



UNITED STATES  
DEPARTMENT OF THE INTERIOR  
GEOLOGICAL SURVEY  
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March 16, 1955

Mr. Robert D. Nininger, Acting Assistant Director  
Division of Raw Materials  
U. S. Atomic Energy Commission  
Washington 25, D. C.

Dear Bob:

Transmitted herewith are three copies of TEI-476, "Search for uranium in the United States," by V. E. McKelvey, October 1954. This report is an expanded, more fully documented version of TEI-199, "Search for uranium in Western United States," by V. E. McKelvey, April 1953. TEI-199 was approved by Mr. Hosted on April 10, 1953 for oral presentation at the Rocky Mountain Section meeting of the A. A. P. G. on April 23, 1953 in Casper, Wyoming.

On January 10, 1955, Mr. Hosted approved our plan to submit this report for publication in the Bulletin of the American Association of Petroleum Geologists. We now plan to publish it as a chapter in a Survey bulletin, as suggested in his letter.

Sincerely yours,

*John H. Eric*  
for W. H. Bradley  
Chief Geologist

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Geology and Mineralogy

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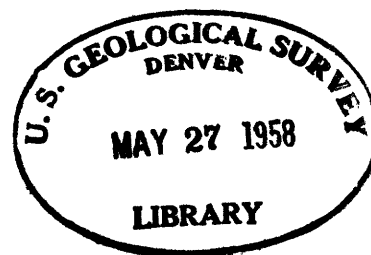
UNITED STATES DEPARTMENT OF THE INTERIOR  
GEOLOGICAL SURVEY

SEARCH FOR URANIUM IN THE UNITED STATES\*

By

V. E. McKelvey

October 1954



Trace Elements Investigations Report 476

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## SEARCH FOR URANIUM IN THE UNITED STATES\*

By V. E. McKelvey

## ABSTRACT

The search for uranium in the United States is one of the most intensive ever made for any metal during our history. The number of prospectors and miners involved is difficult to estimate but some measure of the size of the effort is indicated by the fact that about 500 geologists are employed by government and industry in the work--a number comparable to if not larger than the total number of geologists engaged in the study of all other minerals together except oil.

The largest part of the effort has been concentrated in the western states. No single deposit of major importance by world standards has been discovered, but the search has led to the discovery of important minable deposits of carnotite and related minerals on the Colorado Plateau; of large, low grade deposits of uranium in phosphates in both the western and Florida fields, in black shales in Tennessee, and in coal in the Dakotas, Wyoming, Idaho, and New Mexico; and of some promising occurrences of uranium in carnotite-like deposits and in vein deposits. Despite the fact that a large number of the districts considered favorable for the occurrence of uranium have already been examined, the outlook for future discoveries is bright, particularly for uranium in vein and in carnotite-like deposits in the Rocky Mountain States.

## INTRODUCTION

The search for uranium in the United States is the most intensive ever made for any metal during our history. Although the number of uranium prospectors and miners is difficult to estimate, about 500 geologists are employed by government and industry in the work--a number comparable to if not larger than the total number of geologists engaged in the study of all other metals together.

Large though this effort is, the geologic field work and sub-surface testing involved is small compared with that embraced by the search for oil. This, together with the fact that many occurrences of uranium are closely related to the provinces, rocks, and problems with which petroleum geologists are concerned,

means that petroleum geologists can contribute significantly to the discovery and study of uranium deposits, particularly if they are acquainted with some of the habits and characteristics of uranium deposits. It is not possible to provide an intimate acquaintance with the field of uranium geology here, but it is the purpose of this paper to introduce the subject by briefly summarizing information on the common uranium minerals; the kinds of deposits in which uranium is found; the methods used in the search for uranium; the important deposits found in this country thus far; the outlook for future discoveries; and the recent literature on the geology of uranium deposits in the United States.

### COMMON URANIUM MINERALS

Uranium is found in a great variety of minerals (Fron del and Fleischer, 1952). Nearly 100 species may be listed as uranium minerals, and we may list more than 200 if we count all the minerals in which uranium occurs commonly but is not an essential constituent. Most uranium minerals are black or bright shades of green, yellow, and orange. These are most accurately identified and their uranium content determined by laboratory methods (George, 1949; Rodden and Tregoning, 1950; Grimaldi, et al., 1954) but two criteria either singly or together aid in identifying them in the field. First, some uranium minerals, particularly the brightly colored ones, fluoresce under the ultraviolet lamp. The precipitate formed by evaporating a sulfuric acid solution of uranium minerals also fluoresces, as does a bead formed by the fusion of uranium minerals with sodium or lithium fluoride (Bain, 1950, p. 278). Second, along with thorium and some potassium minerals, uranium minerals are radioactive and generally can be detected by a Geiger or scintillation counter (Senftle and McMahon, 1949; Brownell, 1950; Wright, 1953, 1954a).

The uranium minerals may be classified, according to the other elements combined with the uranium, as oxides, vanadates, phosphates, arsenates, carbonates, sulfates, silicates, niobates, tantalates, titanates, and other minerals in which uranium occurs as a minor constituent.

The common uranium oxides include uraninite and its colloform variety, pitchblende. These oxides are black or brown and have specific gravities of 5 to 9. For the most part they are formed through igneous and hydrothermal processes. The common uranium phosphates are autunite (yellow) and torbernite (green).

These minerals are generally formed by weathering and their presence suggests that primary uranium minerals may be found at depth. Two ~~uraniferous~~ vanadates--carnotite and tyuyamunite--are important constituents of uranium deposits on the Colorado Plateau. Both are a bright mustard or canary yellow.

Most uranium carbonates and sulfates are so soluble that they are not common in nature except as occasional efflorescences in dry regions. Schroeckingerite (greenish yellow) is one of the most important carbonates and zippeite (yellow) is one of the most common sulfates. Of the uranium silicates, uranophane (yellow) is the most common. The rare earth niobates--euxenite, samarskite, and fergusonite--contain variable amounts of uranium. They are dark-colored or black minerals and are not found in large amounts. Brannerite and davidite are the uranium titanates. Both are black and neither is common.

Of all these uranium minerals, only pitchblende, davidite, brannerite, carnotite, tyuyamunite, autunite, and torbernite generally form minable deposits under present economic conditions. The other uranium minerals, however, are commonly associated with uranium ores and are useful as clues to the possible presence of uranium deposits.

Among the minerals that may contain minor amounts of uranium, the most important are carbonate-fluorapatite, fluorite, monazite, zircon, and certain carbonaceous materials. Carbonate-fluorapatite generally contains no more than 0.03 percent of uranium; fluorite and monazite may contain as much as a few tenths of a percent of uranium; and zircon and certain carbonaceous materials, such as thucholite, may contain several percent of uranium.

## TYPES OF URANIUM DEPOSITS

Before discussing the characteristics of the various types of uranium deposits, it is appropriate to mention some economic considerations by which the value and importance of the various types may be gauged. High-grade uranium deposits over the world are those that contain about 0.5 percent of uranium in the ore or in an easily formed mechanical concentrate. The Atomic Energy Commission will buy ores containing 0.1 percent uranium so that we may consider deposits of this grade minable in this country, if they are easily accessible (U. S. A. E. C. and U. S. G. S., 1951, pp. 94-102). As with other ores, we might apply the rule of thumb that if a metal can be recovered as a byproduct of another constituent its



concentration need only be one-tenth as much as it would need be otherwise. For practical purposes we may thus consider that deposits which might yield uranium as a byproduct need contain only about 0.01 percent uranium under present economic conditions in this country.

Uranium is concentrated by a wide variety of processes in a wide variety of deposits (Bain, 1950; Everhart and Mathez, 1951; C. F. Davidson, 1951; Everhart, 1954 a, b). Like other metals, uranium is transported and acted upon by igneous, weathering, and sedimentary processes but, to a greater degree than most metals, uranium is also concentrated by each of these processes. This diversity of origin and occurrence of uranium is one of the fascinating features of uranium geology, but it makes the description and classification of uranium deposits difficult. Thus, on the one hand, the various types of deposits grade into one another so subtly and completely that it is difficult to segregate them descriptively. And on the other hand, positive criteria by which one may identify the process responsible for the formation of many individual deposits, including some of the more important ones, are lacking. For these reasons, the various types of uranium deposits are grouped here simply by the type of rock in which the uranium is found.

#### Uraniferous igneous rocks

Nearly all igneous rocks contain traces of uranium (Evans and Goodman, 1941), but the largest quantities are found, along with many other elements enriched in pegmatites (Coats, TEI-330, p. 87 /).

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/ U. S. Geological Survey reports TEI-330, TEI-390, and TEI-440 include progress reports on nearly every current Survey project in the field of uranium geology. For the sake of brevity, these reports are listed only once in the bibliography, with the U. S. Geological Survey shown as author, rather than by the author of the various sections to which reference will be made. References to individual sections will be given as above.

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In silicic types and particularly in late stage alkalic differentiates. Few of the silicic rocks contain more than 0.001 to 0.002 percent uranium but some of the alkalic rocks, such as the pyrochlore-bearing

albite-riebeckite granites of Nigeria (Mackay and Beer, 1952) and the quartz-bostonite dikes in the Colorado Front Range (Phair, 1952), contain 0.005 to 0.02 percent. Among the volcanic rocks, the glassy phases seem to be most uraniferous (J. A. S. Adams et al., 1953).

The uranium in some of the igneous rocks is mainly in accessory minerals like pyrochlore, monazite, zircon, sphene, and apatite (Larsen et al., 1952), some of which might be concentrated and recovered by mechanical means. In others, however, an appreciable amount is in an acid soluble form (Hurley, 1950; C. F. Davidson, 1951; H. Brown et al., 1953) that might be recovered by leaching. The potential tonnage of uranium in igneous rocks, particularly the plutons, is enormous.

#### Uranium-bearing pegmatites

Many granitic pegmatites contain minor amounts of uraninite and other radioactive minerals (Page, 1950; Lang, 1952). According to Page, uraninite is closely associated with muscovite and biotite; betafite with biotite; euxenite and monazite with beryl; and samarskite with columbite and fergusonite. Calcite and calcite-fluorite pegmatites in the Grenville region of Ontario also contain minor amounts of uraninite (Ellsworth, 1932), and Lang (1952, p. 15) reports a uranium-bearing diorite pegmatite in the Northwest Territories. Some pegmatite dikes contain spectacular crystals of uranium minerals, but few have minable quantities that contain more than 0.01 percent of uranium and the size of individual deposits is not large.

Uraninite-bearing migmatite rocks have been found recently in the Charlebois Lake district (Mawdsley, 1952) and other areas in Saskatchewan (Lang, 1952). Large volumes of some of the migmatite rock contain 0.01 percent uranium or more.

#### Hydrothermal vein deposits

Of the hydrothermal vein deposits, three overlapping types are the most important: 1) nickel-cobalt-native silver-pitchblende veins (Bastin, 1939; Everhart and Wright, 1953); 2) pyrite-galena-pitchblende veins (Everhart and Wright, 1953); and 3) uraniferous fluorite veins (Wilmarth et al., 1952). A fourth type, brannerite-bearing quartz veins (Pabst, 1954), and a fifth, high temperature uraninite veins (Stevenson, 1951) may be mentioned also, though they are not common.

The nickel-cobalt-silver-pitchblende veins may contain important amounts of several base and precious metals, chiefly copper, nickel, cobalt, silver, lead, and bismuth. They are more apt to have a carbonate than a quartz gangue, and commonly occur in metasedimentary and volcanic host rocks. The pyrite-galena-pitchblende veins may contain minor amounts of lead, copper, and several other metals but consist chiefly of pitchblende, galena, quartz, or jasper, and pyrite; felsic intrusives are generally the host rocks. Both types commonly contain conspicuous hematite stains. Fluorite may occur in either type, though it is more prominent in the pyrite-galena-pitchblende veins, and it forms the chief mineral in the uraniferous fluorite veins. The uranium in some of the latter deposits occurs as pitchblende grains disseminated in the fluorite, but in others no uranium mineral has been recognized. The nickel-cobalt-silver veins, of which the Great Bear Lake, Canada (Kidd and Haycock, 1935; James et al., 1950), Joachimsthal, Czechoslovakia (Zuckert, 1926), and Skinkolobwe, Belgian Congo (Thoreau and Terdonck, 1933) deposits are examples, have been by far the most important uranium producers of the past (Merritt, 1949). They have large tonnages of ore that contain more than 0.1 percent uranium, and they are the only uranium ores that yield large tonnages containing 0.5 percent of uranium or more. The pyrite-galena-pitchblende veins, of which the Urgeirica, Portugal (Everhart and Wright, 1953) and Goldfields, Saskatchewan (Robinson, 1950) districts are the most important examples, generally yield smaller tonnages of ore that contain 0.1 to 0.5 percent uranium. The uraniferous fluorite veins generally contain less than 0.1 percent uranium.

When oxidized, the vein deposits of uranium are characterized by secondary uranium minerals like autunite, torbernite, and schroëckingerite, either formed in situ or deposited in cracks in other rocks nearby (Stugard, et al., 1952). Secondary enrichments are uncommon. The weathering process tends to disperse the uranium in the lodes, rather than to concentrate it further; most oxidized vein deposits, therefore, are less uraniferous than the lodes from which they were derived. They generally contain less than 0.2 percent of uranium and in some the uranium may be leached out altogether, leaving a residual radioactivity due mainly to the lagging behind of the more insoluble disintegration products (Phair and Levine, 1953). Such radioactivity is of interest because it indicates the possible presence of higher grade deposits at depth.

## Replacement deposits

Disseminated replacement deposits of uranium are common in the vicinity of pitchblende veins, but other replacement deposits are rare. Davidite replaces basic rocks in Mozambique (Davidson and Bennett, 1950) and is found in irregular lodes in pre-Cambrian schists at Radium Hill, Australia (Mawson, 1944). Uranium-bearing thorianite replaces metamorphosed trachyte near Birch Island, British Columbia (F. C. Armstrong, written communication, 1953). Pitchblende replaces pre-Cambrian carbonaceous slate and schist in the Rum Jungle district of Australia (Sullivan and Matheson, 1952), pre-Cambrian Franklin limestone in Warren County, N. J., and the Jurassic Todilto limestone at Grants, N. Mex. (Towle and Rapaport, 1952). The origin of the Todilto deposits is uncertain, but the association of uranium with fractures and replacement deposits of fluorite (Bucher, 1953) implies a hydrothermal origin. Pitchblende, carnotite, and other uranium minerals replace logs, clay galls, and bones in sandstone ores but, as will be discussed more fully later, the origin of such deposits is in dispute.

## Tuff and tuffaceous sediments

Many volcanic tuffs and tuffaceous sedimentary rocks of Tertiary age in the western United States contain autunite, carnotite, and other secondary minerals on fractures and bedding planes (Hewett, 1923, 1925; Walker, 1953; Walker and Lovering, 1954). Perhaps some of these deposits have a hydrothermal origin (Duncan, 1953 b), but it seems more likely that the uranium has been derived from the enclosing tuffs (which may contain 0.001 to 0.002 percent uranium) during the course of their devitrification, as suggested by Gill and Moore (1954) for the carnotite-bearing tuffaceous sandstone recently found in South Dakota. The uranium in such deposits is irregularly distributed. With a few exceptions, known occurrences are small and minable thicknesses generally contain less than 0.2 percent of uranium.

## Uraniferous coal and associated carbonaceous shale

Most coal and associated carbonaceous shale beds are essentially non-uraniferous but several have been found in recent years in the western states that contain 0.005 to about 0.1 percent of uranium and, of course, correspondingly larger amounts in their ash. The uranium seems to be in an organo-uranium compound or complex (Breger and Deul, TEI-330, p. 121) and is irregularly distributed in the coal. The largest amounts seem to be in carbonaceous shales, high-ash lignites, and sub-bituminous coal.

Denson, Bachman, and Zeller (work described in Vine and Moore, 1952) found in their studies of the South Dakota lignites that in most places only the first lignite bed immediately below the Oligocene White River formation, which unconformably overlies the coal-bearing series there, is uraniferous. Traced laterally, a given bed, uraniferous where it is the first bed below the unconformity at the base of the White River, is found to be non-uraniferous down dip where it is overlain by another lignite higher in the section (Gill, TEI-390, p. 131). Moreover, the uranium content of a given layer is generally highest at the top. Concentrations of uranium also are found where lower beds are intersected by faults or through-going joints. From this and other evidence, Denson and others concluded that the uranium in the lignite was derived from the White River formation and the overlying tuffaceous Arikaree formation by percolating ground waters. Because the White River formation contains abundant volcanic ash, known to be slightly uraniferous in some other localities, they postulated that the uranium was derived from the decomposition of the volcanic ash. Application of this hypothesis to the search for other deposits has given rewarding results in a number of areas.

In view of the fact that the uranium can be adsorbed by lignite from uranium-bearing solutions (Moore, 1954), other sources besides tuff--decaying arkosic rocks or even hydrothermal solutions--might yield uranium to lignites and other adsorbents. Thus, the uranium in a coal bed cut by a shear zone at the old Leyden mine at the foot of the Colorado Front Range is thought to have been derived from hydrothermal solutions (L. R. Page, oral communication, 1952). Despite the relatively low uranium content, some of the uraniferous lignites contain large tonnages of uranium, and it is not inconceivable that uranium may be recovered eventually from these deposits, particularly as a byproduct of other operations.

## Uranium-bearing continental sandstone and conglomerate

Uranium-bearing continental sandstones and conglomerates include the largest uranium source in this country and the largest source in the world--the Colorado Plateau and the Witwatersrand of South Africa, respectively--and the subsequent discussion focuses mainly on deposits in these districts.

The Colorado Plateau deposits have been traditionally called carnotite deposits because of the brightly colored carnotite and other oxidized minerals that characterize them near the surface (Fischer, 1937, 1950). Recently, however, deeper mining and drilling have shown that carnotite is only a shallow oxidation product of the weathering of pitchblende and other dark uranium and vanadium minerals that characterize the deposits at depth (Rasor, 1952; Rosenzweig et al., 1952; Weeks et al., 1953; Weeks and Thompson, 1954). These minerals, along with hydromica, pyrite, and other sulfides, fill pore spaces in tuffaceous, arkosic, and quartzose sandstones and conglomerates and also replace clay galls, logs, and other wood fragments. In addition to woody carbonaceous matter, some of the deposits contain uraniferous asphaltic pellets and lenses (Gott and Erickson, 1952) and a harder form of uraniferous "carbon," insoluble in organic reagents (I. A. Breger, oral communication, 1953), that has been likened to thucholite (S. H. U. Bowie, oral communication, 1952). Uranium, vanadium, copper, or silver may be the dominant metal in the deposits, and minor amounts of molybdenum, cobalt, nickel, lead, zinc, selenium, and arsenic are also present in many of them (Riley and Shoemaker, 1952). Quartz-overgrowths are abundant on the sand grains (Waters and Granger, 1953). In some deposits, the ore seems to be localized near or to replace carbonate cement (Sharp et al., TEI-440, p. 64; Gott et al., TEI-440, p. 67).

The ore deposits are tabular masses, generally elongated in the direction of the long axes of the sandstone or conglomerate lenses in which they occur. The latter are interpreted as fossil stream channel deposits. In the vicinity of ore, associated mudstone lenses are generally green or gray instead of red and, in the oxidized deposits, the sandstone in many places has a freckled appearance instead of its usual uniform reddish brown color (Weir, 1952). Ore has been produced from about 20 formations on the Plateau, ranging in age from Permian to Tertiary, but the principal sources have been the Triassic Moenkopi, Shinarump, and Chinle formations, the Jurassic Entrada, Summerville, and Morrison (including the Salt Wash, Todilto,

Recapture, Westwater Canyon, and Brushy Basin members) formations (Riley and Shoemaker, 1952; T. W. Mitcham, unpublished chart, 1954). Within any given area, however, known minable deposits generally are restricted to one favorable zone or layer, a few or a few tens of feet in thickness. Within this zone, the distribution of ore is confined mainly to the channel sandstones and, within them, is localized in zones where their thicknesses increase, where mudstone partings or fine debris are present, and at channel bends and other places where logs and other carbonaceous matter are abundant (Weir, 1952; Stokes, 1952, 1954; Finch, 1953). The deposits often cut across the bedding to form concretion-like structures called "rolls" by the miners. In a few areas the deposits are localized along joints or faults (Coffin, 1921, p. 162, 170, 214; Benson et al., 1952; Waters and Granger, 1953, p. 10; Shoemaker, unpublished report, 1954), and it has been suggested (E. V. Reinhardt talk at San Francisco meeting of Am. Mining Cong., Sept. 21, 1954) that the rolls also represent ore disseminated from solutions moving along a joint, the position of which is now obscure. Many of the deposits in the Black Hills appear to be localized on structural terraces (Gott et al., TEI-440, p. 66). Despite these exceptions, the sandstone ores as a rule show no obvious relation to local structures other than the sedimentary ones. In contrast to most of the deposits in sandstone and conglomerate, those in the Todilto limestone seem to be concentrated along fractures (Bucher, 1953; Gilkey, 1953).

The regional distribution of the deposits has been correlated with both tectonic and sedimentary features. Within any given formation, the deposits are most prominent in areas where channel deposits are well sorted, but intertongue or are interbedded with mudstones (Craig et al., 1951; D. F. Davidson, 1953 a; Masters, 1953; Gott et al., TEI-440, p. 66; Mullens and Freeman, 1954), or are near the margins of deposition of the formation (Mullens, TEI-390, p. 23; Finch, 1953). They also seem to be abundant in the vicinity of (though not adjacent to) the alkalic laccolithic intrusives (Riley and Shoemaker, 1952; Reinhardt, 1952; Shoemaker, unpublished report 1954) such as those comprising the La Sal and Carrizo mountains, and in some areas they seem closely related to early Tertiary faulting associated with the collapse of salt anticlines (Cater, 1954; Shoemaker, unpublished report 1954). As a result of these controls, singly or together, many of the most important deposits of the Plateau are clustered together in "mineral belts" that have considerable regional continuity. Of these, the Uravan mineral belt is the best defined

(Fischer and Hilpert, 1952), but three others have been recognized recently in Utah and Arizona (Finch, 1953). Recognition of these belts has aided considerably in exploration for new deposits.

Individual deposits on the Plateau range from a few pounds to more than a million tons in size. Their uranium content is generally in the range of 0.1 to 0.5 percent.

The Witwatersrand ores consist mainly of pyrite, uraninite, thucholite, gold, sericite, chloritoid and chlorite, and minor amounts of cobalt, copper, nickel, lead, and zinc sulfides (Young, 1917; Reinecke, 1930; Davidson and Bowie, 1951; C. F. Davidson, 1952, 1953). These minerals are in pore spaces in coarse sandstones and conglomerates, the grains of which contain abundant quartz overgrowths.

The ore-bearing strata have considerable lateral continuity, but ore tends to be concentrated in elongated paystreaks, which are roughly parallel but form a braided pattern, interpreted by Leopold Reinecke and Douglas Johnson (Reinecke, 1940, p. 127) as channels on a gigantic piedmont alluvial fan. The Witwatersrand system is about 25,000 feet in thickness, but ore is confined to a dozen or so thin conglomerates, mostly in the upper half of the system (McLean, 1954). Of these, only one or two are prominent ore-bearers in any given area (Reinecke, 1940, p. 120). Within these layers ore seems most abundant where the conglomerates are thickest and where the pebbles are coarsest and best sorted.

A variety of igneous intrusives has been reported from the Rand. They range in composition from basic to acid to alkalic types, but the most common are altered diabase dikes. Few have any evident relation to ore. Thin quartz veinlets are not uncommon and although some of them contain gold (Young, 1917) and one high in the system contains pitchblende (C. F. Davidson, 1953), such phenomena comprise a minor part of the Rand picture. Likewise the ores seem unrelated to fractures and faults, although a few faults are mineralized where they cross ore bearing horizons.

The Witwatersrand ores have greater lateral continuity and are lower in uranium content than the Plateau ores and the ores in the two fields differ somewhat in the assemblage of dominant metals--chiefly the presence of gold and the absence of vanadium in the Rand ores and the reverse with respect to the Plateau ores. Nevertheless, from the descriptions above it may be seen that the deposits of the Witwatersrand



and the Colorado Plateau have many features in common. The origin of both ores has been hotly debated for decades and is still in dispute. Essentially the same hypotheses of origin, or variants of them, have been presented for ores in both regions: 1) placer concentration of the chief ore metals, followed by recrystallization and some redistribution of them (Lindgren, 1913, p. 378; Bain, 1952; Young, 1917; Reinecke, 1930); 2) precipitation from solution at time of deposition of enclosing sediments, followed by recrystallization and some redistribution (Fischer, 1937; Gruner, 1951; MacGregor, 1953); 3) derivation from volcanic tuffs or other sediments associated with the ore, as the result of weathering and ground water action, after the enclosing rocks were deposited (Koeberlin, 1938; Proctor, 1953); and 4) derivation from hydrothermal solutions, possibly injected into circulating ground waters, after the enclosing rocks were deposited (Dodd, 1950; Waters and Granger, 1953; Cater, 1954; Graton, 1930; C. F. Davidson, 1953; Shoemaker, unpublished report 1954; Kerr and Lapham, 1954).

It is interesting to note that the supporters of the syngenetic and penesynthetic hypotheses include most of the exploration geologists in both areas who are best acquainted with the habits of the ores. This attests to the close relation the ores bear to sedimentary rather than tectonic and igneous features. The epigeneticists admit this relationship but believe that these sedimentary features merely controlled the movement of ore solutions and the deposition of metals derived from other sources after the enclosing rocks were deposited. Without reviewing the arguments for any of these hypotheses it may suffice to say that recent age determinations of the Plateau ores show that the uranium there was deposited during the late Cretaceous or early Tertiary, long after the deposition of the host rocks (Stieff, Stern, and Milkey, 1953), whether the ore was derived from dispersed sources in the sedimentary pile or from hydrothermal solutions.

Regardless of the origin of the sandstone ores, the knowledge already gained about their habits is adequate not only to guide exploration for ore in known districts but to search for new districts as well. Basic to the exploration for individual deposits in known districts are the facts that 1) the deposits in a given area are confined to certain zones and 2) within them, to the vicinity of the boundaries between

permeable and impermeable parts. Of value in the search for new districts are the facts that, with few exceptions, the deposits have been found only in continental deposits and, as C. F. Davidson (1953) points out, the old granitic rocks over which these deposits lie in several districts "have undergone domal uplift since the covering blanket of sediments was deposited, due presumably to intrusion of 'younger' granites which are not always exposed."

#### ~~Uraniferous asphaltite~~ and related substances

Uranium, in places in the form of free, evenly disseminated grains of uraninite, commonly occurs in asphaltites; in hard, lustrous hydrocarbons called thucholite (Ellsworth, 1928); and in similar appearing substances, here referred to as "asphaltite," that contain little or no hydrogen (I. A. Breger, oral communication). These substances occur in many uraniferous veins, pegmatites, sandstone deposits, and certain reservoir rocks in oil fields (Davidson and Bowie, 1951; Faul et al., 1952; Gott and Erickson, 1952; Barthauer et al., 1953). Davidson and Bowie (1951) and others believe that the thucholite in many pegmatites, veins, and in the Witwatersrand originated from the polymerization of migrant natural gases by radiation from uranium-bearing minerals already in those deposits. The facts that "asphaltite" occurs in oil-stained pore spaces, that the uranium is so uniformly distributed that it must have been in the organic matrix while the latter was in a fluid state, and that the "asphaltite" contains an assemblage of other metals similar to that found in smaller concentrations in oil in nearby pools (Erickson et al., 1953) led Gott (TEI-390, p. 257) to the conclusion that the uraniferous "asphaltite" is a residual petroleum. It is thus possible that petroleum fluids may transport uranium to sites of ore deposition (Gott and Erickson, 1952), particularly in sandstone-type deposits.

### Uranium deposits in limestone

Most carbonate rocks are non-radioactive (Beers and Goodman, 1944) and the few that do contain uranium are probably of diverse origins. The only limestone that has yielded commercial amounts of uranium, either from this country or abroad, is the Jurassic Todilto limestone near Grants, N. Mex. As mentioned previously, these deposits seem to be replacements along fractures, are associated with fluorite, and are probably of hydrothermal origin. Carnotite and uranium-bearing fluorite are sparsely disseminated in limestone adjacent to a thin uraniferous black shale in the Mississippian Spergen formation in Missouri (Muilenberg, 1949) and are thought to have been leached from the black shale by ground water (Gott, et al., 1952). Alternatively, it seems possible that the uranium in both the limestone and the shale as well as the fluorite were derived from pneumatolytic solutions. Small amounts of uranium in slightly petroliferous and phosphatic clay galls in the Cambrian Milton dolomite in Vermont and in algal limestone in the Tertiary Uinta formation in Utah may be syngenetic (Gott et al., 1952). Uranium in algal, chalcedonic limestone in the Miocene (?) Brown's Park formation at Miller Hill, Wyoming appears to be most concentrated where the limestone is fractured and brecciated and to have been derived from adjacent tuffaceous sediments (Vind and Prichard, TEI-390, p. 91).

### Uraniferous aluminum phosphate deposits

Uraniferous aluminum phosphate minerals originate as a result of the weathering of phosphorite in a tropical or subtropical climate. Examples are those in Florida (Cathcart et al., 1953), Senegal (Guntz and Arene, 1953; Capdecombe, 1953), and Nigeria (Davidson and Atkin, 1953). The form of the uranium in these deposits is unknown. A few particles of autunite have been identified by Altschuler and Boudreau in the Florida deposits (unpublished report, 1949) but the bulk of the uranium is probably in the phosphate minerals, where it probably substitutes for calcium or phosphorus. In Florida, the aluminum phosphate deposits compose the upper (near surface) part of the Pliocene Bone Valley formation. The aluminum phosphate zone averages about 6 feet in thickness but ranges from less than 1 foot to 60 feet in thickness.

It is generally thickest on topographic highs. From 70 to 80 percent of the zone consists of quartz sand; the remainder is composed of minus 150 mesh particles of wavellite, crandallite (pseudowavellite), carbonate-fluorapatite, and kaolin--easily separable from the sand by washing. Crandallite is most abundant in the lower part of the zone, and wavellite in the upper (Altschuler, TEI-330, p. 171-174). The uranium content of the fine fraction ranges from 0.01 to 0.02 percent or more and is highest near the base of the zone where crandallite first appears (Altschuler, *idem*).

The aluminum phosphate deposits in Florida, and presumably the other fields as well, contain enormous tonnages of uranium. In Florida this material is now stripped as overburden and discarded; but, because the fines contain 15 to 30 percent of  $P_2O_5$  and a similar amount of  $Al_2O_3$ , it is possible that this material may eventually be utilized. If so, uranium probably will be recovered as a byproduct of phosphate or alumina production, or both.

#### Uraniferous black shale

Many marine, bituminous black shales contain 0.005 to 0.02 percent of uranium (Beers, 1945; Russell, 1945; McKelvey and Nelson, 1950; Gott et al., 1952). Examples include the alum shale of Sweden (Westergard, 1944 a, b) and the Chattanooga shale of Tennessee (Conant, 1952; Swanson, 1953). The uranium in these shales is in acid-soluble form, but it probably does not occur in a distinct uranium mineral. In the Chattanooga shale it is concentrated in pyrite-organic matter complexes (Bates and Wright, 1953). The largest amounts of uranium (as much as 0.5 percent) in both the alum and Chattanooga shale are in nodules and lenses of dark bitumen (called kolm in the alum shale). Though the megascopic nodules of bitumen do not contain an appreciable proportion of the total uranium in the shale, the uranium content of the alum shale in parts of Sweden increases as the total equivalent thickness of kolm increases (Josef Eklund, oral communication, 1952). This suggests that microscopic pellets of kolm (believed to be present) may be the uranium carriers in the shale itself. In the Miocene nodular shale in California and the

Pennsylvanian Cherokee shale in Oklahoma the uranium may occur both in phosphate and carbonaceous matter (Whitehead, 1952). Brown and Keller (1952) report that the uranium in a black shale in the Mississippian Spergen limestone in Missouri is in the fine clay fraction, not the organic matter.

Though nearly all marine black shales contain slightly more uranium than the average sedimentary rock, only a small percentage of them contain more than 0.005 percent. The distinguishing characteristics of the uraniferous shales are not known in full, but it can be said at least that as a group they are sapropelic, rather than humic. They are highly carbonaceous (Barton and Sullivan, 1951) and bituminous, high in sulfides, non-calcareous, somewhat phosphatic (or contain phosphatic nodules in the section), and accumulated slowly (their net accumulation apparently proceeded only at the rate of 1 foot per 200,000 to 1,000,000 years, compared to 1 foot per 700 years for other shales), probably under anaerobic conditions. The richest parts of the alum shale in Sweden were deposited in embayments in the Upper Cambrian sea (Eklund, oral communication, 1952), and the uranium in the most uraniferous shale known in this country, the Pennsylvanian Hartville in Wyoming, seems also to have been concentrated near the margin of deposition of that shale. Older shales, as a group, appear to be more uraniferous than younger shales (Russell, 1945).

Very likely the uranium in black shales is extracted by organic matter from the sea, probably by adsorption on plankton. This process has been demonstrated for other metals by Harvey (1945) and Krauskopf (1952) and for uranium by Steel and Gloyna (1953). The reason uranium is more concentrated in some black shales than in others, however, is unknown. It has been suggested that high concentrations may form in restricted areas bordering granitic terranes (Glebov, 1941; Ström, 1948), but this alone does not explain the marked differences often found in the uranium content of two adjacent layers nor the uranium content of such widespread formations as the Chattanooga shale. It seems more likely that the controls have to do with the pH, redox potential, and other physico-chemical factors that affect the precipitation of uranium in the sea. Because some uraniferous shales have a demonstrable capacity to adsorb uranium (Tolmachev, 1943) and because uranium is irregularly distributed in some non-marine carbonaceous shales, where it appears to have been adsorbed from percolating waters, it is not unlikely that uranium can be adsorbed by black shales long after their deposition, or at least until compaction materially reduces their

perviousness. The uniformity of the distribution of uranium in the marine shales suggests, however, that this has not been the dominant process in the concentration of uranium in them.

Black shale formations contain some of the world's largest uranium resources. Despite their low uranium content it is possible that they may eventually yield uranium as a co-product of the production of oil, sulfur, potash, phosphate, and other minor metals.

#### Uraniferous phosphorite

Marine phosphorites commonly contain 0.005 to 0.03 percent of uranium (McKelvey and Nelson, 1950; Davidson and Atkin, 1953). Important examples include the phosphorites in the Permian Phosphoria formation in the Western States (Thompson, 1952, 1953), the Pliocene Bone Valley formation of Florida (Cathcart et al., 1953), and the Upper Cretaceous-Lower Eocene deposits of North Africa (Hebert, 1947; Guntz, 1952; Lenoble et al., 1952). Although traces of secondary uranium minerals have been found in the Moroccan (Arambourg and Orce1, 1951) and Phosphoria deposits; the uranium in the phosphorites seems to be mainly in the mineral carbonate-fluorapatite, where it probably substitutes for calcium (Altschuler et al., 1954, p. 157-158). The uranium content of the rock generally increases as the phosphate content increases, but deposits or beds richest in phosphate are not necessarily richest in uranium, and in the Phosphoria formation the most uraniferous samples known are not the most phosphatic. Some of the departures from the general rule that uranium increases as the  $P_2O_5$  content increases may be due to the inverse relationship uranium bears to the  $CO_2$  content. In the Phosphoria formation the uranium content generally falls off sharply as the  $CO_2$  content rises above 2 percent, regardless of the phosphate content. It is interesting to note that the weakly phosphatic black shales in the Phosphoria contain little or no uranium.

Phosphatic nodules in certain black shales, such as those of Pennsylvanian age in Kansas and Oklahoma (Runnels, et al., 1953), are uraniferous, generally more so than the enclosing black shale. Phosphatic nodules on the present sea-bottom off the coast of California contain about the same quantity of uranium as older phosphorites (Emory and Dietz, 1950). Fossil bones and teeth are also uraniferous and the uranium content seems to be greater in older than younger specimens (Jaffe and Sherwood, 1951).

In the Phosphoria formation, however, beds composed mainly of phosphatic shells, fish scales, and other organic fragments are less uraniferous than other kinds of phosphatic materials.

The concentration of uranium in phosphorite takes place by ion exchange (Neuman, et al., 1949 a, b, c; Moore, 1954) or other chemical adsorption processes. It may thus be deposited at essentially the same time as the phosphorite or at any time thereafter. The uniform distribution of uranium in the marine phosphorites, as well as the presence of uranium in phosphorite on the present sea bottom, suggests that the uranium in most of those deposits is adsorbed from the sea water at the time of deposition or before burial. The increase of the uranium content of bones and teeth with age indicates that an appreciable part of the uranium in them is adsorbed from ground water solutions, possibly long after the bones were deposited. The fact that the uranium content of phosphorite particles in the Pliocene Bone Valley formation of Florida is appreciably higher than in the underlying Hawthorn formation, from which the Bone Valley was derived by submarine reworking of the Hawthorn and its weathered debris, suggests that the Bone Valley particles adsorbed more uranium from sea water during their second exposure to it.

In summary, the uranium content of phosphorite deposits is not wholly predictable but as a general rule appreciable amounts are found only in non-calcareous marine phosphorites that contain more than 25 percent  $P_2O_5$  (in the rock or in the concentrate of phosphatic particles). Residual deposits derived from the weathering of phosphatic limestones are not likely to be appreciably uraniferous unless they have been exposed later to sea water or other uranium-bearing solutions.

#### Uraniferous placers

Because the common uranium minerals are relatively soft and are soluble in the zone of weathering, most uranium minerals are not concentrated in placers (C.F. Davidson, 1953). Exceptions are found, however (Steacy, 1953), particularly in placer concentrations of some of the accessory uranium-bearing minerals of igneous rocks and pegmatites--for example, monazite, zircon, and the "radioactive blacks" euxenite, samarskite, and fergusonite--which contain variable, but in places appreciable amounts of uranium. The relatively small size of the known placer deposits, particularly the "radioactive blacks," combined with the refractory nature of these uraniferous minerals, have not made them important sources of uranium anywhere.

### Summary of the geology of uranium

From the previous description of the various types of uranium deposits, it may be seen that uranium is a chemically active and mobile **metal**. In magmatic processes some of it combines with other elements and crystallizes mainly as accessory minerals, particularly in late stage differentiates such as silicic and alkalic igneous rocks and pegmatites. Some, however, remains with other metals in late stage solutions and is transported away from the magma by hydrothermal and pneumatolytic processes and deposited in veins, and possibly in previous or carbonaceous sedimentary formations, as pitchblende.

During the weathering of these primary concentrations, some insoluble minerals (mainly the accessory minerals of igneous rocks and pegmatites) are freed from their matrix and eventually concentrated in placers. Most of the primary uranium, however, is oxidized, taken into solution in the form of sulfates, carbonates, and other relatively soluble salts, and ultimately transported to the sea, either in solution or adsorbed on clay and organic matter (Fredrickson, 1948). The dispersal of primary concentrations may be interrupted by the formation of secondary concentrations along fractures and in cavities in almost any kind of rock where uranium salts are precipitated because of evaporation, or changes in the pH or redox potential of the **groundwater** solution. Uranium may also be adsorbed by carbonaceous materials-- peat, certain coals, carbonaceous shale and plant fossils--or by phosphatic materials such as bone, phosphorite, or monazite.

In the marine environment, Holland and Kulp (1954) reason that the bulk of the uranium brought to the sea in solution is deposited on the shelves, probably because it is removed by organisms. Available data are not **adequate** to prove or disprove this hypothesis, but it is at least true that the highest concentrations in sediments are formed on the shelf or near its margin, probably as the result of the upwelling of cold, deep CO<sub>2</sub>-rich waters. These waters, rich in phosphate and other nutrients, not only nourish large growths of plankton and other organisms (Hentschel and Wattenburg, 1930) whose death and decay may produce anaerobic bottom conditions (Brongersma-Sanders, 1948), but they are the source of the phosphate and the minor metals deposited in this environment (McKelvey et al., 1953).



The association of uranium with carbonaceous materials in the uranium cycle deserves special summary, particularly because of its bearing on petroleum geology. Carbonaceous matter is associated with many of the types of uranium deposits already mentioned--even with some of the vein and pegmatite deposits, as well as many asphaltites, isolated carbonized fossil plants, sandstone deposits, and many petroleum. In addition, radioactive decay products of uranium are found in many natural gases and oilfield brines (Gott and Hill, 1953). The significance of this association is not completely known. It seems definite that some carbonaceous matter is in some way a precipitator of uranium (Tolmachev, 1943; Frederickson, 1948; Moore, 1954) and that some plants concentrate uranium, at least in small amounts (Cannon, 1952). In addition, it is possible that radiation stemming from uranium in sediments generates petroleum from associated organic matter (Whitehead et al., 1951), that it also polymerizes migrant methane into the carbonaceous substances found in some pegmatite and vein deposits (Grip and Odman, 1944; Davidson and Bowie, 1951), and that petroleum fluids may sometimes transport uranium to sites of ore deposition (Gott and Erickson, 1952). In some places, the association may simply indicate that uranium compounds are more stable under reducing conditions such as generally prevail in environments where carbonaceous matter is also stable.

The progressive migration of uranium from its primary concentrations to sedimentary rocks involves a progressive dispersal of uranium from each phase of the cycle to the next. This is reflected in a change, roughly by a factor of five, in the grade of uranium of deposits formed during each phase. Thus the uranium content of pitchblende deposits is about 0.1 to 1.0 percent; that of deposits formed during weathering is 0.02 to 0.2 percent and that of most sedimentary deposits is less than 0.03.

The relationships described in the uranium cycle have a special bearing on prospecting for they constitute the geologic machinery that produce a metallogenic province. Thus in a region in which uranium is abundant in igneous rocks, pitchblende deposits may be expected also in hydrothermal vein deposits within the igneous rocks or in associated basement rocks; in continental sandstones (if any are present) overlying the plutons and perhaps in carbonaceous rocks also. Secondary uranium deposits may be found in volcanic ash; in lignites and carbonaceous shales; and in many other geologic environments. Discovery of any one of these is as good an indication of the regional presence of the others as can be had.

## METHODS OF PROSPECTING FOR URANIUM

The methods used to search for uranium deposits may be described as (1) geologic, (2) geophysical, (3) botanical, and (4) physical exploration. Not an insignificant number of uranium deposits, and deposits of other minerals too, have been discovered by accident, but unfortunately it is not yet possible to systematize an accidental prospecting method!

### Geologic prospecting

Geologic prospecting is based on the recognition of uranium minerals or on the recognition of geologic features commonly associated with uranium deposits. This is the method that the amateur uses when he picks up a bright-yellow or green mineral, and it is also the method that the geologist uses when he stops to examine a quartz-hematite vein or particular rock type that he knows is commonly associated with uranium. Success in geologic prospecting is proportional to the prospector's knowledge of ore habits and guides and to his industry, luck, and optimism. It is safe to say that few if any mines have been found by pessimists.

### Geophysical prospecting

As mentioned previously, the gamma rays given off by uranium minerals may be detected by use of Geiger and scintillation counters (Wright, 1953, 1954 a; Brownell, 1950; Wilson, et al., 1954). Their use gives the prospector an unusual advantage, for these instruments can detect the presence of radioactive minerals even if they are concealed from sight by a few inches or so of soil or rock. Geiger counters and scintillation counters have been developed in a variety of shapes and sizes, suitable for use by the prospector on the ground, for carborne (Nelson, 1954) and airborne (Stead, 1950; Stead and Davis, 1952) reconnaissance, and for drill-hole logging (Faul and Tittle, 1951; DiGiovanni, et al., 1953). The scintillation counter is much more sensitive than the Geiger counter and therefore will detect much smaller amounts of radioactivity. For this reason, scintillation counters have now largely displaced Geiger counters in airborne reconnaissance. Light planes, such as those used by the Atomic Energy Commission, are used to search for specific deposits in broadly favorable areas (Tavelli, 1951; Foote, 1954). They fly at an

altitude of about 50 feet and are equipped with scintillation counters that detect almost all abnormal radioactivity that field Geiger counters detect on the ground. Larger planes, like the Geological Survey's DC-3, are used for quick reconnaissance of large regions (Stead, 1950; Balsley, 1952). The Survey's plane is flown at an elevation of about 500 feet along traverse lines about a quarter of a mile apart, and it continuously records both radioactivity and magnetic measurements.

All of these instruments, of course, are applied mainly to the direct search for ore, that is, the search for a radioactive anomaly that represents an individual uranium deposit, or an area of above-average radioactivity in which ore deposits might be found (Gross, 1952). But complications arise from the fact that most of the radioactivity detected comes not directly from uranium itself, but rather from its radioactive decay products. These decay products, like radon and radium, sometimes get separated from the parent uranium but even then they may give a clue to the presence of uranium nearby. For example, small pips are observable on the gamma-ray logs of barren holes drilled down dip from many ore-bodies on the Colorado Plateau and therefore can be used in locating the ore itself (Bell and Rogers, 1950); in addition, the level of radiation in the ore-bearing horizon in some areas is much higher in the general vicinity of ore than elsewhere (Hinckley, 1952; Teichman, 1952). Similarly, the air in some mines is radioactive even though no radioactive minerals are observable in the mine walls (Dunning, 1950) and some natural gases and brines are radioactive even though no uranium or thorium deposits are known in the reservoir rocks (Gott and Hill, 1953). Such radioactivity is most likely due to the presence of radon, a highly radioactive gas formed as one of the disintegration products of uranium. Its presence indicates the nearby presence of uranium, though of course in unknown quantities. Radioactive anomalies arising from other daughter products of uranium have been found also in alluvium downstream from uranium deposits in South Dakota (R. S. Cannon, 1953) and on the Colorado Plateau (Chew, 1954). Like placer gold, these dispersed decay products provide useful clues to the presence and location of lode deposits.

Some of the more conventional geophysical exploration methods--resistivity surveys (Davis, 1951), refraction seismic surveys (Wantland and Casey, 1952), and electric logging (Black, TEI-330, p. 71)--have been tried in an experimental fashion on the Colorado Plateau. These methods do not indicate the presence of uranium any more than they do oil, but they show some promise in locating structures, such as buried channels, favorable for the occurrence of uranium.

### Botanical prospecting

Two methods of botanical prospecting have been developed recently to the point where they can be used in the search for some uranium deposits (H. L. Cannon, 1952, 1953, 1954 a, b). One method is based on the fact that certain plants, like juniper and saltbrush, take up uranium from the soil if any appreciable amounts are present. Samples collected from these uranium absorbers in the vicinity of shallow ore deposits contain amounts of two or three parts per million or more of uranium. The other principal method is based upon the fact that certain plants require for their growth large amounts of selenium (Beath, 1943), others require large amounts of sulfur, and others require plant nutrients that are not released from the soil except where large amounts of acids are present, as is the case in the vicinity of sulfide ore bodies. These plants are therefore indicators of selenium, sulfur, or other substances, and inasmuch as these substances are commonly associated with uranium, particularly in the ores of the Colorado Plateau, they may indicate the presence of uranium too. Prospecting by this method consists first of mapping the distribution of the sulfur and selenium indicator plants and then of drilling in the vicinity of the greatest concentration of these indicator plants. It should be emphasized that botanical prospecting can be used only where the ore lies at depths of less than 50 feet or so below the surface and, furthermore, that the indicator plant method can be used only where the indicated elements are known to be associated with uranium in the ore.

### Physical exploration

Most of the methods described thus far are rather inexpensive to use. Some require special equipment and knowledge but, with the exception of airborne reconnaissance, their cost is measured largely in terms of the time of the person applying them. If any of these methods or a combination of them does

point to a local concentration of uranium, the lead is followed by physical exploration--that is, drilling, trenching, test-pitting, or driving underground workings such as shafts or adits. In contrast to the other methods, all methods of physical exploration are expensive. For this reason only promising prospects are tested by drilling or other means, and when any of these methods are used they should be supported and guided by as full a knowledge of the geology of the district as can be had. On the other hand, when prospecting has developed a promising lead, such as an outcrop of ore or a favorable geologic association or structure, there is no substitute for physical exploration of one type or another to determine the extent, grade, and tonnage of the ore.

### Selection of areas for prospecting

The selection of areas in which to use these methods deserves some comment. Two approaches may be distinguished, one the observational or, "uranium is where you find it" approach, the other the analytical or "uranium is where it ought to be" approach. It will be no surprise to economic geologists to learn that most of the producing uranium districts in the world were found through the "uranium is where you find it" approach, as were also some of the important recent discoveries in this country, such as the Grants, N. Mex.; Marysvale, Utah; and Boulder, Mont. districts. Inasmuch as our understanding of the occurrence of uranium minerals or of the geology of this country is little more than skin deep the observational approach will continue to have an important place in prospecting for some time to come. Geologists of the Atomic Energy Commission and the Geological Survey have done a good deal of observational prospecting, not only by way of field reconnaissance but also by way of testing samples in museum collections; old drill cores; seismic shot holes; samples of all kinds of ores, concentrates, and tailings solicited from mining companies; and samples submitted by the public. (See Butler, 1952, for localities checked by the Geological Survey.) It will pay both prospectors and geologists to continue to look for uranium wherever and whenever they have opportunity, regardless of whether or not the specific area is supposed to contain uranium deposits.

The analytical or "uranium is where it ought to be" approach is the forte of the professional geologist. Geologists are notoriously poor prospectors, but they can be proud of the record they're building in the search for uranium. Most of their success has been achieved by the application of simple empirical relationships--the reasoning that if one phosphate rock is found to contain uranium, other similar phosphate rocks may contain it also. By examining rock associations similar to those already described, many previously unknown occurrences of uranium have been found in this country, particularly in phosphate rocks, lignites, and black shales. Geological theory has been little used thus far in the search for new districts simply because it is not well advanced, but the application of knowledge of ore habits and guides to the search for ore in previously known districts, such as the Colorado Plateau, has met with much success. We may confidently expect the scope and power of the analytical approach to increase markedly in the future as the body of data on the occurrence and geochemistry of uranium increases.

Nearly all of the prospecting methods described can be used with both the observational and analytical approaches. The most effective prospecting, of course, makes use of all knowledge and tools available and appropriate to the specific problem.

#### DISTRIBUTION OF URANIUM DEPOSITS IN THE UNITED STATES

The search for uranium in the United States has disclosed the presence of many small vein deposits, of large minable reserves in sandstone-type deposits, and tremendous resources of uranium in lignites, phosphorites, and marine black shales. The distribution of uranium in these and other deposits is shown on figures 1 to 5, and the more important of them are discussed in the following pages. In this discussion, the deposits are grouped according to the type of rock in which they occur, even though, as will be pointed out later, all deposits in some of the groups are not of the same origin. Inasmuch as no highly uraniferous igneous rocks or large uraniferous pegmatites have been found in this country, no attempt has been made to summarize the scattered data on their occurrence and they are omitted from the discussion that follows.

## Uranium vein and replacement deposits

Many uranium-bearing veins and related deposits have been found in recent years in the United States (fig. 1), though only a few have yielded any production. Nearly all are fracture fillings in igneous or metamorphic rocks but a few--such as the Thomas Range fluorspar pipes and the Placerville thucholite deposits--are found in breccia and fault zones in carbonate rocks. A few consist of uraniferous fluorspar deposits, but the majority are metalliferous quartz-sulfide deposits, mainly of the simple type, high in lead, copper, silver, or gold. Some have relatively complex mineral assemblages, but only the Blackhawk district in New Mexico appears to have the pitchblende-nickel-cobalt-native silver association that characterizes the world's largest uranium producers (Gillerman, 1952a); this deposit, however, has no important known reserves. Most of the metalliferous deposits shown on figure 1 contain pitchblende, but only secondary minerals have been found in the Majuba Hill, Goodsprings, Yellow Canary, St. Peters Dome, St. Kevin, Katherine and Michael, Silver Lady, Buckeye, and White Signal districts. Very likely pitchblende will be found on deeper exploration in these areas, though possibly not in minable quantities. Figure 1.

Vein and replacement deposits of uranium in the United States, mainly in igneous and metamorphic rocks. Deposits 11, 12, 15, and 18 are uraniferous fluorspar veins or pipes; the remainder are metalliferous veins or replacements. Names of localities and references to them are as follows: 1) Spokane molybdenite mine, Lincoln County, Wash. (King et al., 1952); 2) Coeur d'Alene district, Shoshone County, Idaho (ThurLOW and Wright, 1950); 3) North Fork-Shoup district, Lemhi County, Idaho (Trites and Tooker, 1953); 4) Boulder-Clancy area, Jefferson County, Mont. (Klepper, 1950; Becraft, 1953; Roberts and Gude, 1953, 1954); 5) Moonlight claims, Humboldt County, Nev. (Williams and Davis, 1953); 6) Stalin's Present mine, Pershing County, Nev. (Kaiser and Page, 1952; Anderson and Wadell, 1952); 7) East Walker River area, Lyon County, Nev. (StaatZ and Bauer, 1953); 8) Majuba Hill, Pershing County, Nev. (Thurston and Trites, 1952); 9) Goodsprings district, Clark County, Nev. (Behre and Barton, 1954); 10) Thomas Range district, Juab County, Utah (StaatZ and Bauer, 1951a, 1952); 11) Sheeprock Mountains, Juab County, Utah (Taylor, TEI-390, p. 215); 12) Yellow Canary claims, Daggett County, Utah (Wilmarth, 1953);

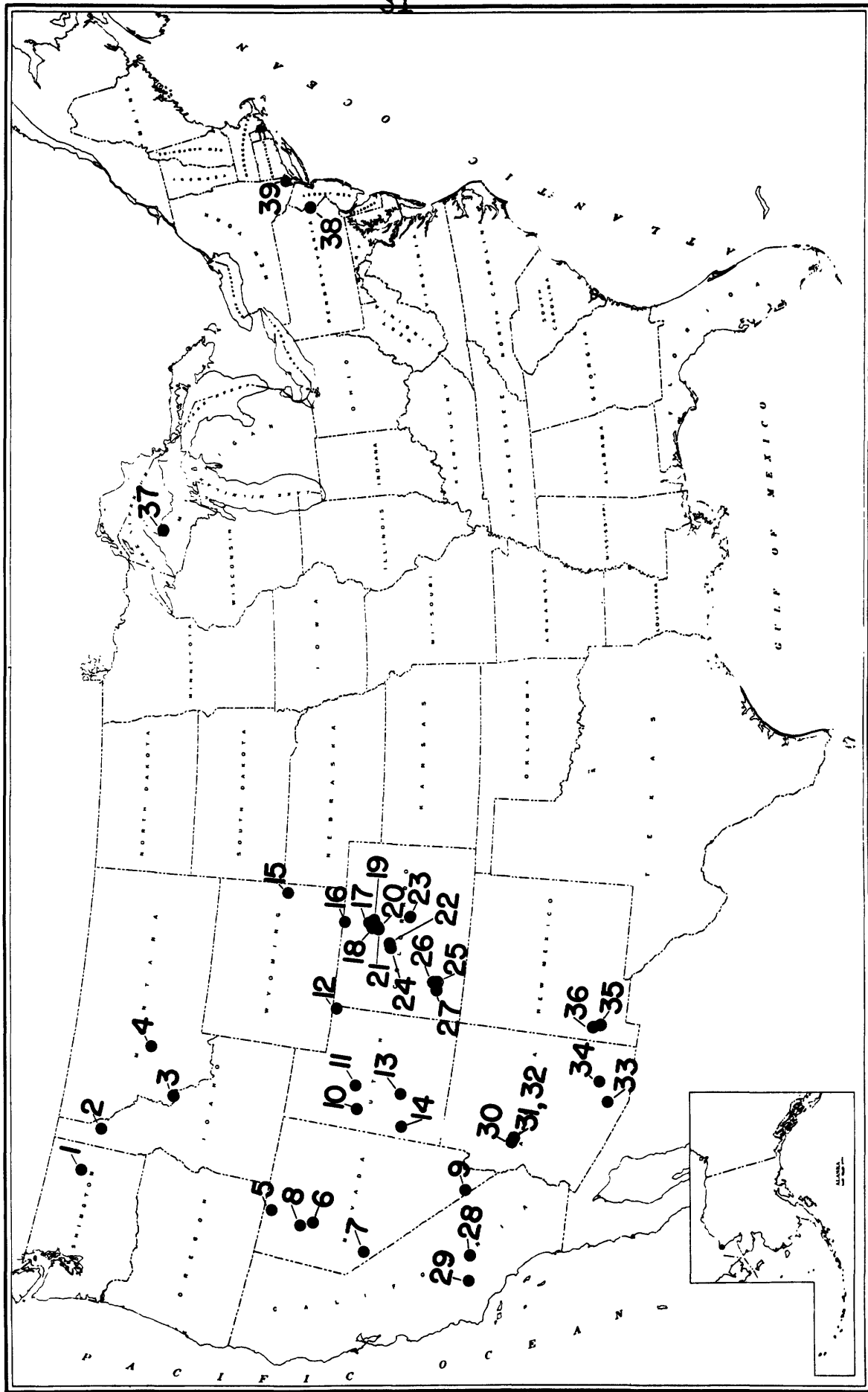


Figure 1. Vein and replacement deposits of uranium in the United States.



- 13) Marysvale, Piute County, Utah (Gruner, et al., 1951; Kerr, et al., 1952); 14) Staats Fluorspar mine, Beaver County, Utah (Wilmarth et al., 1952; Taylor, TEI-390, p. 215); 15) Silver Cliff Mine, Niobrara County, Wyo. (Wilmarth, 1952); 16) Copper King Mine, Larimer County, Colo. (Derzay and Baker, 1953; Sims and Phair, 1953); 17) Jamestown district, Boulder County, Colo. (Phair and Shimamoto, 1952); 18) Caribou-Grand Island district, Boulder County, Colo. (Ridland, 1950; King, 1952; Moore and Cavender, 1952); 19) Ralston Buttes area, Jefferson County, Colo. (J. W. Adams et al., 1953); 20) Central City district, Gilpin County, Colo. (Armstrong, 1952; Moore and Butler, 1952; Sims et al., 1954); 21) Lawson-Dumont district, Clear Creek County, Colo. (Harrison and Leonard, 1952); 22) Alma district, Park County, Colo. (Pierson et al., 1952; Singewald and Pierson, 1953); 23) St. Peters Dome, El Paso County, Colo. 24) St. Kevin district, Lake County, Colo. (Pierson and Singewald, 1954); 25) Red Mountain, Ouray County, Colo. (Burbank and Pierson, 1953); 26) Lower Uncompaghe district, Ouray County, Colo. (Burbank and Pierson, 1953); 27) Placerville thucholite deposit, San Miguel County, Colo. (Morehouse, 1951; Wilmarth, TEI-330, p. 107); 28) Silver Lady claim, Kern County, Calif. (Nelson and Barrett, 1953); 29) Buckeye claims, Kern County, Calif. (Barrett, 1954); 30) Catherine and Michael claims, Yavapai County, Ariz. (Granger, 1951a); 31) Hillside mine, Yavapai County, Ariz. (Wright, 1950; Axelrod et al., 1951); 32) Kitten No. 1 claim, Yavapai County, Ariz. (Granger, 1951b); 33) Black Dike claim, Pima County, Ariz. (Wilmarth et al., 1952); 34) Sure Fire claim, Pima County, Ariz. (Wilmarth et al., 1952); 35) White Signal district, Grant County, N. Mex. (Gillerman, 1952b; Granger and Bauer, 1952); 36) Blackhawk district, Grant County, N. Mex. (Gillerman, 1952a); 37) Huron River area, Baraga County, Mich. (Vickers, TEI-330, p. 204); 38) Franklin limestone, Warren County, N. J. (Stewart, 1951); 39) Phillips pyrite mine, Putnam County, N. Y. (McKeown and Klemic, TEI-390, p. 197).

The most important of the vein deposits are those at Marysvale, Utah; Boulder, Mont.; and in the Colorado Front Range. The deposits at Marysvale, discovered by a prospector in 1948, are found in steeply dipping quartz veins along the margin of a quartz monzonite intrusive (Gruner, et al., 1951; Kerr, et al., 1952). The walls are extensively pyritized and altered to clay minerals. The uranium occurs in autunite, schroeckingerite, torbernite, uranophane, and other secondary minerals near the surface, but it occurs in pitchblende at depth. Marysvale has been a rather consistent though small source of uranium since its discovery, and it promises continued yield in the future.

The Front Range of Colorado (deposits 16-21, fig. 1) is the only area in the United States where any significant tonnage of pitchblende was mined from hydrothermal veins prior to World War II. Production in recent years has been negligible, but many new occurrences of uranium have been found as a result of the activities of Survey geologists and prospectors (King, et al., 1952, 1953; Sims, TEI-440, p. 75-88). In the Jamestown district, uraninite is disseminated in fluorite in fluorite veins and breccia zones (Phair and Shimamoto, 1952). At the Copper King mine pitchblende occurs in quartz-siderite veins that cut deposits of iron, copper, and zinc sulfides, associated with a skarn zone in granite (Derzay and Baker, 1953; Sims and Phair, 1953). The most important deposits in the Front Range are in the Central City (Armstrong, 1952; Moore and Butler, 1952), Lawson-Dumont (Harrison and Leonard, 1952), Caribou-Grand Island (Ridland, 1950; King, 1952; Moore and Cavender, 1952), and Ralston Buttes areas (J. W. Adams, et al., 1953). At most localities in these areas uranium occurs as pitchblende in small pods or shoots in quartz-pyrite or quartz-carbonate lead-zinc-silver veins that cut pre-Cambrian granite, gneiss, or schist. Some of these districts have a zonal distribution of minerals and Leonard (1952) has found recently that pitchblende generally occurs in a zone intermediate between the central zone, characterized by pyritic gold ores, and the peripheral zone, characterized by lead-zinc-silver ores. This relation has already aided in the discovery of additional occurrences of uranium there and it may help in other districts as well. Another useful guide to the search for pitchblende deposits in the Front Range is the occurrence of Tertiary bostonite dikes. These are highly radioactive and many of the pitchblende deposits seem to be genetically related to them (Phair, 1952).

The pitchblende-bearing veins in the Boulder area, Jefferson County, Mont., were discovered by a local prospector in 1949 and since then uranium has been found at several localities between Boulder and Clancy (Klepper, 1950; Becraft, 1953; Roberts and Gude, 1953, 1954). Small quantities of ore have been mined at the Free Enterprise and Woodrow Wilson mines, and prospects for future discoveries elsewhere in the region seem good. The pitchblende is in quartz or chalcedony veins or silicified shear zones that cut quartz monzonite. Small amounts of precious and base metals are also found in the veins,

None of these deposits is known to contain important reserves of minable ore. The significant thing, however, is that the uranium minerals in the majority of them have been discovered since 1944, when the first serious uranium prospecting began. It is not unreasonable to suppose that further exploration of some of them will yield minable reserves and that new finds in other areas will result from additional prospecting.

#### Uranium deposits in tuffaceous rocks

As shown in figure 2, several deposits of secondary uranium minerals have been found in tuffaceous rocks in the western states. In some of these deposits--those in the Rosamond and Randsburg districts of California, for example--the uranium occurs along fractures or bedding planes, but in others it is concentrated along fossil stream channels, much as in the sandstone deposits. Carnotite or uranophane is the uranium-bearing mineral in several of the deposits, but uranium phosphates are characteristic of many of the deposits, particularly those in California. Most of the known deposits in tuffaceous rocks are small and low grade. Additional prospecting is sure to turn up similar occurrences elsewhere, but, judging from known occurrences, it seems unlikely that many deposits of this type will produce large tonnages of ore minable under present economic conditions. Of more promise in the long run is the possibility that uranium can be extracted by mass leaching methods from the tuffs that have "exuded" these small concentrations of secondary minerals.

#### Uranium deposits in limestones

Only a few uranium deposits of any kind have been found in limestones in the United States (fig. 2), and only those in the previously described Todilto limestone near Grants, N. Mex. have yielded ore. The deposits at Miller Hill, Wyo., discovered by Geological Survey airborne reconnaissance in 1952, contain 0.1 to 0.4 percent uranium but known deposits are small. Despite the paucity of uranium deposits in limestones, the importance of the deposits in the Todilto would seem to justify further search for deposits in similar geologic settings.

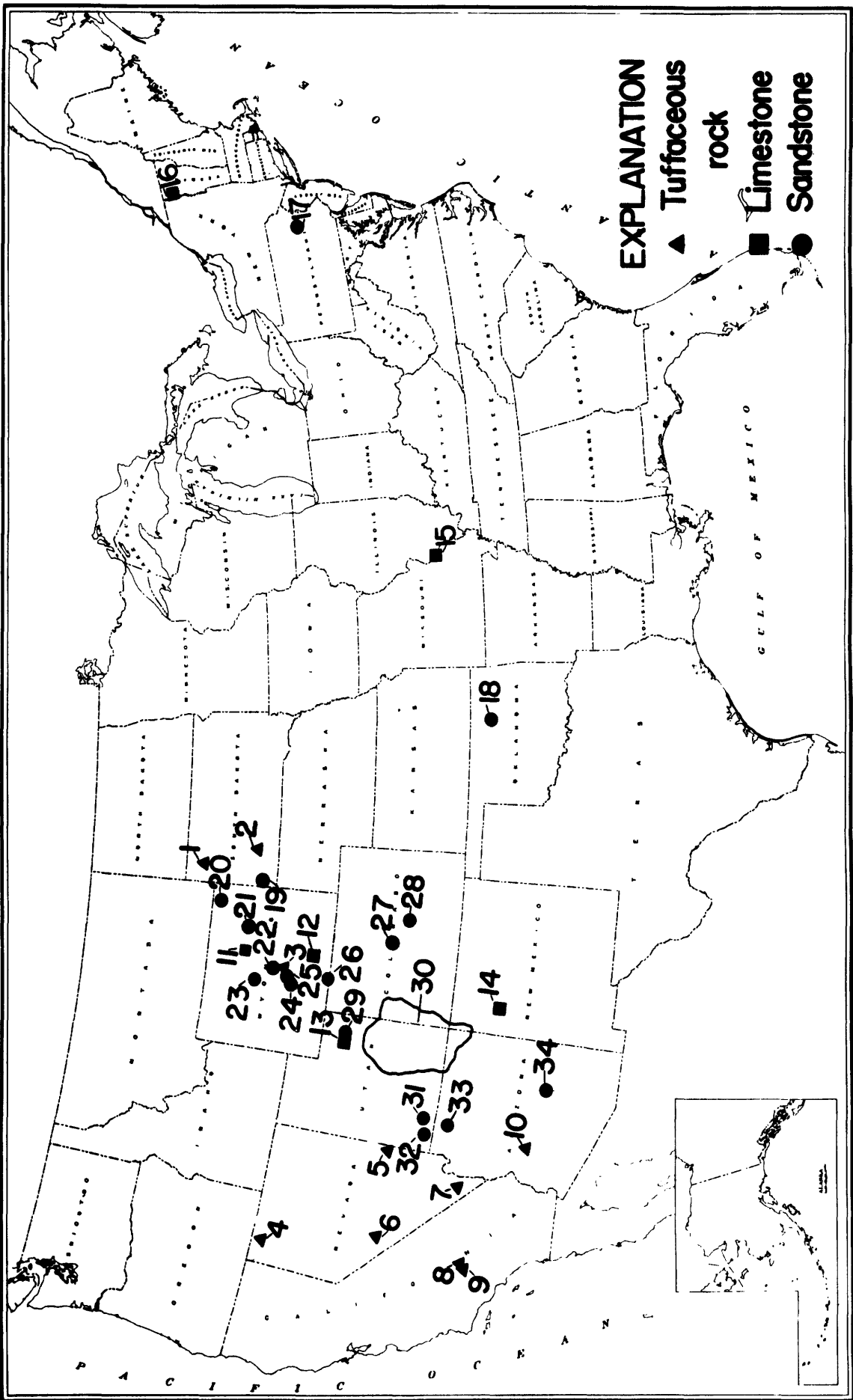


Figure 2. Uranium deposits in tuffaceous rocks, sandstones, and limestones in the United States.

Figure 2. ~~Uranium~~ deposits in tuffaceous rocks, sandstones, and limestones in the United States. Names of uranium-bearing formations and localities and references to them are as follows: Tuffaceous rocks--1)

Oligocene Chadron formation, Slim Buttes, Harding County, S. Dak. (Gill and Moore, 1954) ;

2) Oligocene Chadron and Brule formations, Scenic, Pennington County, S. Dak. (Moore and Levis, 1954);

3) Pliocene (?) rocks, Split-Rock, Natrona County, Wyo. (Love, TEI-390, p. 66); 4) Virgin Valley Opal

district, Humboldt County, Nev. (Staatz and Bauer, 1951b); 5) Tertiary rhyolite tuff, Atlanta mine,

Lincoln County, Nev. (Hewett, 1923); 6) Tertiary welded tuff, Coaldale, Esmeralda County, Nev.

(Duncan, 1953b) ; 7) Tertiary (?) rhyolite tuffs, Sloan, Clark County, Nev. (Hewett, 1923; Behre and

Barton, 1954); 8) Tertiary tuffs and flows, Randsburg, Kern County, Calif. (Walker and Lovering, 1954);

9) Miocene Rosamond series of ~~Haney~~, Rosamond district, Kern County, Calif. (Walker, 1953);

10) Tertiary tuff, Aguila, Ariz. (Hewett, 1925). Limestone-- 11) Jurassic Sundance formation, Mayoworth area,

Johnson County, Wyo., (Love, TEI-390, p. 63). 12) Miocene (?) Brown's Park formation,

Miller Hill, Carbon County, Wyo. (Love, 1953); 13) Eocene Uinta formation, Myton area, Duchesne

County, Utah (Gott et al., 1952); 14) Jurassic Todilto limestone, McKinley County, N. Mex.

(Towle and Rapaport, 1952; Bucher, 1953); 15) Mississippian Spergen limestone, Bussen's Quarry, St.

Genevieve County, Mo. (Muilenberg, 1949; Gott et al., 1952); 16) Cambrian Milton dolomite,

Chittendon County, Vt. (Gott et al., 1952). Sandstones-- 17) Pennsylvanian Pottsville formation and

Upper Devonian Cherry Ridge member of the Catskill formation, Mauch Chunk, Carbon County, Pa.

(Klemic and Baker, 1954); 18) Permian sandstone, Uto claim, Pawnee County, Okla. (Hill, TEI-330, p.

203); 19) Cretaceous Lakota formation, Craven Canyon area, Fall River County, S. Dak. (Page and

Redden, 1952; Bell and Bales, 1954; Gott et al., TEI-440, pp. 64-72); 20) Cretaceous Fall River,

Fuson, and Lakota formation, Devil's Tower area, Crook County, Wyo. (Gray and Tennissen, 1953);

21) Eocene Wasatch formation, Pumpkin Buttes area, Campbell County, Wyo. (Love, 1952; Davidson

D. F., 1953a, b); 22) Eocene Wind River formation, Gas Hills, Fremont County, Wyo. (Love, TEI-390,

p. 63); 23) Eocene (?) ~~Tapee~~ trail (?) formation, McComb area, Fremont County, Wyo., (Love, TEI-440,

p. 175); 24) Eocene Green River formation, Lost Creek, Sweetwater County, Wyo. (Sheridan, et al., 1955);

25) Eocene sandstone, Crooks Gap, Fremont County, Wyo. (Love, TEI-440, p. 180); 26) Miocene (?)

Brown's Park formation, ~~Poison~~ Basin, Carbon County, Wyo. and Moffat County, Colo. (Vine and Prichard, 1954);

27) Permian and Pennsylvanian (?) Maroon formation, Garo prospect, Park County, Colo. (Wyant et al., 1952); 28) Jurassic Morrison formation, Mike Doyle deposit, El Paso County, Colo. (Beróni and King, 1950); 29) Tertiary sandstones, Uintah County, Utah (Wyant et al., 1952); 30) Various formations but principally the Triassic Shinarump and Chinle and the Jurassic Entrada and Morrison formations, Colorado Plateau, Utah, Colorado, Arizona, and New Mexico (Fischer, 1950; and Luedke, 1953); 31) Cretaceous Dakota formation, Bulloch claims, Kane County, Utah (Stugard, 1952; Beróni et al., 1953); 32) Triassic Chinle formation, Silver Reef District, Washington County, Utah (Proctor, 1953); 33) Hack's Canyon, Mohave County, Ariz. (Wyant et al., 1952); 34) pre-Cambrian Dripping Springs quartzite, Gila and Pinal Counties, Ariz. (Kaiser, 1951; Mead and Wells, 1953).

#### Uranium deposits in sandstones

Although other deposits in this country offer promise as future sources of uranium, particularly as byproducts of other materials, our most important production has been and continues to be from the sandstone-type deposits of the Colorado Plateau (fig. 2). Resources in these deposits have supported a steadily increased production that has made the United States one of the world's leading producers of uranium since 1951 (U. S. Atomic Energy Commission, 1951, p. 8; Johnson, 1954). Equally important is the fact that most of the discoveries of minable ore outside of the Colorado Plateau, such as those in the Black Hills area, are also of the sandstone type. A few of the sandstone deposits shown on figure 2, such as those in the Dripping Springs quartzite, Arizona, seem to be associated with fractures and other structural features, but the distribution of most of them is related to sedimentary structures and facies changes.

As the general geology of the Colorado Plateau deposits has already been described, it is only necessary here to discuss the new developments and findings in the field. The uranium deposits on the Plateau are scattered over an area of more than 50,000 square miles in Colorado, Utah, Arizona, and New Mexico (Fischer, 1937, 1950; Shoemaker and Luedke, 1953), and ore is now being produced from more

than 500 mines (U. S. Atomic Energy Comm., 1954, p. 3). Prior to World War II, the principal production and known reserves came from carnotite ores in the area in western Colorado, since defined as the Uravan mineral belt (Fischer and Hilpert, 1952). Diamond drill exploration, guided by the concept of the mineral belt as well as by criteria for defining ground favorable for the occurrence of ore (Weir, 1952; Stokes, 1953) has much extended the size of the reserves in this area and made possible much of the increased production from the Plateau since the war.

Of equal or greater long term importance, however, has been the discovery, mainly by private prospectors, of sizable deposits, some containing a million tons of ore or more (Johnson, 1954), in new districts or other areas previously not known to contain minable ore. The largest single producer on the Plateau now is the Mi Vida mine near Moab, Utah (Dix, 1954; Meyers, 1953; Gruner, et al., 1954). The deposit there was completely unknown until late in 1952--in fact, the Chinle formation in which it occurs was not even known to contain ore in that area. Other important deposits have since been found in the Moab area (Everhart, 1954 a). The Happy Jack mine in the Shinarump formation in White Canyon, Utah, was known only as a prospect until about 1950, but it has since been found to contain large reserves of copper-uranium ore and is now an important producer (Dodd, 1950; Miller, 1953). Important deposits also have been found recently in the White Canyon area (Benson, et al., 1952; de Vergie, 1953). New discoveries, mainly of vanadium-uranium ore, have also been made in the Temple Mountain and other areas in the San Rafael Swell and Green River districts (Reyner, 1950; Finch, 1953). The Grants, New Mexico district is another recent discovery. The best known deposits there are tyuyamunite-pitchblende ores in the Todilto limestone (Towle and Rapaport, 1952), but other deposits of equal or greater importance have been found in the area in the Westwater and Brushy Basin members of the Morrison formation and in the Dakota formation as well (Mirsky, 1953; Everhart, 1954 a; Wright, 1954 b). The Lukachukai district in Arizona is another important new area (Masters, 1953). Exploration there by AEC has disclosed the presence of enough ore to justify a new mill at Shiprock. Important or promising deposits have also been found in the Monument Valley and Cameron areas of Arizona (Finch, 1953; Williams and Barrett, 1953) and the Henry Mountains area of Utah (Bain, 1952). These new discoveries have not only helped bring the Colorado Plateau to a position of prominence as one of the world's large sources of uranium, but they have stimulated the additional prospecting that will help maintain or further extend this position.

Of the sandstone-type deposits discovered outside the Colorado Plateau, those along the margin of the Black Hills in South Dakota and in northeastern Wyoming and those in the Powder River Basin have already yielded some production. The South Dakota deposits, found by a prospector in June 1951, occur in the Fall River and Lakota sandstone and much resemble the Colorado Plateau deposits in shape and size. Since the initial discovery in the Craven Canyon area in Fall River County in the southern Black Hills, deposits have been found near Devil's Tower and in other localities around the northern Black Hills by prospectors, mining companies, and the AEC, in large part by means of airborne reconnaissance (Foote, 1954). The AEC has established a buying station at Edgemont and extensive diamond-drill exploration is in progress.

The Pumpkin Buttes deposits were found in the fall of 1951 in the Wasatch formation as the result of Geological Survey airborne reconnaissance (Love, 1952). Some of the uranium there occurs in small masses, a few inches to a few feet in diameter, that contain as much as 15 percent uranium. These deposits, now called the pumpkin-type, are too small to be minable on a significant scale. Disseminated-type deposits have been discovered since that more nearly resemble those in South Dakota and the Colorado Plateau, and a few of these are now in production. The future of the district as an important source of uranium is dependent upon the discovery of additional deposits of this type.

Other sandstone-type deposits have been found elsewhere in the United States (fig. 2) but none of them has yielded ore. In view of the widespread occurrence of uranium in sandstone deposits in this country as well as the current prospecting enthusiasm, the prospects for additional discoveries of this type of ore seem bright indeed.

#### Uraniferous asphaltite deposits

The distribution of uraniferous asphaltites and related substances is shown in figure 3. The only deposits being exploited are those in the San Rafael district, where the asphaltite is a major constituent of the sandstone deposits in Triassic formations (Gott and Erickson, 1952; Finch, 1953). Numerous occurrences of uraniferous hard "asphaltite" pellets have been found recently in well cuttings in the



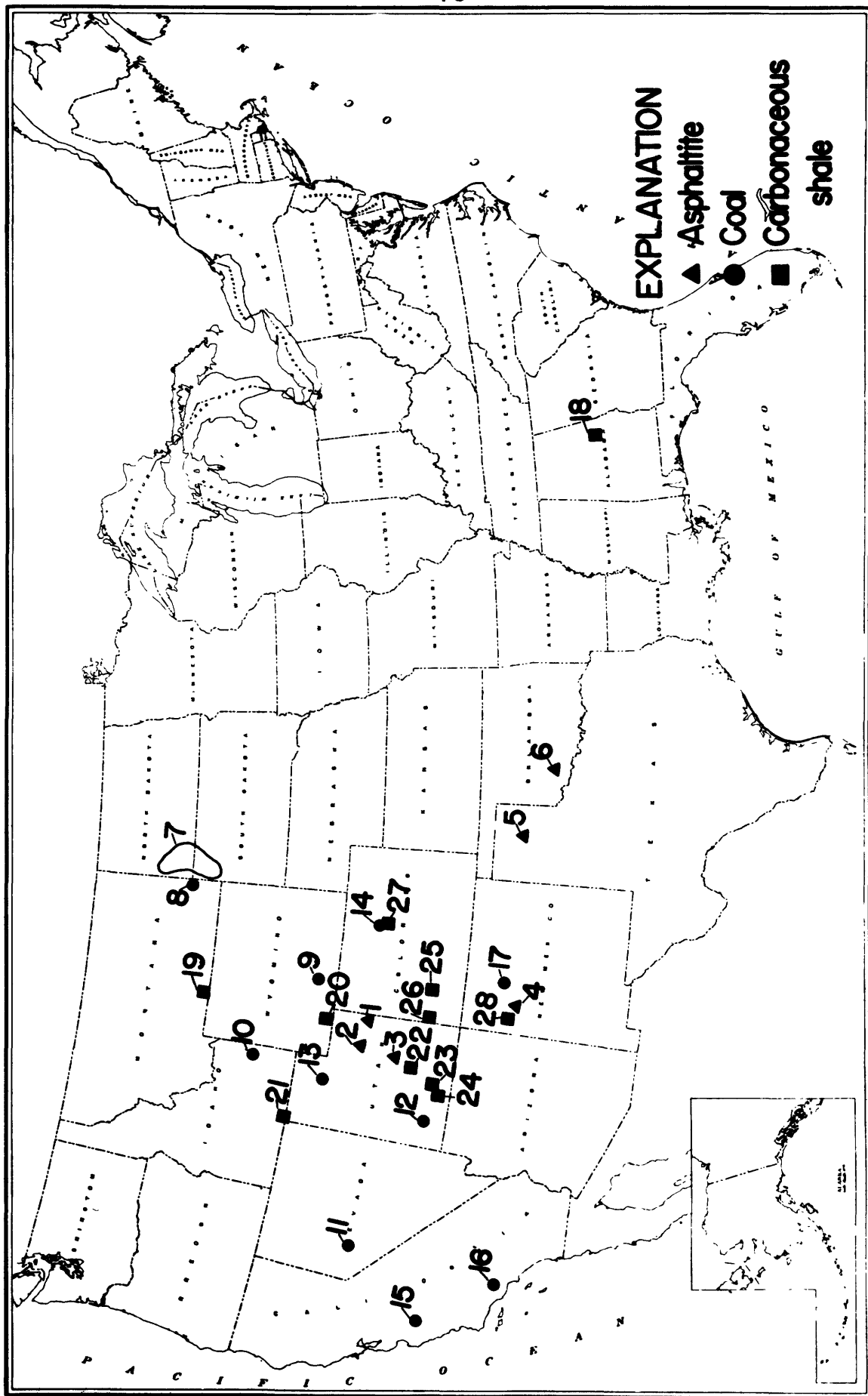


Figure 3. Uraniferous asphaltite, coal, and continental carbonaceous shale deposits in the United States.

Panhandle gas field in Texas, in many other gas fields in Kansas, Oklahoma, Texas, and New Mexico (Faul et al., 1952; Gott, TEI-390, p. 256-258) and in outcrops of Permian beds along the flanks of the Wichita mountains (Hill, TEI-330, p. 202). The "asphaltite" pellets contain 1 to 10 percent uranium and seem to be the source of the radon in the gas fields in that area. None of the known deposits appears to be of commercial importance. Figure 3. Uraniferous asphaltite, coal, and continental carbonaceous shale deposits in the United States. Names of uranium-bearing formations and localities and references to them are as follows: Asphaltite, etc.-- 1) Gilsonite, Uintah County, Utah (Erickson et al., 1953); 2) Elaterite, Duchesne County, Utah (Erickson et al., 1953); 3) Asphaltite in Upper Triassic Shinarump conglomerate, San Rafael Swell district, Emery County, Utah (Gott and Erickson, 1952); 4) Asphaltite in Upper Jurassic Westwater Canyon sandstone member of Morrison formation, Poison Creek, McKinley County, N. Mex., (Gott and Erickson, 1952); 5) "Asphaltite" in Panhandle gas field, Amarillo, Tex. (J. W. Mytton in Erickson et al., 1953); 6) "Asphaltite" in Permian Hennessey, Garber, and Wellington formations, Wichita Mountains, Okla. (Hill, TEI-330, p. 201, Hill, 1954); Coal-- 7) Paleocene Ft. Union formation, Dakota field, North and South Dakota (Gill, Schopf and others, TEI-330, p. 123-138; Gill, TEI-390, p. 131; Moore, TEI-390, p. 123); 8) Paleocene Ft. Union formation, Ekalaka field, Carter County, Mont. (Gill, TEI-390, p. 121; TEI-440, p. 109); 9) Eocene Wasatch formation, Red Desert area, Sweetwater County, Wyo. (Masursky, TEI-330, p. 140; Masursky and Pipiringos, TEI-390, p. 139-143); 10) Upper Cretaceous Bear River formation, Bonneville County, Idaho (Vine and Moore, 1952; Vine, TEI-330, p. 117); 11) Tertiary lignite, Gamma property, Churchill County, Nev. (Gott et al., 1952); 12) Upper Cretaceous Straight Cliffs sandstone, Webster Mine, Iron County, Utah (Zeller, TEI-390, p. 117); 13) Pleistocene Laramie peat, Pettit property, Davis County, Utah (Duncan, 1953c); 14) Upper Cretaceous formation, Old Leyden Coal mine, Jefferson County, Colo. (Wyant et al., 1952) 15) Fireflex Mine, San Benito County, Calif. (Moore and Stephens, 1954); 16) Pliocene and Pleistocene Saugus formation, Newhall, Los Angeles County, Calif. (Moore and Stephens, 1954); 17) Upper Cretaceous Mesaverde group, La Ventana Mesa, Sandoval County, N. Mex. (Bachman and Read, 1951); Carbonaceous shale-- 18) Pennsylvanian Erin shale,

Alabama (Narten et al., (1951); 19) Tertiary Ft. Union (?) formation, Carbon County, Mont. (Narten et al., 1951); 20) Upper Eocene Bridger formation, Sweetwater County, Wyo. (Vine, TEI-330, p. 117); 21) Pliocene Salt Lake formation, Goose Creek, Cassia County, Idaho (Duncan, 1953c; Mapel and Hail, TEI-390, p. 135-139); 22) Cretaceous Dakota sandstone, Wayne County, Utah (Zeller, TEI-390, p. 117); 23) Cretaceous Dakota sandstone, Garfield County, Utah (Zeller, TEI-390, p. 117); 24) Cretaceous Dakota sandstone, Kane County, Utah (Zeller, TEI-390, p. 117); 25) pre-Cambrian slate, Upper Uncompaghe district, San Juan County, Colo. (Pierson et al., 1952; Burbank and Pierson, 1953); 26) Pennsylvanian Paradox member of the Hermosa formation, San Miguel County, Colo. (Baltz, TEI-390, p. 119); 27) Cretaceous Dakota sandstone Jefferson County, Colo. (Narten et al., 1951); 28) Cretaceous Dakota sandstone, Gallup, McKinley County, N. Mex. (Mirsky, 1953).

#### Uraniferous coal and continental carbonaceous shale

Many uraniumiferous coals and carbonaceous shales (fig. 3) have been found in the United States since the first occurrence was discovered in 1945 in the Eocene Wasatch formation on the Red Desert of Wyoming. Most of these deposits are too thin, low-grade, or small to be of importance now or in the future, but some of them contain large resources of uranium, and others are minable now. The most important from the standpoint of resources for the future are the Red Desert deposits and those in the Paleocene Ft. Union formation in the Dakota-eastern Montana field. The uranium in coals in these areas is irregularly distributed, as it is elsewhere, but large tonnages in both fields contain 0.01 to 0.03 percent uranium in the ash. These deposits will yield uranium only if it can be derived as a byproduct of other operations, such as the manufacture of steam power.

Carbonaceous shale in the Cretaceous Dakota formation near Gallup, N. Mex. is being mined as uranium ore on a small scale now (Mirsky, 1953). Carbonaceous shale in small pockets in the Pennsylvania Paradox formation in Colorado, the Pliocene Salt Lake formation in Idaho, and the Cretaceous Bear River formation in Wyoming contains as much as 0.1 percent uranium or slightly more. It is not known yet whether any of these deposits contains minable amounts of shale of this grade, but it is reasonable to expect that some production, probably small, will be derived from deposits of this type.

### Uraniferous phosphorites

The most important uraniferous phosphorites in the United States (fig. 4) are those in the Pliocene Bone Valley formation in Florida and the Permian Phosphoria formation in the western states. Both contain huge tonnages of phosphate averaging 0.01 to 0.02 percent uranium. Even though the content is small, extensive research sponsored by the Atomic Energy Commission has made it possible to recover uranium as a byproduct of the manufacture of triple super phosphate fertilizer (Wimpfen, 1951). Production from the Florida field began late in 1952 and three additional recovery plants have been added since then. Uranium may be obtained from the western phosphorites by the same process in the not-too-distant future, but no large production is anticipated immediately from this source because the western triple super phosphate industry is still relatively small.

The aluminum phosphate zone in the upper part of the Bone Valley formation in Florida also contains huge tonnages of uranium in amounts slightly higher than that in the underlying carbonate-fluorapatite mined for fertilizer. Research sponsored by the Atomic Energy Commission on the extraction of uranium and other coproducts such as aluminum and phosphorus has already led to development of recovery processes which are now being tested on a pilot plant scale (U. S. Atomic Energy Commission, 1954, p. 7).

Figure 4. Uraniferous marine phosphorites and black shales in the United States. Names of localities and references are as follows: Phosphorites--1) Permian Phosphoria formation, Montana, Idaho, Wyoming, and Utah (McKelvey and Nelson, 1950; Thompson, 1952, 1953; Swanson et al., 1953); 2) Pennsylvania nodular black shales in the Coffeyville, Fort Scott, Bourbon, and Hushpuckney, and Stark formations in Kansas and Oklahoma (McKelvey and Nelson, 1950; Runnels et al., 1953); 3) South Carolina phosphate field, Charleston County (D. F. Davidson, 1951); 4) Pliocene Bone Valley formation, Florida (Butler, 1952; Cathcart et al., 1953). Black shales-- 5) Mississippian Heath shale, Fergus County, Mont. (Duncan, 1953a); 6) Pennsylvanian Hartville shale, Wyoming and Nebraska (Duncan, 1953a); 7) Cretaceous Sharon Springs member of Pierre shale, Nebraska and South Dakota (Tourtelot, TEI-390, p. 129); 8) Pennsylvanian and Permian (?) Sangre de Cristo formation, Guadalupita, Mora County, N. Mex. (Zeller and Baltz, 1954; Tschanz, TEI-390, p. 81-90); 9) Pennsylvanian Cherokee shale, Kansas and Missouri (Slaughter, 1945);

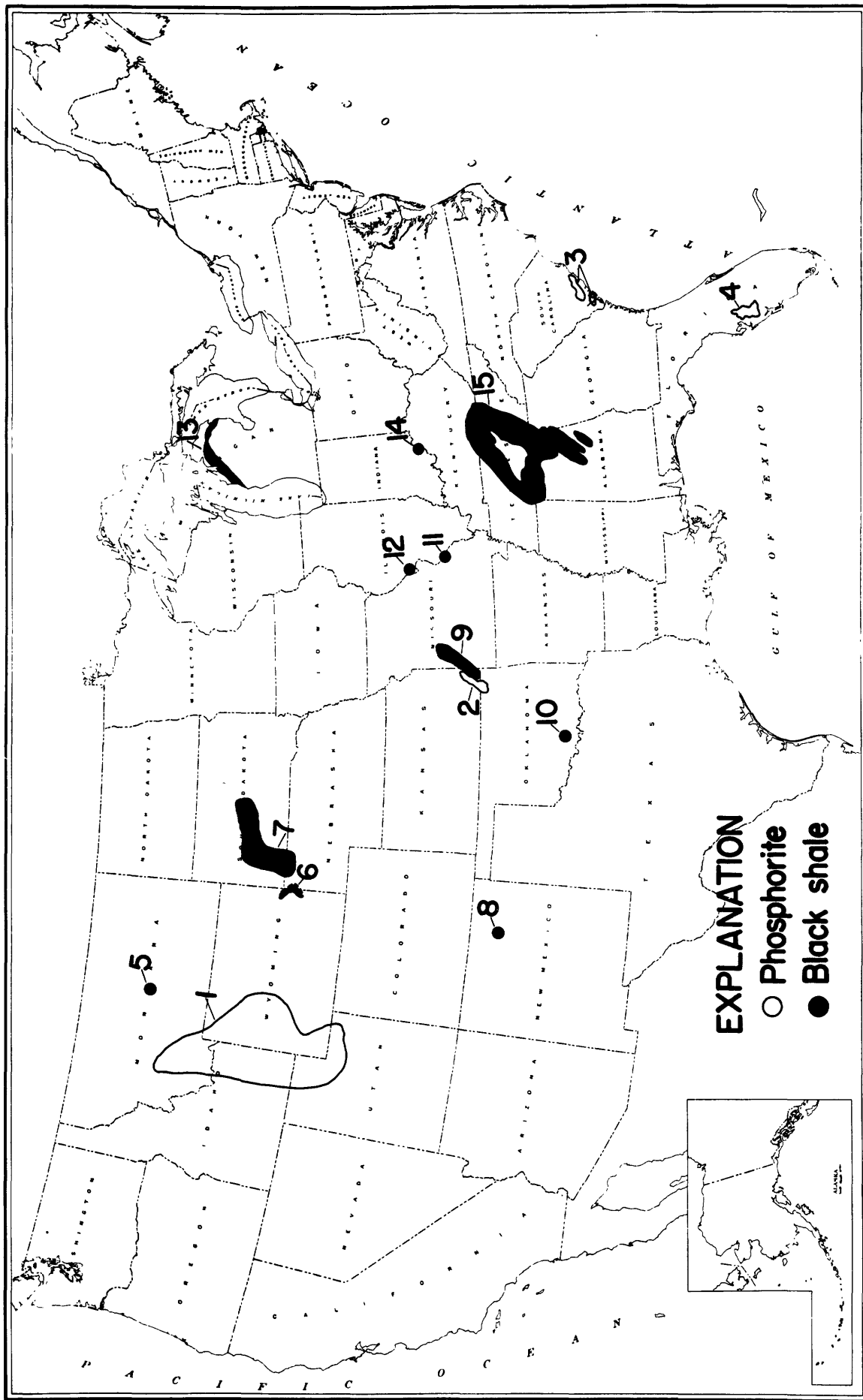


Figure 4. Uraniferous marine phosphorites and black shales in the United States. 72110

10) Shale in the Devonian-Mississippian Woodford chert, Oklahoma (McKelvey and Nelson, 1950); 11) Shale in Mississippian Spergen limestone, Bussen's quarry, Missouri (Gott et al., 1952; Brown and Keller, 1952); 12) Devonian Mountain Glen shale, Illinois (Slaughter and Clabaugh, 1945); 13) Devonian ~~Antrim shale, Michigan~~ (Beers, 1945); 14) Devonian-Mississippian New Albany shale, Indiana (Nelson and Stratton, 1949); 15) Devonian-Mississippian Chattanooga shale, Tennessee and Alabama (Russell, 1945; Conant, 1952; Swanson, 1953).

Recent airborne radioactivity surveys have disclosed the presence of uraniferous phosphorite in several areas outside the Bone Valley field (Moxham, 1954). These localities have not yet been explored, but ground examination in one of them showed the presence of leached phosphatic rock similar to that in the Bone Valley field. Additional reconnaissance of this type may lead to the discovery of other deposits elsewhere on the Atlantic or Gulf Coastal plain.

#### Uraniferous marine black shales

The most important uraniferous black shale yet discovered in the United States is the Devonian Chattanooga shale of Tennessee (fig. 4). The upper part of this formation contains vast quantities of uranium in amounts of 0.01 percent or slightly less. Despite extensive research, the mineralogy of the uranium in the shale is not yet known but most of the uranium seems to be concentrated in pyrite-organic matter complexes (Bates and Wright, 1953).

The most uraniferous black shale thus far discovered in the United States is in the Pennsylvanian Hartville formation in southwestern Wyoming. This shale contains 0.019 percent uranium (Duncan, 1953a), but it is thus far known to be appreciably uraniferous only in the subsurface where it has been penetrated by oil wells--~~the black shale facies passes into limestone facies~~ before the Hartville crops out on the Hartville dome. Whether or not further reconnaissance will disclose a locality at the surface where uraniferous shale crops out remains to be seen.

Copper and uranium deposits in the Coyote district, near Guadalupita, N. Mex., are associated with lenticular carbonaceous marine beds (Tschanz, TEI-390, p. 81), but they have more features in common with the sandstone deposits than they do with other marine black shales. The uranium, which occurs as metatyuyamunite and uraninite as well as other forms not yet identified, is irregularly distributed and is present in sandstone, arkose, and limestone beds as well as carbonaceous shale. The importance of this deposit is not yet known. Several other marine black shales, mainly of upper Paleozoic age, and mainly in the mid-continent region, are also uraniferous (fig. 4), but none discovered yet compares to the Chattanooga in extent and potential resources.

No production of uranium has been realized yet from black shales in this country, but the Atomic Energy Commission is sponsoring research on low cost mining and processing methods on the Chattanooga shale that may make the production of uranium, along with certain coproducts like phosphate, oil, and potash, possible in the foreseeable future (Barr, 1953).

#### Uranium-bearing placers

The only placer deposits likely to yield uranium among those known in the United States (fig. 5) are those of radioactive black minerals in Bear Valley, Idaho (Mackin and Schmidt, 1953). Production of uranium from these deposits is contingent upon the solution of extraction problems. Monazite in other placer deposits in central Idaho is of interest chiefly for its rare earth content, and it is not likely that the 0.1 percent uranium it contains will be recovered. Monazite in alluvial placers in the southeastern states contains 0.3 to 0.4 percent uranium (Mertie, 1953); although these deposits are widely distributed in two extensive northeastward-trending belts, individual deposits of minable grade are small. Figure 5. Placer deposits of monazite, zircon, and radioactive black minerals in the United States. Names of and references to localities are as follows: 1) western zircon and monazite placers (Skidmore, 1944; Chesterman and Main, 1947); 2) Central Idaho monazite, zircon, and "radioactive black" placers (Staley, 1948; Trites and Tooker, 1953; Mackin and Schmidt, 1953); 3) monazite in Cambrian Deadwood conglomerate,

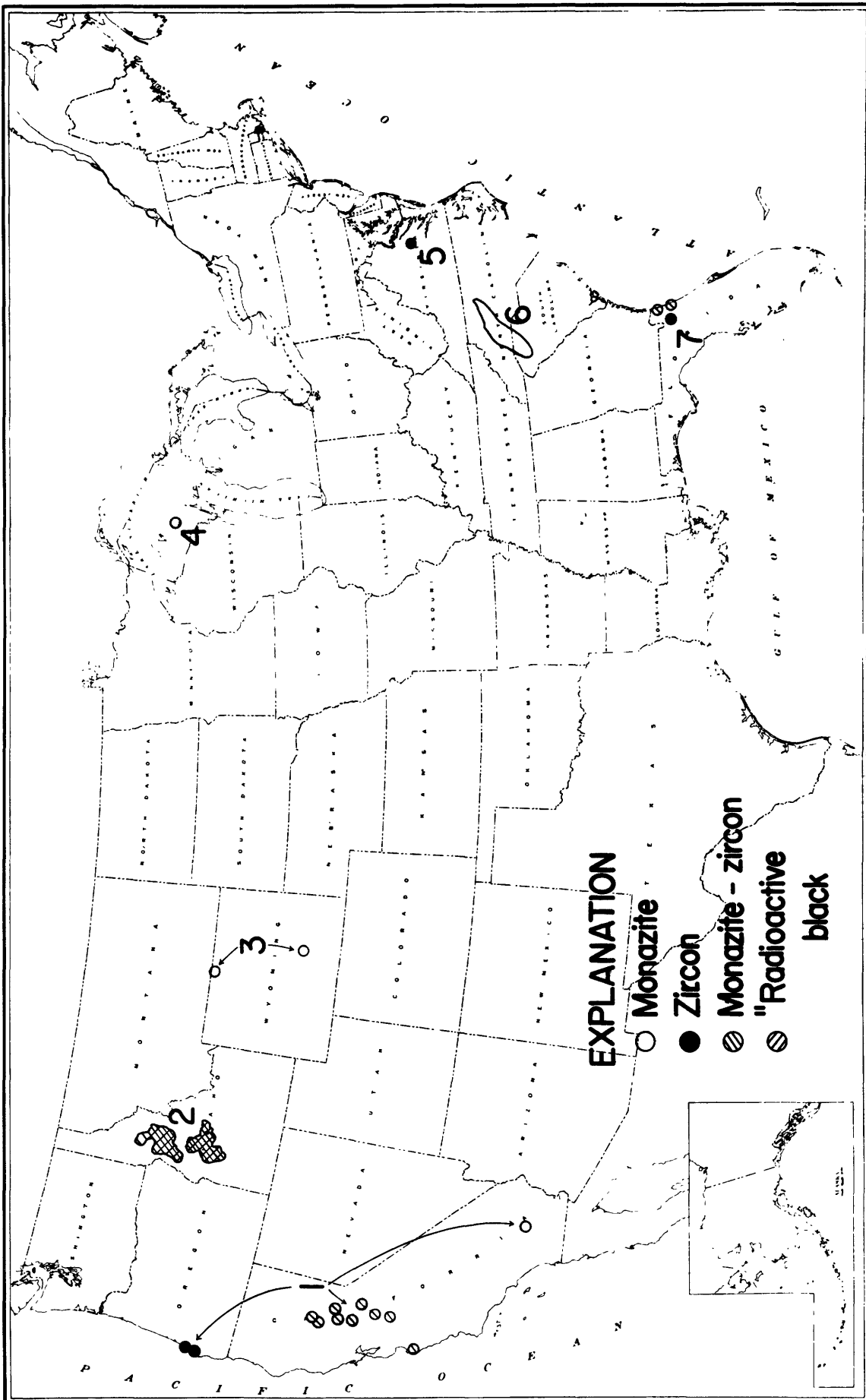


Figure 5. Placer deposits of monazite, zircon, and radioactive black minerals in the United States. 72310



Sheridan, Big Horn and Carbon Counties, Wyo. (McKinney and Horst, 1953); 4) monazite in pre-Cambrian Goodrich quartzite, Marquette County, Mich. (Vickers, 1953); 5) zircon in Miocene Calvert formation near Ashland, Hanover County, Va. (Laughlin, 1919); 6) southeastern monazite placers, North Carolina and South Carolina (Mertie, 1953); and 7) Florida monazite and zircon placers (Slaughter, 1945).

#### Outlook for future discoveries

The outlook for future discoveries of uranium deposits in the United States seems bright. The numerous occurrences of uranium in veins, tuffaceous rocks, lignites, and sandstone-type deposits in the Rocky Mountain States led L. R. Page (oral communication, 1950) to suggest that this area constitutes a uranium province of major importance. Subsequent discoveries tend to confirm this view and we may confidently expect that additional discoveries of primary and secondary deposits of all types will be made in this general area.

The numerous occurrences of ~~pitchblende~~ veins in the western states have about the same relation to the occurrence of larger, minable deposits as smoke does to fire. It is well known that for every large oil field there are scores of smaller ones and the same relationship holds with respect to mineral deposits. Further exploration in the vicinity of the known occurrences (fig. 1) seems sure, therefore, to reveal some minable deposits and additional prospecting in granitic and metamorphic terranes may well turn up important new districts.

The possibilities for discovering additional important sandstone deposits seem particularly promising, both within the Colorado Plateau and elsewhere in the western states. It seems well worth while to examine all lenticular, permeable formations in the western area, whether they are known to contain ore or not. The oldest formation of this type in any given district, particularly the parts where permeable facies interfinger with impermeable ones, seem especially promising. Recognizing the possibility that the sandstone ores may have a hydrothermal source, it seems well also to investigate older carbonaceous rocks in areas of known sandstone-type deposits on the chance of turning up a Rum Jungle-type of deposit.

Just plain looking has led to most of the discoveries of recent years, but the backlog of information now available on the habits of the ores seems sufficient to support a deductive approach to prospecting in

the future that might be much more fruitful than the uranium-is-where-you-find-it approach of the past. The principal basis for such prospecting in the search for sandstone ores must be the analysis and understanding of sedimentary facies and transmissibility relationships. The basic geologic problem is thus one not unlike that encountered in the search for oil--in fact the problem is one more likely to be solved by men with training in petroleum geology, using the oil companies' regional geological approach, than that it is by men whose experience is limited to mining geology. In this connection, one may ask if it is possible that a modification of some of the principles and methods currently being developed by the oil industry in the investigation of hydrodynamic gradients might find application in the search for sandstone ores or at least in the definition of favorable ground.

Although the numerous occurrences of primary and secondary uranium ores in the western states make this area the favored one for future discoveries, other parts of the craton deserve more examination than they have received in the past. This is particularly true for granitic, metamorphic, and redbed terranes.

The prospects for discovering additional phosphorite fields are more limited than for other types of deposits, but they are good on the Gulf coastal plain, where exposures are poor and the subtropical weathering has leached the deposits at the surface and destroyed their distinguishing characteristics.

Despite the fact that rather extensive sampling already undertaken has not uncovered a uraniferous black shale in this country that contains 0.02 percent of uranium or more, it is not unreasonable to suppose that one or more such deposits exist in the United States. Recalling the facts that the most uraniferous parts of the alum shale in Sweden lie in marine embayments and that the Hartsville shale in Wyoming passes into calcareous facies before it reaches the surface in the Hartville uplift, further search for uranium in black shales might be directed along the margins of black shale facies.

## CONCLUSIONS

The 10 years of intensive search for uranium in this country have led to a several-fold increase in production from sandstone-type deposits, to the discovery of many occurrences of uranium in ore-grade concentrations (mostly of insufficient volume to be mined), and to the discovery of large but low-grade

resources of uranium in the lignites, black shales, and phosphorites. The increase in production from the Colorado Plateau speaks for itself, but I may add that production there is likely to increase and to continue at a high level for many years to come.

Discovery of other high-grade vein and sandstone deposits may be expected in future years, but the large low-grade deposits already discovered insure our future even if higher grade ores do not materialize. The low-grade deposits will yield uranium now only at a high price, but the important thing is that they contain virtually unlimited resources that can be made available now if emergency needs demand, or later when higher grade deposits are exhausted. In this connection, Jesse C. Johnson (1954), Director of the Raw Materials Division of the Atomic Energy Commission, recently predicted that supplies of uranium obtainable from high-grade deposits would be adequate to support a large nuclear power industry well into the period when its efficiency in utilization of raw materials has reached an advanced stage, at which time it could afford to utilize higher priced uranium extracted from the low-grade deposits. The reasonableness of this prediction is perhaps more readily realized if we recall that one pound of uranium is considered the potential power equivalent of 1,250 tons of coal. The uranium in a ton of black shale, phosphorite, or uraniferous lignite is thus roughly the potential power equivalent of 250 tons of coal. The concern expressed in recent years in many quarters over the adequacy of power supplies may therefore be postponed until the far distant future, for the resources of uranium in the United States in known low-grade deposits (shale, phosphate, and lignite) have far more potential power equivalent than all other types of our mineral fuels added together. And in the world as a whole, "the energy potentially available in . . . reserves of minable uranium has been estimated as between 20 and 25 times the energy from world reserves of oil, gas, and coal" (Smyth, 1954).

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A strong attempt has been made to cite only references that are available to the public; the few exceptions are indicated as unpublished reports. Many of the other papers cited are not published, but are on "open file". The largest group of these, released by the Technical Information Service of the Atomic Energy Commission at Oak Ridge, Tenn., are available in numerous public libraries all over the country. A list of these libraries is printed in each issue of Nuclear Science Abstracts and is also published in U. S. Geological Survey Circular 281, p. 8, and Bulletin 1019-B, p. 78-79. The location of open file reports released directly by the U. S. Geological Survey is also indicated in Circular 281 and Bulletin 1019-B.

An effort has been made also to restrict references to those of recent date. Those that contain numerous references to earlier reports are indicated by an asterisk (\*). The bibliographies by Allen (1953); Cooper (1951; 1952; 1953a, b; 1954); Croxton (1951); Curtis and Houser (1953); and Wallace and Smith (1955), as well as Nuclear Science Abstracts will be particularly helpful in this regard.

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