

Selected Annotated Bibliography of the Geology of Uranium- Bearing Phosphorites in the United States

By DIANE CURTIS

SELECTED BIBLIOGRAPHIES OF URANIUM GEOLOGY

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INTRODUCTION

The presence of uranium in phosphatic materials has been known since 1908 when Strutt¹ observed that phosphates have a higher radioactivity than most other rocks in the earth's crust. The fact was only of scientific interest, however, until World War II when uranium became important as a source of nuclear energy.

Although much work has been done on the geology of uranium-bearing phosphates, most of the reports are unpublished. This bibliography lists nearly all reports pertaining to uranium in domestic phosphorites that were available to the public as of December 1, 1955.

PHOSPHATE DEPOSITS

Phosphate deposits may be classified into 6 geologic types which are apatite deposits of igneous origin, residual deposits, phosphatized rock, river-pebble deposits, guano, and marine phosphorites.

Apatite is a constituent of many igneous and metamorphic rocks, but has been mined for phosphate in the United States only from the titanium-apatite deposits of Nelson County, Va. (ref. 22). So far as is known this rock has not been analyzed for uranium. According to Davidson (ref. 12, p. 26), the uranium content of samples of apatite from foreign countries ranges from less than 0.001 to 0.03 percent.

Residual deposits are formed by the concentration of phosphate derived from the weathering of marine phosphatic limestones. The brown phosphate rock deposits of Tennessee are an example of this

¹ Strutt, Hon. R. J., 1908, On the accumulation of helium in geological time: Roy. Soc. London Proc., v. 81, ser. A, p. 272-277.

concentration, but they are practically barren of uranium. The brown rock occurs along the northern and western edges of the central basin of Tennessee in the limestone outcrop belt of the Nashville group (of Safford, 1851²) of the middle and upper parts of the Ordovician system.

Phosphatized rock is formed by the solution of phosphate from overlying rock and deposition, interstitially or through a replacement process, in underlying rocks (usually limestone). Examples of phosphate rock of this type are the white-rock deposits around the central basin of Tennessee and the belt of hard-rock deposits in the Alachua formation in northwestern Florida. The uranium content of these deposits is generally low.

River-pebble deposits (alluvial) occur as bars and banks in modern stream channels and in the adjoining lowlands. Deposits of this type in Florida and South Carolina were derived by the reworking of marine phosphorites. The uranium content of river pebble deposits is dependent upon and comparable with the uranium content of the material from which the pebbles were derived.

Guano, the excrement of birds and animals, has been deposited in the bat caves of Texas and New Mexico. The deposits are rich in phosphate but are too small to be an important commercial source of fertilizer. A few tons have been mined from the New Mexico deposits. As far as is known, guano contains practically no uranium.

Marine phosphorites are characteristically thin, but probably represent all the sediment deposited during long periods of geologic time. Phosphorites of this type are believed to be precipitated on shelving margins of large oceanic basins. All marine phosphorites that have been chemically analyzed contain from 0.005 to 0.03 per cent uranium.

The land-pebble deposits of Florida and the deposits in the western phosphate field are the principal source of phosphate in the United States.

The land-pebble district of Florida is in the west-central part of the peninsula. The phosphate deposits are mostly in the Bone Valley formation which is considered by most writers to be of Pliocene age. However, some of the phosphate mined is a residual part of the underlying Hawthorn formation of middle Miocene age. The high-grade phosphate is locally termed "matrix." Phosphate is mined only from the deposits in the northern half of the district, although there are some lower grade phosphate deposits in the southern half.

² Safford, J. M., 1851, The Silurian Basin of middle Tennessee, with notices of the strata surrounding it: *Am. Jour. Sci.*, 2d ser., v. 12, p. 352-361.

The lower part of the Bone Valley formation is composed of quartz sand, clay, and phosphate nodules. The upper part of the formation is a clayey sand with few phosphate nodules. In some areas of the land-pebble district the upper part and the top of the lower part of the Bone Valley have been altered by acidic ground waters. The altered sections that reflect the original rock type are known as the leached zone, and are erratically distributed in the northern part of the land-pebble district. The leached zone apparently does not extend into the southern part of the district.

The P_2O_5 content of the phosphate nodules in the matrix ranges from 30 to 36 percent, and the uranium content ranges from 0.005 to 0.02 percent. Generally, the uranium content of the phosphorite increases as the phosphate content increases. One exception is the leached zone which has a higher uranium content and a lower P_2O_5 content than the matrix.

The most important phosphate deposits in the western field are found in the phosphatic shale member of the Phosphoria formation of Permian age. The Phosphoria formation and its stratigraphic equivalents crop out in Idaho, Montana, Wyoming, and Utah, and have an eastern and a western facies.

The western facies is part of the folded Cordilleran miogeosyncline and is characterized by black shales, cherts, carbonaceous mudstones, and black phosphorites. The eastern platform facies has a predominance of carbonate rocks, with interbedded layers of chert, sand, limestone, and low-grade phosphatic rock.

The P_2O_5 content of the minable beds of the Phosphoria rarely exceeds 32 percent. The uranium content of the phosphorite ranges from 0.01 to 0.02 percent and seems to increase in a general way with an increase in phosphate.

Other examples of marine phosphorites are the blue-rock phosphate of Tennessee which is an unaltered part of the Hardin sandstone member of the Chattanooga shale,³ phosphatic limestones of Permian age in central Texas, phosphate deposits in the Cason shale near Batesville, Ark.,⁴ and phosphatic nodules in black shales in Kansas and Oklahoma.

It has been suggested that the uranium in marine phosphorites substitutes for calcium in the phosphate mineral fluorapatite (ref. 12, p. 28, 29); however, some uranium appears to be associated with the clay minerals and organic material. Most authors agree that the uranium in phosphorites is of syngenetic origin and derived from sea water. The theory of syngenetic origin is supported by the fact that

³ Smith, R. W., and Whitlatch, G. I., 1940, The phosphate resources of Tennessee: Tenn. Dept. Cons., Div. Geology Bull. 48, 444 p.

⁴ Waggaman, W. H., 1912, A report on the natural phosphates of Tennessee, Kentucky, and Arkansas: U. S. Bur. Soils Bull. 81, 36 p.

the uranium content of marine phosphorites is higher than that of continental phosphate deposits.

The marine phosphate deposits of the United States represent a large low-grade reserve of uranium. In 1952 the Atomic Energy Commission announced that the Blockson Chemical Co., near Joliet, Ill., would be the first to extract uranium from phosphate rock. Since then, plants in Texas City, Tex., and in Florida have started to produce uranium as a byproduct in the manufacture of wet-process phosphoric acid.

EXPLANATION OF THE BIBLIOGRAPHY AND INDEX MAPS

This bibliography consists primarily of annotations of published reports and open-file reports of the Geological Survey pertaining to the geology of uranium-bearing phosphorites; a few general papers on the geology of domestic phosphates are included. The references are numbered and are listed alphabetically by author.

Most of the annotations were prepared by Curtis and express the ideas of the authors. Where information has been added for clarification it is included in brackets. Where the author's exact words are used in lieu of an annotation, "Author's abstract" or a similar phrase appears at the end of the quotation.

The stratigraphic nomenclature as used in the bibliography is that of the various authors and does not necessarily correspond to the U. S. Geological Survey usage.

Each locality or general area mentioned in the annotations is assigned a number—for example, Locality 23, Western phosphate field. The localities are listed numerically on page 35 and are shown on the index maps, figures 2 and 3, pages 34 and 35; the locality number precedes the corresponding area in the key to localities.

ACKNOWLEDGMENTS

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SELECTED ANNOTATED BIBLIOGRAPHY

- 1 Altschuler, Z. S., 1953, Southeast phosphate mineralogic and petrologic studies: *in* Search for and geology of radioactive deposits, Semiannual progress report, December 1, 1952, to May 31, 1953: U. S. Geol. Survey Rept. T-330, p. 171-176, issued by U. S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

This is a summary of mineralogic and petrologic studies made of southeast phosphates from August 1952 to May 1953.

A petrologic study of sections from a mine face at Homeland, Fla., where the aluminum phosphate zone (leached zone) transgresses the original stratigraphy, indicates that the mineralogy varies according to the degree of alteration of the rock. The minerals, listed in order from the base to the top of the section, are montmorillonite and apatite in the unaltered area; pseudowavellite, kaolinite, apatite, and montmorillonite where alteration is first observed; pseudowavellite and montmorillonite near the top in areas of more intense alteration; and wavellite at the top of the section. Quartz, which is abundant in all samples, increases regularly from the base to the top.

The uranium content of the sections is increased by supergene processes at the base of the pseudowavellite-apatite zone.

Determination of the origin of the surface sands and of the source of the uranium are two major problems in regard to the leached zone of the land-pebble district. Field evidence indicates either a residual or depositional origin for the surface sands, and that the uranium in the leached zone could be a concentrated product of a once thicker section of slightly phosphatic, clayey, quartz sand.

- 2 Altschuler, Z. S., Clarke, R. S., Jr., and Young, E. J., 1954, Occurrence of uranium in phosphate deposits, petrology; in *Geologic investigations of radioactive deposits*, Semiannual progress report, June 1 to November 30, 1954: U. S. Geol. Survey Rept. TEI-490, p. 203-204, issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

Samples of apatite of unusually high uranium content were studied by autoradiographic and nuclear emulsion methods to obtain knowledge of the distribution of uranium within them. One specimen, consisting of apatite cement in an arkose, had 0.74 percent U; another, a fossil bone from South Dakota, had 0.083 percent U. In both specimens the uranium was found to be uniformly distributed on a microscopic scale and not localized or concentrated in inclusions. Concentration of uranium occurred on a microscopic scale, peripheral areas of the bone being much richer than internal areas. It is interesting to note that uranium in these highly enriched materials occurs in the same manner that it does in normal sedimentary apatite of much lower grade (0.01-0.02 percent U), revealing that the lower grade apatites are far from saturated with uranium.

In study of well cuttings from the Clark-James tract, in the Land Pebble Field of Florida, it was found that the uraniferous material is iron stained and impregnated apatite. Although this area may have been secondarily altered and enriched in uranium, it is not analogous to the aluminum phosphate zone of the Peace River basin, as it lacks the secondary aluminum- and calcium-aluminum phosphates. In addition, an appreciable part of the uranium in the Clark-James tract is associated with goethite and limonite. This is revealed by analyses of magnetic and specific gravity splits in which it was found that uranium paralleled iron more closely than it did phosphorous or calcium.—*Authors' Section on Petrology*

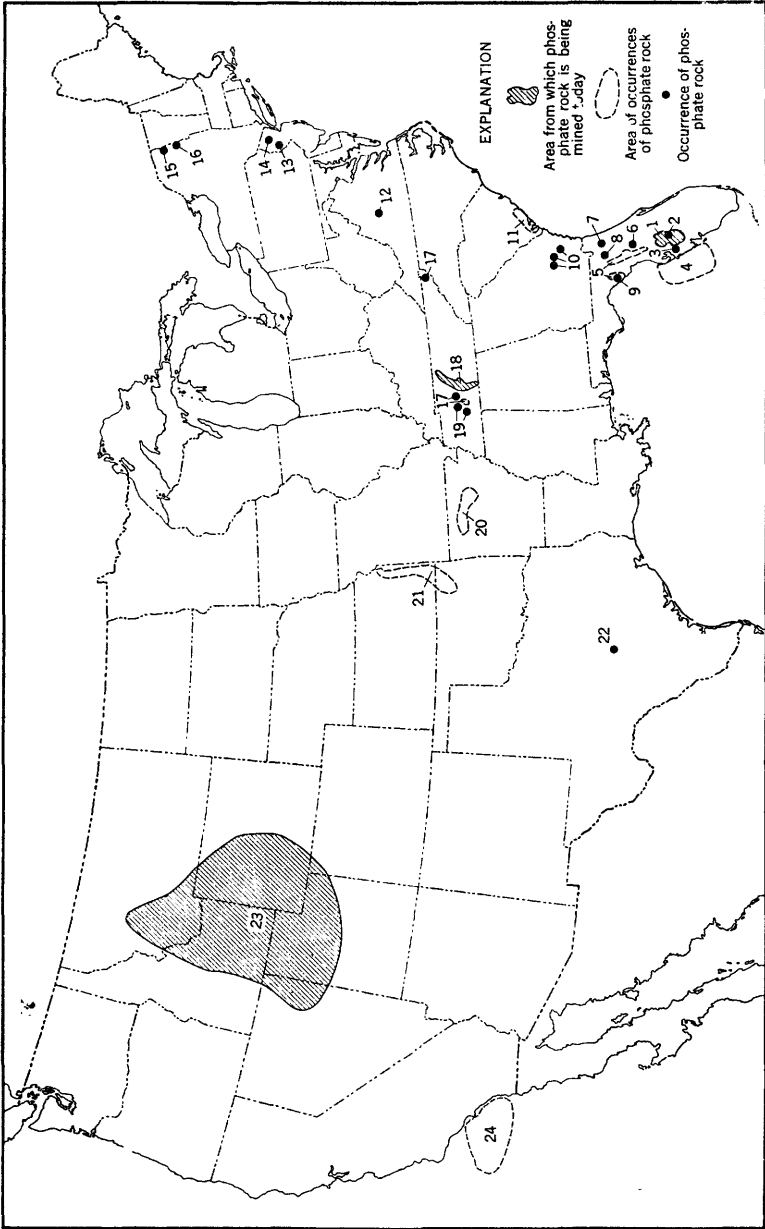


FIGURE 2.—Index map of uranium-bearing phosphorites in the United States.

KEY TO LOCALITIES

[Nos. on figures 2 and 3]

Locality No.

1. Land-pebble phosphate district, Florida.
2. Phosphate mine at Homeland, Polk County, Fla.
3. Anomalous radioactivity, Manatee County, Fla.
4. Area of phosphorite occurrences in the eastern Gulf of Mexico.
5. Hard-rock phosphate field, Florida.
6. Anomalous radioactivity, Marion County, Fla.
7. Anomalous radioactivity, Clay County, Fla.
8. Anomalous radioactivity, Union County, Fla.
9. Anomalous radioactivity, Steinhatchee area, Florida.
10. Anomalous radioactivity, Altamaha River drainage, Georgia.
11. Phosphate field (land rock and river pebble), South Carolina.
12. Titanium-apatite deposits, Amherst and Nelson Counties, Va.

Locality No.

13. Mulligan Quarry, Hunterdon County, N. J.
14. Canfield phosphate mine, Morris County, N. J.
15. Rutgers Mine, Clinton County, N. Y.
16. Mineville district, Essex County, N. Y.
17. White rock phosphate, Tennessee.
18. Brown rock phosphate, Tennessee.
19. Blue rock phosphate, Tennessee.
20. Phosphate field, Arkansas.
21. Area of occurrences of phosphatic nodules in black shale, Oklahoma and Kansas.
22. Phosphorite prospect, Marble Falls, Tex.
23. Limits of Phosphoria formation, western phosphate field.
24. Area of phosphorite samples taken off the coast of southern California.
25. Area of phosphate deposits in northern Alaska.

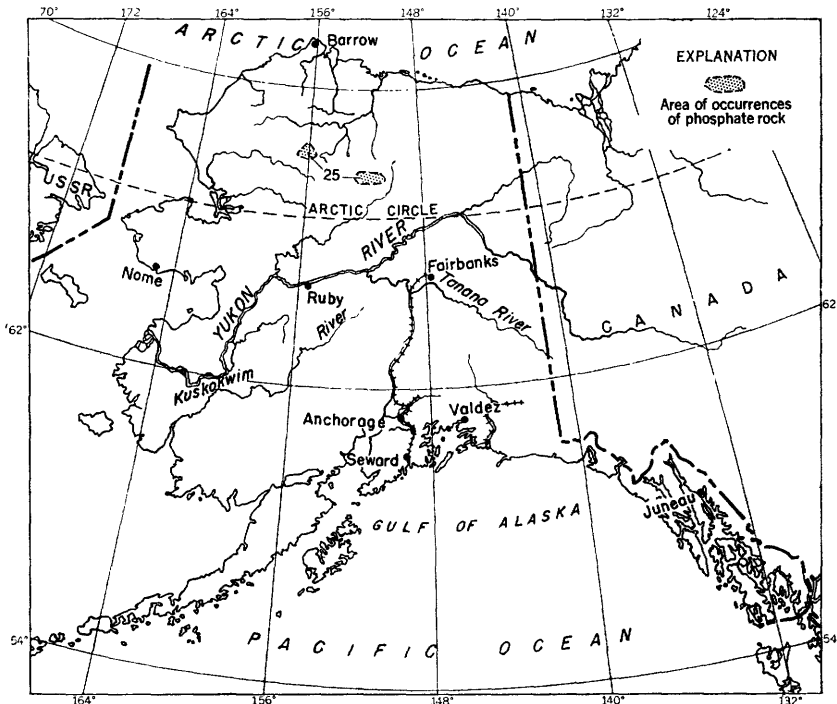


FIGURE 3.—Index map of uranium-bearing phosphorites in Alaska.

- 3 Altschuler, Z. S., Jaffe, E. B., and Cuttitta, Frank, 1956, The aluminum phosphate zone of the Bone Valley formation, Florida, and its uranium deposits: Proc. Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955, v. 6, p. 507-513; U. S. Geol. Survey Prof. Paper 300, p. 495-504.

The Bone Valley formation of Pliocene age, which contains most of the land-pebble phosphates, occurs in west-central Florida, east of the Tampa Bay region. It unconformably overlies the Hawthorn formation of early and middle Miocene age and is covered by a surface mantle of quartz sands. It contains graded bedded pebbly and clayey phosphatic sands in its lower two-thirds, which are mined, and a less phosphatic massive-bedded clayey sand, approximately 8-10 feet thick, in its upper third, which is discarded.

The upper part of the Bone Valley formation has been leached, altered to aluminum phosphates, and enriched in uranium in a widespread though discontinuous zone which averages about 6-7 feet in thickness and underlies several hundred square miles of the Peace and Alafia drainage basins. The areal distribution patterns with respect to the thickness, tonnage, and grade of the aluminum phosphate zone conform strikingly to the topography of the river valleys.

The Bone Valley formation was altered by weathering and ground water, and the vertical changes through the aluminum phosphate zone show a progressive change in mineralogy and texture. In typical sections carbonate-fluorapatite still prevails at the base, incipiently leached and altered. In the middle of the zone, the calcium aluminum phosphates crandallite and millisite are found, and at the top the aluminum phosphate wavellite predominates. The changes have been brought about by phosphatization of clay and by alumina alteration of apatite.

Much apatite and clay have been leached and replaced in the aluminum phosphate zone, and its rock is generally white, friable, and highly porous; however, its character has been greatly influenced by the primary Bone Valley petrography. Thus, where graded bedded pebbly rock is altered, coarse, frequently graded, vesicularity results; where massive clayey sand is altered, fine porosity prevails, and aluminum phosphates are more common.

The uranium content of unaltered rock of the lower part of the Bone Valley is approximately 0.008 percent; its P_2O_5 content is about 15 percent. Unaltered rock of the upper part of the Bone Valley contains much less uranium and P_2O_5 . By contrast, a well-developed section of aluminum phosphate zone typically has 0.012 percent uranium and approximately 8-10 percent P_2O_5 . Within the aluminum phosphate zone, uranium increases as calcium does, and the more calcic phosphates are more uraniumiferous. In addition, supergene processes have caused a subzone of basal enrichment in the aluminum phosphate zone in which individual apatite specimens contain as much as 0.X percent uranium. Except for a single trace occurrence of autunite, no uranium minerals have been found in the Bone Valley formation.

The aluminum phosphate zone is a potentially valuable resource of uranium, phosphate, and alumina, particularly as it must be stripped anyway to mine the underlying apatite deposits, and its rock can be readily beneficiated by removal of quartz, the major diluent.—*Authors' abstract*

- 4 Barnes, V. E., 1954, Phosphorite in eastern Llano Uplift of central Texas: Texas University Bur. Econ. Geology, Rept. Inv. no. 23, 9 p.

A radioactive deposit of phosphorite, estimated to be 11 feet thick, is exposed about 1½ miles south of Marble Falls, Burnet County, Tex., in a road-material pit on the eastern side of an outlier of Carboniferous age. The deposit consists of interbedded phosphate rock and limestone with phosphatic nodules. Stratigraphically the deposit lies above shale typical of that in the Barnett formation of Mississippian age, and beneath spiculitic limestone at the base of the Pennsylvania Marble Falls formation. Other thin phosphate zones are known in the Llano uplift, all of which are abnormally radioactive.

The phosphorite is composed mostly of well-rounded grains between 0.1 and 0.6 mm in diameter. Most of the grains are oölitic, a few appear to be structureless pellets, and others are parts of organisms.

Phosphatic nodules are found in limestone beds, the lower of which is highly fossiliferous in places. Brachiopods are most abundant, and gastropods, cephalopods, and corals are common. The upper limestone beds are less fossiliferous and contain fewer phosphate nodules. The phosphatic nodules in the limestone are pale to dark yellowish-brown on the fresher surfaces, and a dark yellowish-orange where weathered.

Chemical analysis of a sample of the bed from 3 inches to 5 feet above the base of the deposit showed a P_2O_5 content of 13.92 percent, and a chemical analysis of the bed from 5 to 8½ feet above the base showed a P_2O_5 content of 15.18 percent. The phosphorite is estimated to contain about 0.017 percent U_3O_8 (by comparison, using a Geiger counter and an analyzed sample of phosphate rock known to contain 0.029 percent U_3O_8). [Analysis of a sample of phosphorite from the same area by the U. S. Geological Survey shows 0.006 percent equivalent uranium.]

The deposit is estimated to contain 5,000 tons of phosphorite. An additional 35,000 tons of phosphorite may be present in an outlier to the northeast, although no abnormal radioactivity was noted there. These deposits are of low grade, small tonnage, and have a questionable commercial value.

- 5 Bergendahl, M. H., 1955, Wavellite spherulites in the Bone Valley formation of central Florida: *Am. Mineralogist*, v. 40, nos. 5 and 6, p. 497-504.

Megascopic spherulitic aggregates of wavellite have been recently found in the Florida land-pebble phosphate field. Petrographic studies were made to establish the identity of the mineral. Chemical and spectrographic data revealed the spherulites to be practically pure wavellite; the remainder is composed of phosphatic cement partly altered to wavellite. The origin of wavellite is considered to be secondary, a replacement of apatite that has undergone ground-water leaching.—*Author's abstract*

- 6 Carswell, L. D., and McKelvey, V. E., 1954, Effects of weathering on phosphate rocks; in *Geologic investigations of radioactive deposits*, Semiannual progress report, June 1 to November 30, 1954: U. S. Geol. Survey Rept. TEI-490, p. 193-194, issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

The investigation of the effects of weathering on the composition of phosphate rock continued, with the collection of a suite of about 80 samples from various levels of the Anaconda Copper Mining Company's mine at

Conda, Idaho, and the transmittal for analysis of several hundred samples cut by the San Francisco Chemical Company from exploratory workings in the Crawford Mountains. Analyses furnished by both the Anaconda Company and the San Francisco Chemical Company on samples collected from their mines show a steady decrease in phosphate content in high-grade rocks of the lower bed from about 33 percent P_2O_5 near the surface to 30 percent or less a few scores or hundreds of feet below the surface. Results of a few analyses made by the U. S. Geological Survey on the San Francisco Chemical Company's samples from the Crawford Mountains show that, as the phosphate content decreases, the percent loss on ignition increases in [an] amount that nearly compensates for the decrease in phosphate. This suggests that the chief effect of weathering is leaching of carbonaceous matter and carbonates.

Coatings of a secondary uranium mineral, probably tyuyamunite, were found by the San Francisco Company in its Crawford Mountain workings, showing that some uranium is leached during weathering and redeposited at depth. Uranium analyses on the samples show no indication, however, of any notable enrichment nor of any persistent trend in variations in the uranium content with depth.—*Authors' complete text*

- 7 Cathcart, J. B., 1950, Notes on the land-pebble phosphate deposits of Florida; *in* Snyder, F. G., (ed.), Symposium on mineral resources of the southeastern United States, 1949 proceedings: p. 132-151, The Univ. of Tenn. Press, Knoxville, Tenn.

The phosphate deposits in Florida are the land-pebble deposits of marine origin and of Pliocene age such as those in the Bone Valley formation, the hardrock deposits of continental origin, formed as replacement bodies in earlier limestone and as fluvial concentrations in Pliocene stream channels, and the river-pebble phosphate of continental origin which is found as bars and on flood plains along modern streams.

The phosphorites contain small quantities of uranium, which probably is in the phosphate mineral (a fluorapatite). The supposition that the source of the uranium was sea water is supported by the fact that the marine Bone Valley formation has a higher uranium content than the continental hardrock. The Bone Valley formation has a higher uranium content, and possibly accumulated more slowly than the underlying marine Hawthorn formation. This fact suggests that the longer the time of exposure of the phosphate nodules to the sea water, the greater their uranium content.

- 8 Cathcart, J. B., 1953, Economic geology, land-pebble phosphate district (Florida); *in* Geologic investigations of radioactive deposits, Semi-annual progress report, June 1 to November 30, 1953: U. S. Geol. Survey Rept. TEI-390, p. 175, issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

The Peace River area, Florida, may be divided into three physiographic units: the ridge, the flatwoods, and the valley and flood plain of the river. The aluminum phosphate zone is thickest, most continuous, and highest in P_2O_5 and U in the flatwoods region, is thin and discontinuous, or absent in the ridge area, and is absent in the flood plain and valley of the Peace River. Analytical data indicate that areas of high P_2O_5 and high U are generally the same, and in general these high areas are also the thicker sections. However, detailed drilling has shown the extreme lateral vari-

ations in both thickness and analyses, from possibly minable to unminable areas in as little as 200 feet. It seems likely that very detailed drilling will be necessary before mining in order to predict feeds for a plant, and that some surge capacity and mixing facilities will be necessary to maintain a uniform feed.

- 9 Cathcart, J. B., 1954, Drilling of airborne radioactivity anomalies in Florida, Georgia, and South Carolina: U. S. Geol. Survey Open-file Rept., 11 p.

Areas of abnormal radioactivity, as recorded by airborne surveys in Florida, in general were proved by drilling to be underlain, at shallow depths, by uranium-bearing phosphatic rocks. In Marion County, Fla., drilling within the area of anomalous radioactivity showed aluminum phosphate material very close to the surface; check holes drilled outside the areas of anomalous radioactivity showed thick, barren quartz sand at the surface. However, several areas of anomalous radioactivity were drilled and checked with a scintillation counter without finding any anomalous radioactivity. In the area near Olustee Creek, in Union County, Fla., and in the Steinhatchee area, the reason anomalous radioactivity was not found may be that the anomalous areas, as shown on county road maps, are misplotted. County roads in both cases are shown cutting across the edges of the anomalous areas, and if the line enclosing the area of anomalous radioactivity were moved only a short distance, the roads would be out of the areas and would be blank as the drilling indicated.

In Clay and Manatee Counties, Fla., and in the Altamaha River drainage in Georgia, the anomalies were very slight, only about twice background, and reasons for finding no anomalous radioactivity on the ground are not known.

In general, therefore, it would seem that anomalies which are greater than about twice background indicate the presence of uranium-bearing phosphatic rocks at or near the surface, while those anomalies which are only about twice background may or may not indicate the presence of phosphate rock.—*Author's abstract*

- 10 Cathcart, J. B., 1956, Distribution and occurrence of uranium in the calcium phosphate zone of the land-pebble phosphate district of Florida: Proc. Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955, v. 6, p. 514-519; U. S. Geol. Survey Prof. Paper 300, p. 489-494.

The land-pebble phosphate district, in west-central peninsula Florida, comprises more than 1,000 square miles, mostly in Polk and Hillsborough Counties. Lower grade phosphate deposits also occur in the south.

The Tampa limestone of early Miocene age is exposed only in the northernmost part of the area, where the Hawthorn formation of early and middle Miocene age thins to a feather edge. The Hawthorn formation contains minor to trace amounts of phosphate particles; and where the carbonate has been removed by weathering, the residual concentration of phosphate particles and quartz sand is called "bedclay," and may form a part of the matrix.

The Bone Valley formation of Pliocene age has been leached by acid ground waters, forming a zone characterized by aluminum phosphate minerals. This zone, locally called the "leached zone," commonly contains between 0.010 and 0.015 percent uranium.

The matrix, or calcium phosphate zone, constituting the lower phosphorite part of the Bone Valley formation, and the upper residual part of the Hawthorn formation, consists essentially of equal parts of quartz sand, phosphate particles (+150 mesh), and slime (-150 mesh). The central area of the Bone valley formation contains predominantly coarse (+14 mesh) phosphate, and the surrounding areas contain predominantly fine (-14+150 mesh) phosphate. The analysis of many thousands of samples has shown that the coarser phosphate particles are higher in uranium and lower in P_2O_5 content than the finer material. Uranium content of the coarser material (pebble) averages between 0.010 and 0.020 percent, and the P_2O_5 content averages about 31.5 percent. The uranium content of the finer materials (concentrates) is commonly between 0.005 and 0.015 percent, and the P_2O_5 content averages about 34 percent. A direct relation between P_2O_5 content and U content is present, however, within a size fraction: in pebble samples of the same size, the U content tends to increase as the P_2O_5 increases.

The uranium content of the quartz sand fraction of the matrix is less than 0.001 percent, and the slime fraction of the matrix usually contains small amounts of uranium, averaging less than 0.005 percent, although some samples very high in P_2O_5 content have a higher uranium content.

It is believed that the uranium is syngenetic, and was absorbed by the phosphate particles as they formed on the sea floor. This might account for the observed higher uranium content of the coarser materials, because they were probably exposed for longer periods of time to the action of sea water than were the smaller particles.—*Author's abstract*

- 11 Cathcart, J. B., Blade, L. V., Davidson, D. F., and Ketner, K. B., 1953, The geology of the Florida land-pebble phosphate deposits; in *Origine des gisements de phosphates de chaux*: Cong. Geol. Internat., 19^e, Alger, Comptes rendus 1952, Sec. 11, Fas. 11, p. 77-91 (see p. 77).

The land-pebble phosphate district is on the Gulf Coastal Plain of Florida. The phosphate deposits are in the Bone Valley formation, dated Pliocene by most writers. These strata overlie the Miocene Hawthorn formation, and are overlain by unconsolidated sands 3 to 20 feet thick.

The mineable phosphate deposits, called "matrix" in the district, range from a featheredge to about 50 feet in thickness and consist of phosphatic pellets and nodules, quartz sand, and montmorillonitic clay in about equal proportions. Locally the matrix displays cross-bedding and horizontal laminations, but elsewhere it is structureless. The phosphorite particles, composed largely of carbonate-fluorapatite, range in diameter from less than 0.1 mm to about 60 cm, and in P_2O_5 content from 30 to 60 percent. Coarse-pebble deposits, containing 30 to 34 percent P_2O_5 , are found mainly on basement highs; and fine-pebble deposits, containing 32 to 36 percent P_2O_5 are found in basement lows. Deposits in the northern part of the field contain more phosphate particles and their P_2O_5 content is higher than those in the southern part.

The upper part of the phosphatic strata is leached to an advanced degree and consists of quartz sand and clay-sized particles of pseudowavellite and wavellite. The leached zone ranges in thickness from a featheredge to 60 feet.

The origin of the land-pebble deposits is incompletely known. Possible modes of origin are a residuum of Miocene age, or a reworked residuum of Pliocene or Quarternary age.—*Authors' abstract*

- 12 Davidson, C. F., and Atkin, D., 1953, On the occurrence of uranium in phosphate rock; in *Origine des gisements de phosphates de chaux*: Cong. Geol. Internat., 19°, Alger, Comptes rendus 1952, Sec. 11, Fas. 11, p. 13-31 (see p. 29).

It has been known since the investigations of Strutt over forty years ago that phosphorites, apatite crystals, and fossil bones are richer in uranium than the average rocks of the earth's crust. In the present study a quantitative examination has been made of the uranium content in commercial phosphate rocks from North Africa, America [Florida, South Carolina], various localities in Europe, and the Oceanic Islands. A considerable range of values has been found, the Ocean Island phosphorites possessing a low radioactivity and the phosphate rocks of marine deposition showing high uranium, especially where the carbonate content is low. Fossil bones and apatite crystals also contain a little uranium, the highest value found being 0.55 percent eU_2O_8 in a Middle Old Red Sandstone fossil fish from Sutherland [Great Britain]. Aluminum phosphates, such as variscite and turquoise, may display a significant radioactivity. It is concluded that, at least in most instances, the uranium is present in the apatite of the phosphorite of bone as a proxy for calcium, and that it is derived principally from percolating waters. Where the apatite or phosphorite is of a porous nature the substitution has usually proceeded uniformly throughout the mass; where it is compact or impervious replacement is concentrated towards the edges.—*Authors' summary*

- 13 Dietz, R. S., Emery, K. O., and Shepard, F. P., 1942, Phosphorite deposits on the sea floor off southern California: *Geol. Soc. America Bull.*, v. 53, no. 6, p. 815-848.

Submarine phosphorite deposits are found off the coast of Southern California from Monterey Bay south to the Gulf of California. Samples of phosphorite were collected from the sea bottom, as well as from the tops and sides of offshore banks. The deposits are found in Miocene to Recent sediments, but no positive identification of the age of the strata could be made.

The mode of occurrence of the phosphorite ranges from thin flat slabs to nodular masses. Phosphorite also is found as coatings on hard compact rock, as fillings in porous rock, and as a cement of fragments of darker phosphorite and other rocks.

The nodules are generally hard and dense, and have smooth glazed surfaces and a fresh appearance. Their surface consists of a thin discolored layer of phosphorite or of manganese oxide. Freshly broken surfaces are usually light to dark brown. Collophane is the principal mineral form of the phosphate. Francolite(?) is sometimes associated with the collophane. The majority of the nodules are irregularly layered, many are conglomeratic, and nearly all the phosphorite is somewhat oölitic. Many nodules enclose foreign material such as foraminiferal tests, grains of clastic minerals, and glauconite.

Six samples that were analyzed chemically have an average of 28.15 percent P_2O_5 , 44.91 percent CaO, and 3.11 percent F. Insoluble residues

comprised from 6 to 30 percent of the samples; the fine fraction consisted dominantly of amorphous silica and carbonaceous material; the coarse fraction consisted of glauconite, mineral grains, carbonaceous particles, and siliceous animal remains.

That the phosphorite was deposited essentially in place is suggested by the following facts: the one-sided mammillary surfaces formed by growth layers on many nodules; the large size of many of the nodules, and their lack of abrasion; the close resemblance of the sediment enclosed in the nodules with the surrounding sediment; and the nondepositional environment [probably meaning the paucity of clastic sediments being deposited at present] which prevails on the sea floor off southern California.

The authors conclude that the nodules were deposited on the present banks, shelves and canyon walls during the Quaternary, and that previously an abundance of Miocene foraminifera had been eroded or weathered out of Miocene formations and concentrated on surfaces upon which the phosphorite deposition gradually took place.

- 14 Emery, K. O., and Dietz, R. S., 1950, Submarine phosphorite deposits off California and Mexico: *Calif. Jour. Mines and Geology*, v. 46, no. 1, p. 7-17.

This paper is mostly a résumé of the paper by Dietz, Emery, and Shepard (ref. 13) with the addition of data on the radioactivity of some of the nodules. Samples of phosphorite were taken from submarine areas off the coast of southern California. The sea sediments are Miocene to Recent in age. The beta-radioactivity of 10 nodules from areas off the coast of California ranged from 41 to 65 counts per minute per gram. The background was 22 counts per minute.

- 15 Gould, H. R., 1953, Phosphate studies in the eastern Gulf of Mexico; *in* Search for and geology of radioactive deposits, Semiannual progress report, December 1, 1952, to May 31, 1953, p. 176-180: U. S. Geol. Survey Rept. TEI-330, issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

The purpose of the investigations of the phosphorite deposits in the eastern Gulf of Mexico was to determine the areal distribution, quality, source and mode of formation of the phosphatic sediments.

Preliminary results show that the continental shelf between Tarpon Springs and Fort Meyers, Fla., consists of an inshore zone 20 miles wide and an outer zone 100 miles wide. The inshore zone is characterized by detrital sands composed chiefly of quartz. Generally, only traces of phosphorite were found in this zone. Visual comparison with chemically analyzed samples indicate that samples from this zone have a P_2O_5 content of less than 0.50 percent and a uranium content of less than 0.0001 percent. However, a few of the samples analyzed chemically have maximum contents of 13.4 percent P_2O_5 and 0.004 percent uranium.

Almost no phosphorite was detected in the offshore zone, which is characterized by calcareous sands of organic origin. These sediments have a P_2O_5 content of less than 0.15 percent and a uranium content of less than 0.0001 percent.

The characteristics of the phosphorite in the two zones suggest that it is detrital material transported by streams from peninsular phosphate deposits and from adjacent phosphatic beaches.

- 16 Harris, R. A., Davidson, D. F., and Arnold, B. P., 1954, Bibliography of the geology of the western phosphate field: U. S. Geol. Survey Bull. 1018, 89 p.

Nearly all papers published before September 1952 on the geology of phosphate deposits in Alberta and British Columbia, Colorado, Idaho, Montana, Utah, and Wyoming have been included in this bibliography. There is also a section on the mineralogy and chemical composition of phosphorites in other regions. The section on areal geology includes only the publications that describe the geology of areas in which the Phosphoria formation or its partial stratigraphic equivalents, the Park City and Embar formations, are found. The other sections include papers on the stratigraphy, regional structure, fuels, and mineral deposits other than phosphate. Entries are liberally cross indexed.

- 17 Jacob, K. D., Hill, W. L., Marshall, H. L., and Reynolds, D. S., 1933, The composition and distribution of phosphate rock with special reference to the United States: U. S. Dept. of Agriculture Tech. Bull. 364, 90 p.

A brief review of the phosphate deposits and the production and reserves of phosphate rock in the United States is given. The flotation process of concentrating low-grade phosphate ores is discussed with reference to its value in the conservation of the phosphate deposits in the southeastern part of the United States.

The results of an analytical study of 46 samples of mineral calcium phosphates representing nearly all of the more important domestic types and sources of this material are presented. Data are also given on the composition of 11 samples of bone ash, apatites, and foreign phosphate rocks, and on the percentages of fluorine and phosphoric acid in a large number of additional samples from deposits throughout the world.

Phosphoric acid, lime, alumina, iron, silica, carbon dioxide, fluorine, and, in most samples, sulphate are the predominating constituents of domestic phosphate rock. Magnesium, titanium, sodium, potassium, manganese, chromium, copper, zinc, arsenic, chlorine, and iodine are present in nearly all samples, but only in comparatively small quantities. Small percentages of vanadium are also present in many samples.

Phosphate rock from continental deposits usually contains 3 to 4 percent of fluorine, whereas that from insular deposits contains smaller quantities. As a general rule, the fluorine-phosphoric acid ratios in a particular type of rock are approximately constant. Although fresh bones are very low in fluorine, fossil bones frequently contain high percentages of this element. Evidence is presented to show that the fluorine in phosphate rock and fossil bones originates principally from contact of the phosphates with fluorine-bearing waters, and that, to a certain extent, there is a rough correlation between the fluorine content and the geological age of these materials.

The commercial types and grades of domestic phosphate rocks contain approximately the following percentages of minor constituents—MgO, 0.0 to 0.5; TiO₂, 0.02 to 0.15; Na₂O, 0.1 to 0.8; K₂O, 0.05 to 0.65; MnO, traces to 0.3; Cr₂O₃, 0.00 to 0.15; V₂O₅, 0.00 to 0.40; CuO, <0.0005 to 0.01; ZnO, <0.0005 to 0.025; As₂O₃, 0.001 to 0.015; and Cl, 0.00 to 0.10. The iodine content ranges from approximately 1 to 130 parts per million.

Pyrite is a common constituent of Tennessee blue rock and phosphatic limestone, South Carolina land rock, and rock from Cokeville, Wyo.

The organic matter isolated from phosphate rock carries high percentages of nitrogen and sulphur, and the ash of this material is rich in iron.

In comparison with the other types of domestic phosphate rock, Tennessee brown-rock phosphate is characterized by the presence of high percentages of aluminum, iron, and manganese, and by the absence of vanadium. It usually contains more potassium than sodium, whereas the reverse is the rule with the other types.

Tennessee blue-rock phosphate is similar to Tennessee brown rock in that it is comparatively high in iron. It is also high in acid-soluble sulphate, but its outstanding characteristic is its high content of acid-insoluble sulphide, principally pyrite.

Florida land-pebble phosphate has no outstanding chemical characteristic. The percentages of fluorine in the different commercial grades of this material are, however, approximately constant, whereas in the other types of phosphate rock the fluorine content varies, as a general rule, directly with the phosphoric acid.

Florida hard-rock phosphate is characterized by its comparatively high content of iodine, and low content of sulphate and chlorine.

In general, the phosphates from deposits in the Rocky Mountain States are comparatively high in chromium and vanadium, and low in iodine. Certain samples, notably those from deposits at Conda, Idaho, and Cokeville, Wyo., are exceptionally high in organic carbon and organic sulphur, whereas rock from the Garrison, Mont. deposit is low in organic carbon and in total sulphur.

In comparison with phosphate rock, Florida waste-pond phosphate is low in phosphoric acid and exceptionally high in silica and alumina. The composition of Florida soft phosphate varies considerably with different samples.

Nearly all of the elements present in phosphate rock occur also in bone ash.

Analyses of the mechanical fractions separated from samples of ground phosphate rock and from Florida soft and waste-pond phosphates showed that, as a general rule, the phosphoric acid, calcium, and fluorine concentrate somewhat in the "sand" and "silt" fractions, whereas the alumina and silica concentrate to a marked extent in the "clay" and colloid fractions, particularly the latter.

Phosphate rock does not contain significant quantities of phosphoric acid soluble in neutral ammonium citrate solution, and less than 30 percent of the total phosphoric acid is soluble in 2 percent citric acid solution. The percentages of phosphoric acid dissolved by these reagents from a particular sample of phosphate increase with increase in the fineness of the particles.

The principal phosphatic component of phosphate rock from continental deposits is fluorapatite, which is present almost entirely in the sub-microcrystalline condition. Hydroxyfluorapatite is an important constituent of rock from insular deposits. The available data indicate that domestic phosphate rock may contain small quantities of carbonate apatite and hydroxyapatite.—*Author's abstract*

- 18 Ketner, K. B., 1955, A bibliography of phosphate deposits in southeastern United States: U. S. Geol. Survey Open-file Rept., 18 p.

The bibliography includes references published before 1954 on the geology of phosphate deposits in South Carolina, Georgia, Alabama, and Florida.

- 19 McKelvey, V. E., 1955, Search for uranium in the United States: U. S. Geol. Survey Bull. 1030-A, p. 1-69. (See p. 16, 17, 37.)

Uranium is concentrated in phosphorites by chemical adsorption processes, either at the time of deposition of the phosphorite, or before the phosphatic material was buried. Generally, appreciable amounts of uranium are found only in noncalcareous marine phosphorites with a P_2O_5 content of more than 25 percent. Residual deposits derived from the weathering of phosphatic limestones usually have a low uranium content unless they have been exposed to sea water or other uranium-bearing solutions.

- 20 McKelvey, V. E., 1956, Uranium in phosphate rock; Proc. Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955, v. 6, p. 499-502: U. S. Geol. Survey Prof. Paper 300, p. 477-481.

Marine phosphorites commonly contain 0.005 to 0.03 percent uranium. The uranium content increases roughly with increasing phosphate content but is generally low in rocks that contain more than a few percent CO_2 . Aluminum phosphate deposits that have been derived from the weathering of marine phosphorites and phosphatic nodules in some marine black shale formations contain similar amounts of uranium. Most of the uranium in these materials does not occur as a separate mineral phase but substitutes for calcium in carbonate fluorapatite or crandallite. A few occurrences of tyuyamunite and torbernite have been reported from highly weathered marine phosphorites, however, and these and other secondary uranium minerals, such as carnotite and autunite, are not uncommon in fossil bones and teeth that have been exposed to uranium-bearing solutions after burial. Because the marine phosphorites are of wide extent they contain large tonnages of uranium, some of which can be recovered, under favorable conditions, as a byproduct of the manufacture of triple super phosphate.—*Author's abstract*

- 21 McKelvey, V. E., and Carswell, L. D., 1956, Uranium in the Phosphoria formation: Proc. Internat. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1955, v. 6, p. 503-506; U. S. Geol. Survey Prof. Paper 300, p. 483-487.

The Phosphoria formation of Permian age and its close stratigraphic relatives consist of two overlapping couplets, each composed of a lower carbonaceous, phosphatic unit, overlain by a cherty or carbonatic unit. Phosphate deposits are found in the Phosphoria formation over an area of about 135,000 square miles in Montana, Idaho, Utah, and Nevada, but the richest deposits are confined to a central area in eastern Idaho and adjacent parts of Montana, Wyoming, and Utah. Nearly all the phosphatic beds are uraniferous but their uranium content ranges from about 0.001 to 0.065 percent. Although some highly phosphatic beds are only weakly uraniferous, the phosphate beds that are more than 3 feet in thickness and

that contain more than 31 percent P_2O_5 ; generally contain 0.01 to 0.02 percent uranium. Most of the differences in uranium content of the phosphate rocks cannot be correlated with other observable differences in their physical or chemical properties. As a rule, however, beds composed of pellets and oölites are more uraniferous than those composed of fish scales, brachiopod shells, and other organic remains; and highly weathered phosphate beds contain less uranium than their unweathered equivalents.

Most of the uranium seems to occur in carbonate-fluorapatite, where it probably substitutes for calcium; but tyuyamunite has been discovered in one area where the rocks are highly weathered.—*Author's abstract*

- 22 McKelvey, V. E., Cathcart, J. B., Altschuler, Z. S., and others, 1953, Domestic phosphate deposits, in Pierre, W. H., and Norman, A. G., ed., Soil and fertilizer phosphorus in crop nutrition, v. 4, p. 347-376, of Agronomy, a series of monographs, prepared under auspices Am. Soc. Agronomy: New York, Academic Press, Inc.

There are six important geologic types of phosphate deposits in the United States. They are apatite deposits of igneous origin, residual phosphorites, marine phosphorites, river-pebble deposits, phosphatized rock, and guano. The characteristics of each type are discussed and representative chemical analyses are given.

Concentrations of one type or another are found in 30 of the states, although only some of the states—Pennsylvania, Virginia, North Carolina, South Carolina, Georgia, Alabama, Florida, Tennessee, Kentucky, Arkansas, Idaho, Wyoming, Utah, and Montana—have produced phosphate rock.

At present, the only production is from the land-pebble district and the hard-rock field of Florida, the brown-rock field of Tennessee, and from the Permian phosphorite deposits in Idaho, Montana, Wyoming, and Utah. Future production is likely to be limited to these fields.

The authors discuss the types of phosphate deposits found throughout the United States, and estimate the total reserves of minable phosphate to be 5 billion tons of rock containing 1.5 billion tons of P_2O_5 . In addition, the reserves of lower grade material total nearly 50 billion tons of rock that contains 12 billion tons of P_2O_5 .

- 23 McKelvey, V. E., and Nelson, J. M., 1950, Characteristics of marine uranium-bearing sedimentary rocks: Econ. Geology, v. 45, no. 1, p. 35-53.

All marine phosphorites tested before 1949 contain from less than 0.01 to 0.02 percent uranium. The Permian Phosphoria formation in the west and the Pliocene Bone Valley formation in Florida represent the largest deposits of this type in the United States.

Uranium is also found as a constituent of phosphatic nodules from shales; the uranium content of the nodules is higher, generally, than that of the surrounding shale. Such uraniferous phosphatic nodules are found in the shale at the top of the Checkerboard limestone member of the Coffeyville formation and in the Fort Scott limestone of Oklahoma; and in the Hushpuckney and Stark shales of Kansas.

In general, the uranium content of the phosphorite increases as the phosphate content increases, although there are many exceptions in this country. The uranium is believed to be in the phosphate mineral which is a fluorapatite.

Local factors may influence the amount of uranium deposited. In the Bone Valley formation in Florida, for example, analyses of samples

suggest that there is a higher uranium concentration in the phosphorites with a clay-size matrix than in those with a sandy matrix. The uranium content of phosphorite beds may also vary with the thickness of a given formation, depending on whether or not the uranium-bearing materials cause the increase in thickness or are diluted by the increased amounts of non-uraniferous materials.

Phosphorite formations are characteristically thin, but probably represent the entire depositional products of long periods of time.

The uranium in phosphorite is of syngenetic origin; it is probably derived from sea water either by direct precipitation as an inorganic uranium salt, or by the selectivity of organisms or substances for which it has an affinity.

If it is assumed that the uranium is precipitated and fixed in the sediments in these ways, its later concentration may result from conditions that lead to the concentration of the phosphate, organic matter, or other substances with which the uranium is associated. An environment that does not favor the influx of large amounts of clastic material or the precipitation of large amounts of carbonate is a basic necessity for the deposition of uranium in a marine basin. The height of the adjacent land masses, the dimensions and configuration of the basin of deposition, and the climate control the development of such an environment.

The authors believe that relatively thin beds of phosphorite such as those described should be investigated further because they are likely to contain significant amounts of uranium.

- 24 McKelvey, V. E., Swanson, R. W., and Sheldon, R. P., 1953, The Permian phosphorite deposits of western United States; *in* Origine des gisements de phosphates de chaux; Cong. Geol. Internat., 19^e, Alger, Comptes rendus, 1952, sec. 11, fasc. 11, p. 46-64.

The Permian Phosphoria formation and its stratigraphic equivalents comprise about 135,000 square miles of marine sediments in Idaho, Montana, Wyoming, and Utah. There are two facies of the formation; the western one is of the folded Cordilleran miogeosyncline, and the eastern one is a platform facies. The western facies is characterized by black shales, cherts, carbonaceous mudstones, and rich black phosphorites. The eastern facies has a predominance of carbonate rocks, with interbedded layers of chert, sand, limestone, and weakly phosphatic rock.

The phosphorites of the Phosphoria formation are a colloform carbonate-fluorapatite mixed with detrital silicates and other material. Minor amounts of more than 35 metals, including uranium, are found in the Phosphoria formation. Uranium and the rare earths are more abundant in the phosphorites than in other rocks of the Phosphoria formation. The uranium probably occurs in the carbonate-fluorapatite mineral. Most of the metals are not abundant in calcareous phosphorites; in fact, uranium appears to decrease in the phosphorites as the CO₂ content rises to as much as 4 percent.

The grade of minable phosphate beds is usually not more than 32 percent P₂O₅. The P₂O₅ content seems to increase westward to about the center of the geosynclinal facies, as does the amount of carbonaceous matter and the quality of the phosphate rock. However, the carbonate content, the size of the phosphorite particles, and the grain size of the clastic material decrease to the west. Some of the minor metals, such as uranium and

vanadium, are more abundant in the geosynclinal facies in the west, than in the eastern platform facies.

The composition and facies changes of the phosphorite are indicative of marine deposition controlled mainly by pH, CO₂ content, temperature, and depth. The presence of phytoplankton is also a contributing factor in the deposition of the phosphorite. The authors present an excellent discussion of the theory of the origin of the deposits which is similar to, but modified from, that proposed by Kazakov.

- 25 McKeown, F. A., and Klemic, Harry, 1953, Reconnaissance for radioactive materials in northeastern United States during 1952: U. S. Geol. Survey Rept. TEI-317 A., 68 p., issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

The geology and radioactivity of magnetite-apatite mines and prospects, which are not significant as possible sources of radioactive elements, are presented in table form. A few deposits that have a possible potential as sources of radioactive elements are described in detail; some of these are described briefly below.

The Mineville group of magnetite mines is in the Mineville district, near Mineville, Essex County, N. Y. The Miller, Old Bed, and "21" Bonanza-Joker, are three faulted parts of one complexly folded ore bed in the Mineville group. The ore is massive and granular; apatite is a constituent of the gangue in rich as well as lean ore. The Old Bed is the richest ore body and contains the highest percentage of phosphorous (1 to 1.25 percent). Granular high-grade ore generally contains the least amount of apatite and other gangue minerals. Medium- to fine-grained ore (magnetite grains less than about 2 mm across) contains radioactive fluorapatite-rich layers and stringers, as well as disseminated fluorapatite.

Chemical analysis of a sample of hand-picked apatite grains shows a uranium content of 0.018 percent and a thorium content of 0.04 percent. The amount of radioactivity of various samples seems to be a function of the amount of red or flesh-colored apatite present in the sample.

The Canfield phosphate mine is about 2 miles west of Dover, Morris County, N. J. The ore is a granular aggregate of magnetite and greenish-gray apatite, with quartz, feldspar, and biotite as minor constituents. The mine was originally explored for magnetite, but the high apatite content made the material worthless as an ore of iron, and the mine was abandoned. Among the rocks on the dump, those with the highest apatite content are also the most radioactive. Radioactive monazite is also present in small amounts.

The rocks of the Rutgers mine, Clinton County, N. Y., and the Mulligan quarry, Hunterdon County, N. J., also have some apatite, but the geology is described only briefly in this report.

- 26 Mansfield, G. R., 1927, Geography, geology, and mineral resources of part of southeastern Idaho: U. S. Geol. Survey Prof. Paper 152, 207 p.

The principal mineral resource of southeastern Idaho is phosphate rock, which occurs at two horizons, upper Mississippian and Permian, but only the Permian rock has much commercial value. This rock is characterized chiefly by its oolitic texture and generally dark color and by its odor when freshly broken, which resembles that of crude petroleum. It is a bedded deposit of marine origin and will have to be mined in the same manner as coal.

The phosphate rock is really a mixture or "solid solution" of several phosphatic minerals, but the chemical composition is approximately that of tricalcium phosphate, $\text{Ca}_3(\text{PO}_4)_2$. There are numerous accessory constituents, among which vanadium is noteworthy. Some tendency has been noted toward enrichment by weathering.

The western phosphate reserve now includes 2,269,055 acres, of which 664,911 acres is in Idaho. The Idaho portion comprises 268,299 acres formally classified as phosphate land and hence released from any form of phosphate withdrawal and 396,612 acres unclassified and still remaining withdrawn. There are in addition some privately owned lands. The government-owned phosphate land is classified and made available for exploitation under regulations which are specified. Not all the reserved land has yet been examined, but 52 townships in Idaho and 6 townships in Wyoming, which are regarded as phosphate bearing, are described in this paper in some detail, and estimates of their tonnages are furnished, together with revised estimates of tonnage for other parts of the western field. The estimates thus far available for Idaho alone indicate a reserve of about 5,000,000,000 tons of high-grade phosphate rock.

The history of the western phosphate industry is briefly sketched, including an account of the litigation, its settlement, and the subsequent laws affecting phosphate lands. The producing companies are briefly described and information is given regarding the production, marketing, and utilization of the rock, together with a statement about processes of manufacture of phosphate and of phosphorous.—*Author's summary, chap. 7, Mineral Resources*

- 27 Mansfield, G. R., 1940, Phosphate deposits of the United States: *Econ. Geology*, v. 35, no. 3, p. 405-429.

A variety of types of phosphate deposits, representing a wide range in geologic age, are found in the United States. Guanos containing from 4 to 32 percent P_2O_5 have been reported chiefly from Texas and New Mexico, where they are locally of some commercial importance. Phosphatic marls of both Cretaceous and Tertiary age are found in the sedimentary rocks of the eastern Coastal Plain; the P_2O_5 content is low, ranging from less than 1 percent to 4.5 percent. Low-grade phosphatic limestones are widely distributed in both the eastern and western parts of the United States and range in age from Paleozoic to Tertiary. Apatite is a constituent of many igneous and metamorphic rocks, but is rarely found in commercial concentrations. The only apatite produced in the United States is from the titanium-apatite deposits in Nelson County, Va. Phosphate rock in the North Carolina, Georgia, and Alabama fields is of low grade and has not been explored extensively. Medium-grade phosphate rock deposits in South Carolina were among the greatest sources in the world before the exploitation of the Florida and Tennessee fields. Some phosphate has been produced from the brown-rock phosphate deposits in Kentucky, and from the phosphate deposits in the Cason shale of Ordovician age in Arkansas. The most important deposits of phosphate rock are found in Florida, Tennessee, and the western field.

The principal types of phosphate rock in Florida are the land pebble, hard rock, soft rock, and river pebble. The land-pebble phosphate is in the marine Bone Valley formation of Pliocene age and is the most im-

portant commercial deposit of the four types mentioned. The residual hard-rock deposits are in the Alachua formation of Pliocene age. Soft rock is finely divided phosphatic material and is present in small amounts in both the land-pebble and hard-rock fields. River-pebble phosphate, mostly of Recent age, occurs as bars and banks in stream channels in the adjoining lowlands.

The Tennessee phosphates occur in the western part of the central basin of the state and in valleys of the western part of the Highland Rim surrounding the basin. The phosphates are of three types: brown, blue, and white rock. Brown-rock phosphates are residual deposits derived from phosphatic limestone formations of Ordovician age, and are now the most important commercially. The blue rock is an unaltered portion of the Hardin sandstone member of the Chattanooga shale of basal Mississippian or Late Devonian age. The white-rock deposits are secondary deposits formed by solution of phosphatic minerals in the overlying blue rock, and by redeposition in openings in the underlying limestone.

The phosphate deposits in the phosphatic shale member of the Permian Phosphoria formation in Idaho, Montana, Wyoming, and Utah contain the commercial deposits of the western field.

The geology of the deposits and the mining and prospecting methods used are discussed briefly; reserves are given for most of the fields.

- 28 Moxham, R. M., 1954, Airborne radioactivity surveys for phosphate in Florida: U. S. Geol. Survey Circ. 230, 4 p., 9 figs.

Airborne radioactivity surveys totaling 5,600 traverse miles were made in 10 areas in Florida, which were thought to be geologically favorable for deposits of uraniferous phosphate. Abnormal radioactivity was recorded in 8 of the 10 areas surveyed. The anomalies are located in Bradford, Clay, Columbia, De Soto, Dixie, Lake, Marion, Orange, Sumter, Taylor, and Union Counties. [Airborne radioactivity survey maps of all the areas covered are included in the circular.]

Two of the anomalies were investigated briefly on the ground. One resulted from a deposit of river-pebble phosphate in the Peace River valley; the river-pebble samples contain an average of 0.013 percent equivalent uranium. The other anomaly resulted from outcrops of leached phosphatic rock containing as much as 0.016 percent equivalent uranium. Several anomalies in other areas were recorded at or near localities where phosphate deposits have been reported.

At least two of the airborne radioactivity anomalies described above have been caused by deposits of uraniferous phosphatic materials. Most of the other anomalies were detected in areas in or near which phosphate has been reported, so it would appear that the anomalies are in some manner related to uranium associated with phosphatic materials. However, it should be pointed out that, at nearly every locality at which phosphate has been reported, the material is said to be covered by as much as 50 feet of overburden. If radioactive source rocks of the tenor with which we are dealing are covered by more than 1 foot of inert overburden, the radiation intensity should be reduced to an undetectable level at the 500-foot flight level. So, if the anomalies described above are to be attributed to phosphatic materials, we must assume that (1) the

deposits are at or near the surface of the ground or (2) radioactive materials are being transported to the surface from buried deposits.

The results of the surveys indicate that the phosphate deposits of Florida contain sufficient uranium to be detected by airborne radioactivity detection equipment provided there is some surface expression of the deposits. The significance of the radioactivity anomalies in the areas of buried phosphate deposits cannot be ascertained until adequate exploration work is undertaken.—*Author's abstract*

- 29 Nininger, R. D., 1954, Minerals for atomic energy: 367 p. (See p. 38–39 and 73–74.), D. Van Nostrand Co., Inc., New York, Toronto, London.

Uranium occurs in marine phosphorites of the western Phosphoria formation and the Bone Valley formation in Florida, and in phosphatic nodules of black shales in Oklahoma and Kansas. The uranium in these marine phosphates is of syngenetic origin. Nonmarine phosphorites, such as those in Tennessee, and the Florida hard-rock phosphates, are not appreciably uraniferous.

Uranium-bearing phosphorites range in age from Paleozoic to Pliocene and seem to be equally favorable as sources of uranium. Generally, the beds with the highest P_2O_5 content are likely to have the highest uranium content, although there are some exceptions. The uranium appears to be primarily in the phosphate mineral which is a fluorapatite, although some uranium is probably associated with the clay minerals and organic material.

The first uranium production from phosphates was in 1952 from the central Florida deposits. The Bone Valley formation of Pliocene age is the most uraniferous. The underlying Hawthorn formation of Miocene age has a lower P_2O_5 and uranium content than the Bone Valley formation.

The Permian Phosphoria formation which crops out in Idaho, Montana, Wyoming, and Utah is appreciably uraniferous. The uranium content varies from one area to another; it increases, for example, westward from Wyoming into Idaho, and decreases westward in Montana. The north-west phosphates contain several minor metals other than uranium.

- 30 Patton, W. W., Jr., 1955, Phosphate deposits in northern Alaska: U. S. Geol. Survey Open-file Rept., 13 p.

Phosphate deposits have been found in the Kiruktagiak River and Tiglukuk Creek areas in the Brooks Range in northern Alaska. The phosphate beds are in a 40-foot-thick zone of phosphate rock, limestone, and mudstone in the upper part of the Lisburne group of Mississippian age.

The phosphate rock is dark grey to black on fresh surfaces, light grey or brown on weathered surfaces, and is often coated with a characteristic bluish-white bloom. Secondary purple fluorite was noted in veinlets and on bedding plane surfaces of the phosphate rock. Phosphate pebbles a maximum of one-half inch in diameter are often found on bedding surfaces. The thickness of the phosphorite ranges from a fraction of an inch in highly argillaceous rock to 2 feet in highly calcareous rock.

The P_2O_5 content of the rocks generally ranges from 14 to 32 percent, although some samples contain as much as 34 percent. Chemical analyses

indicate a maximum of 0.024 percent equivalent uranium and 0.02 percent uranium.⁵

Detailed stratigraphic sections and chemical analyses (P_2O_5 only) are given for Monotis Creek in the Kiruktagiak River area and for Skimo Creek in the Tiglukpuk Creek area.

- 31 Runnels, R. T., Schleicher, J. A., and Van Nortwick, H. S., 1953, Composition of some uranium-bearing phosphate nodules from Kansas shales: *Kans. State Geol. Survey Bull.* 102, Pt. 3, p. 93-104.

This report discusses samples of uranium-bearing phosphate nodules taken from seven different shale beds of Pennsylvanian age in Kansas. The localities examined are in Wyandotte, Labette, Linn, Crawford, Douglas, and Wilson Counties. The shales examined are listed below, in ascending order, and some are described briefly.

Shale from the Cherokee group: A black, fissile shale a few feet above the Mulky coal and below the Fort Scott limestone. Round to oval phosphate concretions are abundant throughout.

Little Osage shale member of the Fort Scott limestone.

Anna shale member of the Pawnee limestone: The shale occurs just below the Myrick Station limestone member. The phosphate nodules have a high purity (34 percent P_2O_5) and a high uranium content (0.02 percent U_3O_8).

Lake Neosho shale member of the Altamont limestone.

Shale of the Pleasanton group: The shale has a consistent black fissile bituminous facies. The top 18 feet is barren of nodules in contrast to the underlying 10 feet which contains abundant nodules. The phosphatic nodules of this group differ slightly from those in other groups in that many of these have a core of iron sulfide.

Muncie Creek shale member of the Iola limestone: Some nodules from this shale have very high contents of P_2O_5 (37 percent) and U_3O_8 (0.03 percent). There is evidence [not given] that these nodules have been reworked and probably redeposited during final deposition and initial compaction of the shale.

Heebner shale member of the Oread limestone: This is a persistent black shale occurring between the Plattsmouth and Leavenworth limestone members. The nodules are generally well formed and numerous. According to the author the phosphate content is fairly high (32 percent P_2O_5), although the uranium content is not anomalous (0.017 percent U_3O_8).

The average composition of the phosphatic nodules is 30.2 percent P_2O_5 , 0.017 percent U_3O_8 , and 3.2 percent F. The mineral form has tentatively been identified as a carbonate-bearing fluorapatite, which is chemically between fluorapatite and dahlite. The X-ray diffraction patterns suggest a single carbonate-fluorapatite mineral, but the sedimentary origin of the nodules points to the possibility of the presence of dahlite.

⁵ Matzko, J. J., 1953, Reconnaissance for uranium in Alaska; in *Geologic investigations of radioactive deposits*, Semiannual progress report, June 1 to November 30, 1953: U. S. Geol. Survey Rept. TEI-390, p. 224; issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

Matzko, J. J., 1954, Reconnaissance for uranium in Alaska; in *Geologic investigations of radioactive deposits*, Semiannual progress report, December 1, 1953, to May 31, 1954: U. S. Geol. Survey Rept. TEI-440, p. 187; issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

The phosphate nodules may be a potential source of fertilizer because their phosphate content is comparable to that of commercial rock phosphate. The potential value of the uranium is unknown.

- 32 Russell, W. L., 1944, The total gamma ray activity of sedimentary rocks as determined by Geiger counter determinations: *Geophysics*, v. 9, no. 2, p. 180-216.

This report presents in table form the radioactivity of 510 samples of sedimentary rocks including shales, limestones, sandstones, and dolomites. Results are given for formations in Arkansas, Kansas, and Oklahoma that contain phosphatic nodules. The reference has been included because it is one of the few publications that give the results of radioactivity determinations of these rocks.

- 33 Swanson, R. W., McKelvey, V. E., and Sheldon, R. P., 1953, Progress report on investigations of western phosphate deposits: *U. S. Geol. Survey Circ.* 297, 16 p.

A comprehensive investigation of the western phosphate deposits has been in progress since 1947. Most of the field work is now completed but final reports will not be completed for some years. The scope of the investigations and preliminary conclusions, however, are summarized in this report.

The principal phosphate deposits are found in the Phosphoria and Park City formations over an area of about 135,000 square miles in Montana, Idaho, Wyoming, and Utah. The rocks composing these formations in the western part of the field are chiefly dark phosphatic shales and cherts that were deposited near the margin of the Paleozoic Cordilleran miogeosyncline; those to the east are thinner, were deposited on the stable continental platform, and include conspicuous limestones and sandstone that grade eastward into redbeds in Wyoming and Utah. Complex structures characterized by parallel-trending tight folds and thrust faults were developed subsequently in the area of the miogeosyncline, whereas simpler structures characterized by random orientation were developed in the platform area.

Two black phosphatic shale members characterize the Phosphoria formation. The lower and more important of these members is thickest and most phosphatic in southeast Idaho and pinches out in southern Montana, central Wyoming, and eastern Utah. The upper member is best developed in southwestern Montana but is prominent also in western Wyoming. Chert characterizes the intervening member, but limestone and sandstone are important constituents to the north and east. Also toward the north and east, chert and sandstone above the upper phosphatic shale are important.

The Bear River region of southeastern Idaho and adjacent parts of Wyoming and Utah contains the greatest total amount of phosphate as well as the thickest beds of high-grade phosphate, although some high-grade beds of mineable thickness occur in other parts of the field, particularly in western Montana. Several valuable deposits were discovered during this investigation, most noteworthy of which are a 6-foot bed of acid-grade rock in the Centennial Mountains at the Montana-Idaho State line, a 12-foot bed of 33 percent P_2O_5 rock in the Caribou Range, Idaho, several strippable deposits of acid- and furnace-grade rock in southeastern Idaho, and a 12-foot bed of 20 percent P_2O_5 rock at the top of the formation north of Cokeville, Wyoming.—*Authors' abstract*

- 34 Thompson, M. E., 1953, Distribution of uranium in rich phosphate beds of the Phosphoria formation: U. S. Geol. Survey Bull. 988-D, p. 45-67.

Five sets of "close" samples were analyzed radiometrically for uranium, and chemically for P_2O_5 , CaO, organic matter, and loss on ignition. A Rosiwal analysis was made of thin sections of one set of samples. The results of the analyses have been plotted on graphs and on scatter diagrams, and coefficients of correlation are given for uranium with CaO, P_2O_5 , organic matter, and loss on ignition. Preliminary studies indicate that the concentration of uranium in these samples of phosphate rock is not due wholly to phosphate content but may depend in part on organic matter or on other components. The correlations of uranium with P_2O_5 are poor in the groups of samples with smaller amounts of uranium but are good in the groups of samples containing more uranium.—*Author's abstract*

- 35 Thompson, M. E., 1954, Further studies of the distribution of uranium in rich phosphate beds of the Phosphoria formation: U. S. Geol. Survey Bull. 1009-D, p. 107-123.

Rock from the Phosphoria formation is pelletal rather than oölitic, and is generally dark brown to black. The phosphatic material is chiefly pelletal phosphate of the carbonate-fluorapatite type.

The five sets of close samples (narrow and contiguous samples across a lithologic unit) from Idaho, Wyoming, and Utah, which are described in the preceding article by this author (ref. 34), were also analyzed chemically for F and CO_2 in an effort to determine whether there is any correlation between these constituents and equivalent U and P_2O_5 . The formula used for the coefficient of correlation is that given by Snedecor.⁶

The samples with a high percentage of equivalent uranium show much better correlation of equivalent uranium with P_2O_5 than do the samples of a low percentage of equivalent uranium. The samples that show good correlation of equivalent uranium with P_2O_5 show better correlation of CO_2 with P_2O_5 .

The size of the phosphorite pellets was measured in the thin sections of two sets of samples. This was done in an effort to determine whether or not the size of the pellets in phosphate rock might have a direct relation to the amount of uranium present. Cumulative curves and frequency histograms were plotted from the size measurements obtained. Comparison of these with the uranium concentration for each sample did not show a significant correlation between size of phosphorite pellets and amount of uranium.

- 36 Anonymous, 1950, Uranium found in Florida phosphate limited to certain deposits: Eng. Min. Jour., v. 151, no. 8, p. 93.

Land-pebble phosphate, hard-rock phosphate, and river-pebble phosphate are the three types of phosphatic rock found in Florida. Mr. Cathcart's report is concerned primarily with the land-pebble deposits, the only type which contains the uranium. The most productive part of the land-pebble district is in Polk and Hillsborough Counties, in the west-central part of Florida.

⁶ Snedecor, G. W., 1946, Statistical methods applied to experiments in agriculture and biology: Iowa State Coll. Press, p. 138.

In the two counties named, which contain the high-grade part of the land-pebble phosphate district, uranium occurs principally in the Bone Valley formation. Fresh unweathered Hawthorn formation has little or no uranium, but leached Hawthorn, rich in P_2O_5 , contains a small amount of uranium. The Pleistocene sands have no uranium except where they contain reworked phosphatic material from the Bone Valley formation.

South of the high-grade district, in Manatee and Hardee Counties, the Bone Valley, Hawthorn, and Pleistocene formations contain only very minor amounts of uranium.

The uranium in the land-pebble deposits was probably syngenetic in origin. The uranium seems to be associated with the phosphate.

Two types of rocks in the land-pebble phosphate district contain the uranium. First is the rock composed of sand, clay, and abundant phosphate nodules, termed "matrix." Uranium is present in nodules as proved by analyses of samples from which everything but the phosphate nodules have been removed. In this case it is possible that the uranium takes the place of the calcium in the phosphate mineral. Uranium is also present in the clay fraction (slime). Certain rocks which are composed of clay-sized particles and are white and kaolin-like and highly phosphatic, also contain small amounts of uranium. Green "matrix" clays, however, contain almost no phosphate, and little or no uranium.—*Résumé of a talk by J. B. Cathcart (U. S. Geol. Survey)*

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