 33, pp. 55–59, 1914.
127 Krusch, P., op. cit., pp. 79–80. Anonymous, Metal und erz, vol. 21, p. 347, 1924.

has been identified at Dendang on Billiton [128] and in Borneo. In 1940, Malaya produced 85,384 long tons of tin and the other countries nearby furnished 67,394 additional for a total of 152,778 long tons or about 155,000 metric tons. In view of the above prevalence of monazite, conservation of it could have yielded 3,100 metric tons at only 10 percent recovery.

Only the Netherlands East Indies has produced any monazite and this came as an experimental by-product from their tin operations. Statistics indicate 1,570 tons produced in 1936–38. Records do not list production in Malaya and N. E. I. under the Japanese administration.

Australia.

Monazite has been known from New South Wales and Queensland for about half a century [129] but production began during 1943.[130] Early samples came from the alluvial tin and had less than 2% ThO_2,[131] which makes them almost worthless for radioactive elements. Production is from the coastal sands found from Byron Bay (N.S.W.) northward for 60 miles along the Queensland coast. The deposits occur in the littoral zone and are 1 to 5 feet thick; the sands extend 25 to 30 feet back from the low water mark, where sand dunes cover them. Ilmenite, rutile, zircon, and garnet are the most abundant minerals. Comparisons listed give the impression that the crude sand has only about 0.01 percent monazite but is valuable for its ilmenite. Even such extensive deposits probably do not contain 1,000 tons of monazite.

The ilmenite sands of Tasmania and the tin ores of Mt. Bischoff also have a small amount of monazite.

Australia has some refractory uranium deposits at Mt. Paynter and at Radium Hill in South Australia.[132] The deposits are essentially pegmatites containing uraniferous titanoniobates in an ilmenite matrix; autunite appears as a weathering product along fractures. The deposit was estimated to have 90,000 tons of ore containing about 0.2% U_3O_8.

The Moonta copper mines have combustible, thucholite-like substances carrying considerable uranium. No estimate of the amount is available.

RESOURCES OF POTENTIAL PRODUCING COUNTRIES.

A number of countries have produced no uranium or radium but obviously can enter the field when the current situation is clarified and an industrial requirement is established. Sweden certainly is significant [133] and the indications are that the Union of South Africa may be an important contributor.[134] The

[128] Hintze, C., op. cit., p. 342.

[129] Dunstan, B., Mining World, Aug. 26, 1905.

[130] Minerals Yearbook, U. S. Bur. Mines, p. 866, 1945. Anonymous, Eng. and Min. Jour. Queensland, vol. 145, pp. 164–165, Oct. 1944.

[131] Hintze, C., op. cit., pp. 366 and 370.

[132] Mineral Resources of the U. S. for 1912: U. S. Bur. Mines, pp. 1026–1028, 1913. Brown, H. Y. L., *in* Gee, L. C. E., Uranium ores and other rare metals in South Australia: S. Australia Dept. of Mines, p. 9, Adelaide, 1911. Mawson, D.,

[133] Minerals Yearbook for 1943, p. 828, U. S. Bur. Mines, 1944.

[134] Anonymous, Eng. and Min. Jour., p. 150, New York, March 1946.

entire coast of Africa is potential monazite territory. It is not feasible now to assign a potential reserve to these places, on the small amount of evidence in the literature, any closer than the possible magnitude of their potential. Any figures given in this section should be considered with the above limitation.

Sweden.—The only known uranium deposits of any significance in Sweden are in the alum shale and the Dictyonema shale.[135] Thucholite-like hydrocarbons occur with several iron ores, at Varutrask and at Boliden.[136] Uraninite is represented by a single specimen at Varutrask and by a pegmatite of uncertain content between Goteborg and Varberg at Torpa.[137] The occurrence of mesothermal lodes is precluded by the pegmatite type of mineralization all around the periphery of the Shield even more than by the complete absence of known mesothermal lodes of any sort. No sediments suitable for carnotite sandstone type deposits are known. Weathering is so shallow that even oxidized secondary minerals are curiosities.

The alum shales are found in six areas of Sweden and have varying but high uranium content in all. Shales in at least two of the areas have nodular masses of a hydrocarbon, called kolm, containing about 0.5% U_3O_8. The kolm was mined at Stora Stolan in 1909 to be used for radium recovery.[138] It had 0.5% U_3O_8 here and 0.36 and 0.4 percent at Karlsro and Ulunda.[139] About 200 tons of kolm were obtained from about 8,000 tons of alum shale from a 1.5 m zone at Stora Stolan. The venture was not a success but it does indicate 80,000 tons of kolm, with 400 metric tons of U_3O_8 per square kilometer, at least in some areas. The area adjoining Stora Stolan is underlain by 389 square kilometers of kolm-bearing strata. Kolm is described also from Narke.[140] It is less abundant in Ostergotland and Kinnekulle.

All alum shales in the Peltura scaraboides horizon are uraniferous,[141] and these constitute the principal oil shales of Sweden. The oil shale plant at Kvarntorp has piled its ash instead of back-filling it into the open pit.[142] The uranium content of 7.5 to 10 m of shale in Narke (Kvarntorp) and Vastergotland (Stora Stolan) is 225 grams U per ton (0.026% U_3O_8).[143] In Ostergotland (Skaningstorp) 4.7 m of shale have 0.015% U_3O_8. The shales in Skane have no kolm but are much thicker than in Narke or Vastergotland and have up to 130 grams per ton or 0.015% U_3O_8.[144] That the total amount of uranium in the alum shales of Sweden probably is considerable, can be calcu-

135 Westergard, A. H., Borrningar genom alunskifferlagret pa Oland och i Ostergotland 1943: Sveriges geol. undersökning, ser. C., no. 463, p. 18, 1944.

136 Grip, E., and Odman, O. H., On thucholite and natural gas from Boliden: Sveriges geol. undersökning, ser. C, no. 464, 1944.

137 Anonymous, Ind. and Eng. Chem., p. 83, London, Jan. 20, 1926.

138 Lundquist, G., Hogbom A., and Westergard, A. H., Beskrivning till Kartbladet Lugnas: Sveriges geol. undersökning, ser. Aa, no. 172, p. 65, 1931.

139 Lundquist, G., *et al.*, op. cit., p. 65.

140 Westergard, A. H., Sveriges Olenidskiffer: Sveriges geol. undersökning, ser. Ca, no. 18, pp. 79–83 (Narke), pp. 41–46 (Ostergotland), pp. 50–58, 1922.

141 Westergard, A. H., Borrningar genom alunskifferlagret pa Oland och i Ostergotland, 1943: Sveriges, geol. undersökning, ser. C, no. 463, p. 18, 1944.

142 Anonymous, Chem. Age, vol. 51, no. 1320, p. 377, London, 1944.

143 Westergard, A. H., op. cit., p. 18.

144 Westergard, A. H., Borrningar genom Skanes alunskiffer 1941–1942: Sveriges geol. undersökning, ser. C, no. 459, p. 13, 1944.

lated from the content and the area that the shale is known to underlie; but only a small part may be recoverable. The climate will interfere seriously with maintenance of large extraction plants.

The Dictyonema shale of Ostergotland has 140 grams U per ton or 0.016% U_3O_8 and 3.2 m average thickness.

Of the uranium in shales only that contained in kolm is easily concentrated by mechanical means. The residue is tightly bound up in the shale and can be separated from the clay minerals only by chemical methods and then with great difficulty. These shales are outstanding for their high uranium content and reasonably large areal extent. Also, except for the possible Onwatin slate, they are the oldest bituminous series, which may be a pertinent fact.

The East African Crystalline Area.—An almost continuous strip of crystalline rocks extends along the east side of Africa from Southern Rhodesia to east of Cairo, Egypt. The mass is broad as well as long but it is broken at several places by Rift Valleys and thereby loses any qualification which it may have had to be classed as a Shield or equidimensional massif. However, monazite and refractory uranium minerals appear at numerous places along its length. Occurrences are listed from north to south.

Egypt.—The Nile mouths at Damietta and Rosetta have been worked for ilmenite and monazite on their beaches.[145] Content is not stated. The minerals probably came from the crystalline rocks far upstream.

Uganda, Kenya, Tanganyika.—Monazite, polycrase and euxenite have been found in the S.W. Ankole district of Uganda. Monazite is an important constituent of the alluvials in the Juba River of Somaliland. It is reported also from Patta Island in Kenya Colony.[146] Close to Nanyuki near the head of the Tana River, monazite and refractory uranium minerals are reported in the Loldaiga Hills.[147] The Somaliland monazite originated in the crystallines but occurs now, at least in part, in the Nubian sandstone and recent stream deposits.[148] Several monazite localities are on record for Tanganyika Territory [149] and it appears in the sands of the Shira River near Chiromo, in Nyasaland.[150] The frequency of occurrences along this area indicates that it is a monazite province and the mineral is to be expected in commercial amounts in the coastal sands near the mouths of the principal rivers like the Juba, Ruvuma and Zambesi.

Nigeria.—Monazite appears with cassiterite in concentrates from the alluvial and eluvial tin deposits in Nigeria.[151] The ThO_2 content is said to be relatively low and the total monazite present is not unusual.

Union of South Africa.—Uraninite and refractory uranium minerals have been reported in pegmatites of ancient granite and gneiss of Southwest

[145] Minerals Yearbook for 1944: p. 866, U. S. Bur. Mines, 1945.

[146] Hintze, C., Handbuch der mineralogie, vol. 1, pt. 4, p. 344, Berlin, 1933.

[147] Anonymous, Mining Journal, vol. 179, p. 826, London, 1932.

[148] Voeltzkov, A., Reise in Ostafrica i. d. Jahr. 1903–1905 (1911).

[149] Hintze, C., op. cit., pp. 344–345. Krenkel, E., Geologie Africas, pp. 412–413, Leipzig, 1925.

[150] Hintze, C., op. cit., p. 366.

[151] Johnstone, S. J., Monazite from new deposits in Africa: Soc. of Chem. Ind. Jour., vol. 33, p. 55.

Africa,[152] Namaqualand,[153] and Swaziland.[154] Here the content is only that usual for pegmatite occurrences and recovery of considerable quantity cannot be expected from this source. Carnotite has been reported from the Karroo System sediments near Beaufort West but there is nothing in the account to indicate the magnitude of the deposit.

Of greater import, are the Witwatersrand gold reefs. Cooper [155] reported uraninite in the concentrates from the Central Rand Mines. The quantity was of the order of 0.0013 parts per million. Pirov [156] confirmed by measurement, radioactivity in certain Rand ores. Du Toit [157] mentions that the diamonds from six mines in the East Rand and from the Gold Estates Reef at Klerksdorp are greenish. Crookes' experiments have shown that green color is induced in diamonds by radiation. The green color in the Banket diamonds shows that these reefs have higher uranium content than had been indicated by the early mill studies. Du Toit lists green diamonds from the Black Reef at Klerksdorp [158] as well as from older strata and mentions uranium compounds in the reef (p. 81) but lists them as definitely secondary. The recent interest in uranium everywhere has spread to the Rand according to a recent announcement [159] which states:

"From indications, many parts of the Witwatersrand gold mines may contain considerable quantity of ores from which uranium may be extracted. This possibility is now being investigated."

Since the Rand mines mill over 60,000,000 tons of ore annually as they extract the gold, this is the largest, ready source for industrial uranium.[160] Occurrence of uraninite in the Black Reef, which is rarely mined for gold, indicates that many reefs uneconomic for gold may have significant uranium.

Pitchblende was reported in the Messina No. 5 shaft, at the extreme northern border of the Transvaal.[161]

Monazite and refractory uranium minerals occur in the alluvial tin deposits of Swaziland, in the ilmenite beach sands at the mouth of the Komati River, and on Durban beaches.[162] The content is low and probably will not be attractive with so many better sources of radioactive materials within the country.

152 Dahms, A., Zeitschr. prakt. Geologie, vol. 20, p. 243, 1912.

153 Gevers, T. W., Phases of mineralization in Namaqualand pegmatites: S. Africa Geol. Soc. Trans., vol. 39, pp. 331–379, 1936.

154 Prior, G. T., Mining Mag., vol. 12, p. 101, 1900. Mollengraaff, S. Africa Geol. Soc. Trans., vol. 4, p. 141, 1898.

155 Cooper, R. A., Mineral constituents of the Rand concentrates: S. Africa Chem. Met. and Min. Soc. Jour., vol. 24, pp. 90–95, 1923.

156 Pirov, H., Distribution of the pebbles in Banket and other features of the rocks: S. Africa Geol. Soc. Trans., vol. 23, p. 94, 1924.

157 Du Toit, A. L., Geology of S. Africa, p. 80, Oliver and Boyd, Edinburgh, 1939.

158 Du Toit, A. L., op. cit., p. 81.

159 Eng. and Min. Jour., p. 150, New York, March 1946.

160 Simpson gives radiometric drill hole readings of 1,000 times background as equivalent to 0.3 to 0.5 percent uranium; his logs show reefs with 20 times background upwards or 0.01 percent U_3O_8. This is a value at least consonant with the evidence of the green diamonds and with the author's 1941 heavy mineral study of the Witwatersrand ore.

161 South Africa Min. and Engr. Jour., vol. 37, p. 654, 1927.

162 Partridge, F. C., Note on Durban Beach sands: S. Africa Geol. Soc. Trans., vol. 41, p. 175, 1928.

South African geologists generally consider that the primary source of the Witwatersrand gold is in alluvials derived from the Swaziland System of crystalline rocks. The original alluvial gold and most of the matrix minerals in the original gravel have been reorganized considerably by circulating groundwater. The uraniferous character of the Swaziland crystallines suggests that the uranium mineral in the gold deposits is also alluvial; however as uranium is more mobile than gold in groundwater, so greater reorganization of its carrying minerals is to be expected and the variations recognized for gold may be modified for uranium.

Looking around for the place most likely to supply industrial uranium in amounts required at a reasonable cost and in the immediate future, the Witwatersrand looks like the best place because of the prepared state of the material.

AMHERST COLLEGE,
AMHERST, MASS.,
April 19, 1950.