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DOMESTIC PHOSPHATE DEPOSITS

By

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ABSTRACT

Most of the world's phosphate deposits can be grouped into six types: 1) igneous apatite deposits; 2) marine phosphorites; 3) residual phosphorites; 4) river pebble deposits; 5) phosphatized rock; and 6) guano. The igneous apatites and marine phosphorites form deposits measurable in millions or billions of tons; the residual deposits are measurable in thousands or millions; and the other types generally only in thousands of tons.

Igneous apatite deposits have been mined on a small scale in New York, New Jersey, and Virginia. Marine phosphorites have been mined in Montana, Idaho, Utah, Wyoming, Arkansas, Tennessee, North Carolina, South Carolina, Georgia, and Florida. Residual phosphorites have been mined in Tennessee, Pennsylvania, and Florida. River pebble has been produced in South Carolina and Florida; phosphatized rock in Tennessee and Florida; and guano in New Mexico and Texas. Present production is limited almost entirely to Florida, Tennessee, Montana, Idaho, and Wyoming.

Incomplete but recently partly revised estimates indicate the presence of about ⁵~~3~~ billion tons of phosphate deposits in the United States that is minable under present economic conditions. Deposits too lean in quality or thickness to compete with those in the western and southeastern fields probably contain tens of billions of tons.

I. INTRODUCTION

Phosphorus has been called the "bottleneck of the world's hunger" (Rorty, 1946). This is true for large parts of the world, particularly Asia, but the United States, fortunately, has large reserves of mineral phosphate available to replace the phosphate removed from the soil by crops and erosion. The chief purpose of this account of the characteristics, distribution, and reserves of domestic phosphate deposits is to provide a background for the consideration of problems of phosphorus in relation to fertilizer and crop production; but the authors wish to show also that increased domestic consumption of phosphorus fertilizer need not be limited by the phosphate reserves of the United States.

II. PRINCIPAL TYPES OF PHOSPHATE DEPOSITS

Phosphorus makes up about 0.12 percent of the earth's crust—in fact it is the eleventh most abundant element. It forms complex compounds with a wide variety of metals—more than 150 minerals are known that contain 1 percent or more P_2O_5 . Most of the phosphorus in the earth's crust, however, is found in one mineral family, the apatite group $(Ca_{10}(PO_4, CO_3)_6(F, Cl, OH)_2)$. Due to its essential content of an anionic radicle, the PO_4 tetrahedron, as well as of a simple anion, usually fluorine, and a simple cation, usually calcium, apatite serves as a host for a great many minor substitutions. Thus, small amounts of VO_4 , AsO_4 , SiO_4 , SO_4 and CO_3 or CO_4 may be present in place of equivalent amounts of PO_4 . The fluorine position may be occupied

completely or in part by F, Cl or OH. In addition minor amounts of U, Mg, Mn, Sr, Pb, Na, Ce, Y and other rare earths may substitute for calcium. The variety of structural elements in apatite enhances the number of substitutions which occur, as cationic replacements involving loss or gain of valence may be compensated for by anionic replacements of opposite nature. These facts account in great measure for the rich suite of minor metals found in many apatite deposits and so important in the agricultural use of phosphate rock.

In nature phosphate is concentrated by igneous, sedimentary, weathering, and biologic processes. The geology of the important producing types of deposits is treated here to promote greater understanding of the potentialities of these deposits in this country. They are six in number, namely apatite deposits of igneous origin, marine phosphorites, residual phosphorites, river-pebble deposits, phosphatized rock, and guano (Table 1).

1. Apatite deposits of igneous origin

Apatite deposits of igneous origin are found as intrusive masses, hydrothermal veins or disseminated replacements, marginal differentiations along or near the boundaries of intrusions, and pegmatites. These deposits are generally associated with bodies of nepheline syenite, ijolite, alaskite, limestone, pyroxenite, ilmenite, magnetite, or nelsonite.

The largest of the apatite deposits of igneous origin are intrusive sheets associated with syenite, pyroxenite or amphibolite

Table 1.—Characteristics of principal types of phosphate deposits

Type (and examples)	Origin	Associated rocks	Shape and structure of deposits	Principal phosphate minerals	Common minor metals	Range of reserves in individual fields (tons of rock)
1. Igneous apatites						
a. Apatite intrusions (Kola peninsula, USSR; Eastern Uganda; Palabora, East Transvaal)	Differentiation from cooling basic magma	Nepheline syenite, ijolite, limestone, pyroxenite, magnet- ite	Inclined sheets, in some places interleaved with other rocks around a circular core	Fluorapatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$)	Sr, rare earths	$10^6 - 10^{10}$
b. Apatite marginal differentiations (Eastern Adirondacks)	Metasomatic differ- entiation along con- tacts of alaskite intrusions	Alaskite, magnet- ite	Steeply inclined irregular masses	Fluorapatite	2/	$10^3 - 10^6$
c. Apatite pegmatite (Southern Ontario)	Late stage differ- entiation from cooling basic magma	Pyroxenite, sye- nite, calcite, phlogopite, titanite	Steeply inclined tabular masses	Fluorapatite	Sr, rare earths, As	$10^3 - 10^5$
d. Hydrothermal veins, disseminations and replacements (Norwegian apatite veins, Virginia nelsonite)	Late stage emanation from basic magma, generally cutting or partly replacing earlier differentiates	Ilmenite, nelson- ite, anorthosite	Steeply inclined tabular masses or irregular dis- seminated bodies	Fluorapatite Chlorapatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{Cl}_2$); Hydroxylapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$)	2/	$10^4 - 10^7$
2. Marine phosphorites						
a. Geosynclinal phos- phorites (Western U. S.; North Africa; Kara Tau, U.S.S.R.)	Organic or inorganic precipitation on margins of oceanic basins	Carbonaceous mud- stone, chert	Widespread blanket, folded to varying de- gree	Carbonate-fluorapatite ($\text{Ca}_{10}(\text{PO}_4)_3\text{CO}_3)_6\text{F}_{2-3}$)	V, Cr, rare earths, Co, Ni, Mo, U, Zn, Ag, As, Cd, Cu, Tm, Be	$10^9 - 10^{11}$

Table 1.—Characteristics of principal types of phosphate deposits (Cont'd)

Type (and examples)	Origin	Associated rocks	Shape and structure of deposits	Principal phosphate minerals	Common minor metals	Range of reserves in individual fields (tons of rock)
b. Platform phosphorites (Cretaceous glauconite marls of Gulf Coastal Plain; Tennessee "blue-rock"; eastern part of the western field)	Organic or inorganic precipitation in epicontinental seas; often reworked from older phosphatic formations	Limestone, dolomite, quartz sandstone, glauconite, carbonaceous mudstone	Widespread blanket, locally moderately warped	Carbonate-fluorapatite	V, Cr, rare earths, Co, Ni, Mo, U, Zn, Ag, As, Cd, Cu, Tm, Be	$10^6 - 10^{10}$
3. Residual phosphorite (Tennessee brown-rock deposits)	Insoluble residuum remaining after decomposition of phosphatic limestone in humid climate	Limestone, clay, quartz sand	Near-surface blanket lying on irregular etched bed-rock surface	Carbonate-fluorapatite	As, U	$10^4 - 10^8$
4. River pebble (Florida, South Carolina river-pebble fields)	Fluvial transport of weathered-out phosphorite particles in humid or subtropical regions of low relief	Quartz sand	River bars, channel fillings and terraces	Carbonate-fluorapatite	Z/	$10^4 - 10^7$
5. Phosphatized rock a. Calcareous terrane (Florida hard-rock, Tennessee white-rock, Nauru and Ocean Islands)	Replacement of limestone or clay in tropical or subtropical climate by phosphate derived from overlying phosphatic rocks or guano	Limestone, dolomite, clay, quartz sand	Near-surface irregular blanket	Carbonate-hydroxyl-fluorapatite ($\text{Ca}_{10}(\text{PO}_4, \text{CO}_3)_6(\text{OH}, \text{F})_{2-2.5}$); Hydroxylapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$); Whitlockite ($\text{Ca}_3(\text{PO}_4)_2$); Brushite ($\text{H}_2\text{CaPO}_4 \cdot 2\text{H}_2\text{O}$); Monetite (H_2CaPO_4); Wavellite ($\text{Al}_3(\text{OH})_3(\text{PO}_4)_2 \cdot 5\text{H}_2\text{O}$); Pseudowavellite ($\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot 4\text{H}_2\text{O}$); Taramite ($\text{K}_2\text{Al}_6(\text{PO}_4)_6(\text{OH})_2 \cdot 18\text{H}_2\text{O}$)	Zn, Ag, Cd, Ca	$10^4 - 10^9$

Table 1.—Characteristics of principal types of phosphate deposits (Cont'd)

Type (and examples)	Origin	Associated rocks	Shape and structure of deposits	Principal phosphate minerals	Common minor metals	Range of reserves in individual fields (tons of rock)
5. b. Igneous terrane (Daito Jima, Malpelo, Grand Connetable islands)	Replacement of igne- ous rock or clay by phosphate derived from guano	Trachyte, andes- ite, basalt, granite, gabbro	Near-surface irregular blanket	(Al,Fe)PO ₄ ·2H ₂ O). High Al member occurs in acid igneous rocks, high Fe member in inter- mediate and basic rocks Orthorhombic series: Variscite (AlPO ₄ ·2H ₂ O) Barrandite (Al,Fe)PO ₄ ·2H ₂ O Strengite (FePO ₄ ·2H ₂ O). Monoclinic series: Metavariscite Clinobarrandite Metastrongite	2/	10 ⁴ - 10 ⁶
6. Guano (Islands along Peruvian and Chilean coasts)	Accumulation of sea fowl or bat excreta	All varieties (no genetic re- lationship)	Surficial irregular blanket	Carbonate-hydroxylapatite Hydroxylapatite Whitlockite Brushite Monetite	2/	10 - 10 ⁶

1/ Metals listed are those present in amounts greater than 5 times their average concentration in the earth's crust, exclusive of detrital impurities.

2/ No information available.

and in some places with limestone or magnetite. These sheets are inclined and in some places roughly interleaved around a circular core. The apatite-rich layers range in thickness from tens to hundreds of feet or more and are traceable for hundreds of feet or even a few miles. Their P_2O_5 content is as much as 35 percent, and reserves are measurable in millions of tons. The higher grade rock is not beneficiated. Lower-grade rock containing 5 to 25 percent P_2O_5 may be beneficiated by grinding and sieving or magnetic separation to yield a high-grade apatite concentrate. No attempt is made to beneficiate the very low grade magnetite-apatite rock for phosphate. On smelting, such rock yields a phosphate-rich slag. No important deposits of this type are known in this country, but three of the largest apatite deposits in the world are of igneous origin, namely the Khibin deposits on the Kola peninsula, U. S. S. R. (Fiebig, 1937); the eastern Uganda deposits (Davies, 1947); and the Palabora deposits in East Transvaal (Shand, 1932). The Kiruna magnetite deposits in Sweden and the Iron Mountain hematite deposits in Missouri (thought to be weathered magnetites) are apatite-rich iron ores of this type (Lindgren, 1933, p. 793).

The vein, disseminated, marginal, and pegmatite deposits are either less extensive or of lower quality, or both, and hence are of less economic importance. Most of the reserves are measurable in thousands rather than millions of tons, and the P_2O_5 content of large masses is generally less than 20 percent. Examples include the hydrothermal apatite-ilmenite (nelsonite) disseminated deposits in Virginia.

(C. S. Ross, 1941); the apatite veins in Norway (Lindgren, 1933, p. 764); the apatite-magnetite marginal deposits associated with alaskite in the eastern Adirondacks (Lindgren, 1933, p. 794); and the apatite pegmatite deposits in southern Ontario (Adams and Barlow, 1910).

The apatite that predominates in all of these deposits is fluorapatite; chlorapatite is rare in large deposits. Strontium and the rare earths commonly make up 1 to 3 percent of the mineral and substitute for calcium in the crystal structure (Table 2). Other metals are not abundant.

2. Marine phosphorites

Marine phosphorites are believed to be inorganically and organically precipitated on shelving margins of large oceanic basins. As cold water rises from the depths along the continental slopes its pH increases with increase in temperature and with the decrease in partial pressure of CO_2 , and phosphate is then precipitated (Kazakov, 1937; and McKelvey, et al., in press). The marine phosphorites may be divided into two principal facies--geosynclinal and platform, the one commonly the stratigraphic equivalent of the other.

The geosynclinal deposits--of which those of western United States (Mansfield, 1927; McKelvey, et al., in press), North Africa (Cayeux, 1941), and the Kara-Tau of the Soviet Union (Vol'fkovich, 1945) are the world's outstanding examples--are associated with chert, black carbonaceous shale, and minor amounts of limestone. The phos-

Table 2.--Production and resources of phosphate rock in the United States
(Tonnes are in millions of long tons)

Source and type	Production		Inferred		Additional inferred resources	
	Marketed product a/	P ₂ O ₅ content b/	Reserves minable under present conditions	Marketable P ₂ O ₅ product content	minable under changed con- ditions	P ₂ O ₅ content
Florida						
Land pebble	116.8 g/	39.0	1,000 d/	330 d/	2,000 d,e/	600 d,e/
In matrix	---	---	---	---	800 d,f/	180
In leached zone	1.3 g/	0.3	---	---	50 b/	12
River pebble	13.9 i/	4.8	1,040 h,i/	330	500 h,i/	140
Hard rock	1.0	0.2	k/	k/	k/	k/
Soft rock	---	---	---	---	20,000 h/	4,000
Hawthorn formation	---	---	---	---	---	---
Total Florida	133.0	44.3	2,040	660	23,350	4,932
South Carolina						
Land rock	9.3 l/	2.5	---	---	9 h/	2.4
River rock	4.1 i/	1.0	---	---	m/	m/
Total South Carolina	13.4	3.5	---	---	9.	2.4
Tennessee						
Brown rock	28.7 n/	8.6	85 h/	15	m/	m/
Blue rock	1.3 n/	0.4	---	---	83	25
White rock	0.02	0.007	---	---	15	4
Phosphatic limestone	---	---	---	---	5,300 a/	1,100
Total Tennessee	31.9 o/	9.6 o/	85	15	5,398	1,129
Western field (Phosphoria formation)						
Arkansas	6.0	1.7	3,000 p/	870	20,000 q/	5,800
Other states (Ala., Ky., N.O., Pa.).	.03	.01	---	---	20 h/	5
	.17	.05	---	---	1/	1/
Grand total (rounded)	185	60	5,100	1,500	49,000	12,000

Table 2.—Production and resources of phosphate rock in the United States (Cont'd)

- a/ Figures rounded off from those compiled by Jacob (1950) supplemented by figures for 1949 from the Bureau of Mines Mineral Yearbook.
- b/ Approximate.
- c/ Includes some river pebble and soft rock.
- d/ Preliminary figures based upon recent U. S. Geological Survey investigations.
- e/ Includes about 1 billion tons in the northern part of the district containing 27-30 percent P_2O_5 . The remainder is in the southern part of the district.
- f/ All in the northern part of the field; comprised of: 1) 1.5 billion tons, in deposits more than 5 feet thick, 20 percent (300 million tons) which is minus 150 mesh in size and contains 15 to 30 percent P_2O_5 and a similar amount of Al_2O_3 ; 2) 2.5 billion tons in deposits more than 1 foot thick, 20 percent (500 million tons) which is minus 150 mesh in size.
- g/ Some river pebble is included with land pebble.
- h/ Figures rounded off from estimates compiled by Mansfield, 1942.
- i/ Includes some soft rock.
- j/ Includes soft rock.
- k/ Included with hard rock.
- l/ Some river rock included with land rock.
- m/ Data not available.
- n/ Virginia apatite and some blue-rock included with Tennessee brown-rock.
- o/ This figure is higher than the sum of the individual items because separate data for the different types of Tennessee phosphate are not available for the years prior to 1905.
- p/ Preliminary, incomplete estimates based upon recent investigations of the U. S. Geological Survey; about one fourth is acid-grade (31 percent P_2O_5) and the remainder is furnace-grade (24 percent P_2O_5).
- q/ Preliminary, incomplete estimates based upon recent investigations of the U. S. Geological Survey; rocks are of minable thickness, contain more than 24 percent P_2O_5 , but lie below entry level.

phate deposits consist of layers of phosphatic pellets, generally less than 0.1 to 2 mm in diameter, that were deposited as blankets over thousands of square miles. Many of these layers are 3 feet or more in thickness and contain 25 to 35 percent P_2O_5 . The fluorapatite content in the minable layers of such formations is commonly 3,000 to 25,000 kg per m^2 , and the fluorapatite content of the whole formation may be 25,000 to 75,000 kg per m^2 .

Most of the platform deposits are associated with limestone, glauconite sandstone, quartz sandstone, and, less commonly, clay; some are associated with bituminous shales; and a few are associated with manganese- and iron-ore deposits. The glauconitic marls of Alabama and Mississippi (E. A. Smith, 1892; Monroe, 1941) are examples of the first group; the "blue-rock" deposits of Tennessee (Smith and Whitlatch, 1940) of the second; and the manganiiferous phosphatic shales of Arkansas (Branner and Newsom, 1902) of the third.

The phosphate in the platform deposits generally occurs as large nodules or pebbles, most of which are 2 to 10 mm in diameter (but some of which may be 25 or even 50 mm in diameter), sparsely disseminated in a matrix of non-phosphatic sediment. Some phosphate is in the form of phosphatized shells or fish remains. In younger, unconsolidated deposits, the phosphatic particles can be segregated from the matrix by washing or flotation. In many platform deposits the P_2O_5 content of the pebbles is only 15 to 25 percent. The fluorapatite content of such formations generally ranges from 100 to 1,500 kg per m^2 but may be as much as 5,000 to 10,000 kg per m^2 .

The best platform deposits have resulted from submarine reworking of older, less phosphatic formations. They commonly are found as basal conglomerates of formations formed by transgressing seas (Goldman, 1922; Pettijohn, 1926; Kazakov, 1937).

The phosphate mineral in the marine phosphorites is generally carbonate-fluorapatite (Altschuler and Cisney, 1952). Marine phosphorites, particularly the geosynclinal facies, contain a host of minor constituents, some of which are important as by-products recoverable in the manufacture of fertilizers and chemicals and some of which are essential to plant growth. These trace constituents include vanadium, strontium, nickel, molybdenum, zinc, copper, rare-earths, silver, and uranium (Oertel and Stace, 1947; Robinson, 1948; Jacob et al., 1933; Hill et al., 1932; Hébert, 1947; McKelvey and Nelson, 1950).

Reserves of the marine phosphorites are measurable in millions or billions of tons, mainly accounted for by geosynclinal deposits. With a few exceptions, the platform deposits are not of commercial value at present.

3. Residual phosphorites

Carbonate-fluorapatite is less soluble than calcite, and therefore is residually concentrated during the weathering of marine phosphatic limestones. These residual phosphate deposits are most common in humid climates; those in Tennessee (Smith and Whitlatch, 1940) and Kentucky (Phalen, 1915) are good examples. These deposits

resemble the marine phosphorites, (from which they are generally derived) in the composition of their phosphatic particles, but they differ in distribution and extent. Most of these deposits are at or near the surface, and they occur on irregular, deeply etched bedrock surfaces. The P_2O_5 content ranges from 15 to 35 percent or more and the fluorapatite content may be 1,000 to 10,000 kg per m^2 .

Reserves of the residual deposits are measured in thousands or at most millions of tons. Some residual phosphorites, those in Tennessee for example, are important producers because of their high quality and thin cover.

4. River-pebble deposits

Some of the clastic phosphate that is left behind during the weathering of phosphatic limestones is moved by runoff to the streams. In humid regions of low relief, such as Florida (Mansfield, 1942a) and South Carolina (Rogers, G. S., 1915), phosphate nodules commonly make up the only coarse detritus on the stream bottoms. These concentrations are known in the industry as river-pebble deposits and are easily recoverable. Reserves are measureable in millions of tons. Known deposits of this type, however, cannot be mined now in competition with other types because the P_2O_5 content of the nodules is too low (presumably due to leaching in the stream), and the deposits are too small and patchy.

5. Phosphatized rocks

In regions of subtropical or tropical weathering where decaying

vegetation lowers the pH of meteoric waters, the carbonate-fluor-apatite in sedimentary rocks is eventually decomposed. Some of it disappears in runoff but in some places it is reprecipitated after travelling only a short distance, particularly if the phosphatic solutions encounter aluminous or iron-bearing rock or limestone in a different chemical environment. These deposits consist of encrustations on surfaces of joints or cavities, or an irregular, tabular replacement of bedrock, or residual boulders. The mineral composition depends upon the lithology of the replaced rock. Phosphatized limestone generally consists of some form of calcium phosphate; whereas iron and aluminum phosphate minerals of the variscite and metavariscite series are common in phosphatized volcanic rocks and wavellite and pseudowavellite in clays. The P_2O_5 content of these deposits depends on the degree of replacement. Some deposits have 35 percent or more P_2O_5 . Although minor metals are not abundant, gallium may be prominent in wavellite. These deposits are generally of limited extent and with few exceptions their reserves are measurable in thousands or millions of tons. Examples are the white-rock deposits of Tennessee (Smith and Whitlatch, 1940) and the hard-rock deposits of Florida (Mansfield, 1942a).

The phosphate in the phosphatized rocks of most insular deposits is derived from guano rather than from phosphatic limestone. The deposits of Fais, Angaur, and Kita-daito (Rodgers, 1948) have originated in this way.

Guano

Accumulations of the droppings of sea-fowl and bats are rich in nitrogenous materials and phosphates. Leaching or decomposition of the nitrogenous material of this guano yields a residue rich in phosphate. It is interesting to note that the largest guano accumulations are found in the vicinity of the cold, phosphate-rich waters (Sverdrup et al., 1946, p. 942) from which the marine phosphorites precipitate. The abundant supply of phosphate in these waters nourishes a luxuriant plankton growth which in turn supports a large fish population on which the sea fowl feed. Conditions most favorable for the accumulation of guano deposits are found along the west coast of the continents in low latitudes where cold waters upwell and where the dry, subtropical climate inhibits destruction of the guano (Hutchinson, 1950, p. 6) and such deposits occur along the west coasts of Lower California, South America, and Africa.

The mineralogy of guano is complex and depends to some extent on the stage of decomposition and leaching. Slightly decomposed deposits contain soluble ammonium and alkali oxalates, sulphates, and nitrates and a variety of magnesium phosphates and ammonium-magnesium phosphates. Largely decomposed guano consists essentially of calcium phosphates.

The guano deposits are limited in extent and their reserves are seldom measured in millions of tons--in fact most of the rich deposits are already exhausted. The P_2O_5 content of guano is generally less than 20 percent, but, because the P_2O_5 is readily available and

because other nutrients, particularly nitrogen, are present, guano is a valued fertilizer. Minor metals are not abundant in guano.

7. Other types

Other sources of "mineral" phosphates are bone piles found at ancient salt licks and water holes; glauconite, and phosphatic iron ores that yield a basic slag in the manufacture of steel (Hertzog, 1935). The bone piles are no longer important. Glauconite contains only 1 to 5 percent P_2O_5 , but, as it also contains K_2O , it has had some use as a fertilizer; reserves are measurable in millions and billions of tons. Phosphatic iron ores include marine deposits of the type found in the Clinton formation as well as apatite-rich magnetite deposits of igneous origin. The basic slag (Thomas meal) made from these ores contains 8 percent or more P_2O_5 . Reserves of the phosphatic iron-ore source rocks, which contain only 0.5 to 5 percent P_2O_5 , are measured in millions of tons.

III. DISTRIBUTION AND GEOLOGY OF DOMESTIC DEPOSITS

All the principal types of phosphate deposits are found in this country, and concentrations of one type or another are found in 30 of the States (Fig. 1). Only about half of these States--Pennsylvania, Virginia, North Carolina, South Carolina, Georgia, Alabama, Florida, Tennessee, Kentucky, Arkansas, Idaho, Wyoming, Utah, and Montana--have ever produced phosphate. Current production of phosphate rock, listed in order of rate of production

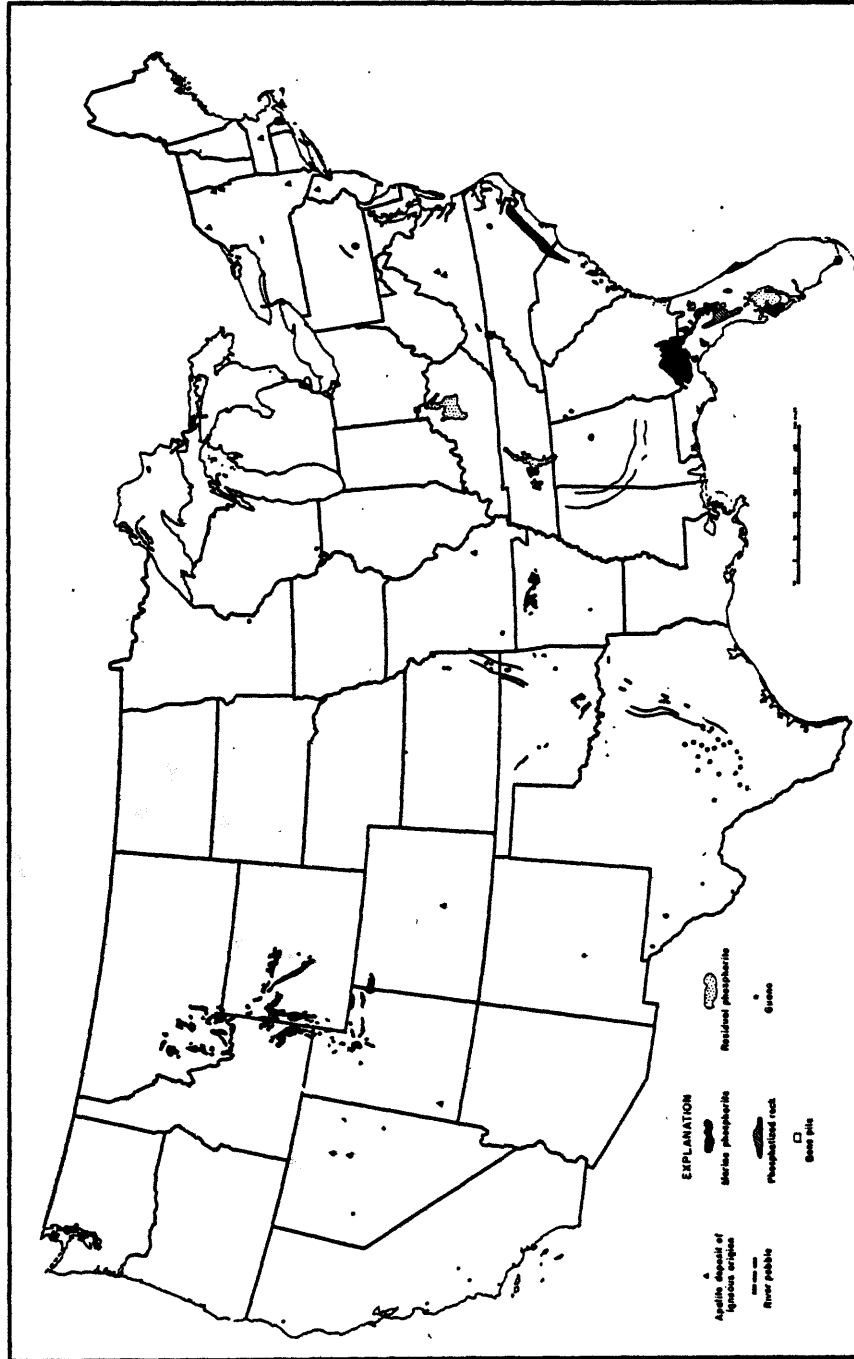


Figure 1. --Distribution of phosphate deposits in the United States. Only those in Montana, Wyoming, Idaho, Utah, Tennessee, and Florida are being mined now or are likely to be of commercial value in the foreseeable future.

(Table 2), comes from only four fields: the land-pebble field of Florida; the brown-rock field of Tennessee; the western field; and the hard-rock field of Florida. Because future production is likely to be restricted largely to these same fields, we place the chief emphasis on them in our description of domestic deposits.

1. Florida land-pebble field

The Florida land-pebble field has produced about 117 million tons during the period from 1891, when mining began, through 1949 (Table 3). In 1949 it produced about 6.7 million tons (Johnson and Tucker, 1951)—slightly more than one-third of the world's production and about three-fourths of our domestic production.

The Florida land-pebble deposits are part of the Bone Valley formation of probable Pliocene age which extends over an area of about 2600 square miles, chiefly in Polk and Hillsborough Counties, in the west-central part of the Florida peninsula (Eldridge, 1893; Sellards, 1915; Matson 1915; Roundy, 1941; Mansfield, 1942a; Cathcart et al., in press). The Bone Valley formation was deposited on the eroded surface of the underlying phosphatic Hawthorn formation of Miocene age by a transgressing sea that reworked and partly sorted the thick, residual phosphatic mantle found on the Hawthorn at the close of the Miocene. Since its deposition, the upper part of the Bone Valley has been deeply weathered (Fig. 2). Much of the phosphate in this upper leached zone has been removed and some contains phosphatized clay. The Bone Valley deposits are thus complex—partly residual, partly

marine reworked, and partly phosphatized clay.

All the phosphate recovered from the land-pebble field is in the lower, less-weathered part of the Bone Valley formation, called the matrix. The matrix rests on a "bed clay" at the top of the Hawthorn formation which has a karst surface (Fig. 3). The thickness of the matrix ranges from 1 to 50 feet and averages about 12 feet; the thickest deposits are commonly in old sinkholes in the Hawthorn formation.

The matrix consists of an unconsolidated mixture of phosphorite pellets and pebbles, boulders of partly phosphatized limestone, quartz sand, and montmorillonite clay. The matrix typically consists of about one-third phosphorite particles coarser than 0.1 mm; one-third quartz-sand, and one-third clay. Depending partly on the thickness and the relative abundance of phosphorite particles in the matrix, the content of recoverable phosphorite ranges from about 500 tons to 35,000 tons per acre and averages about 5,000 tons per acre in the minable part of the field.

The P_2O_5 content of the phosphate particles ranges from about 28 to 36 percent. The P_2O_5 content is higher, 32 to 36 percent, in the northern part of the field, and generally lower, 28 to 32 percent, in the southern part. The northern part may be further subdivided into two general areas: a central area where the phosphate particle size is generally coarse and the P_2O_5 content of the particles is 32 to 33 percent; and a peripheral area where the particle size is

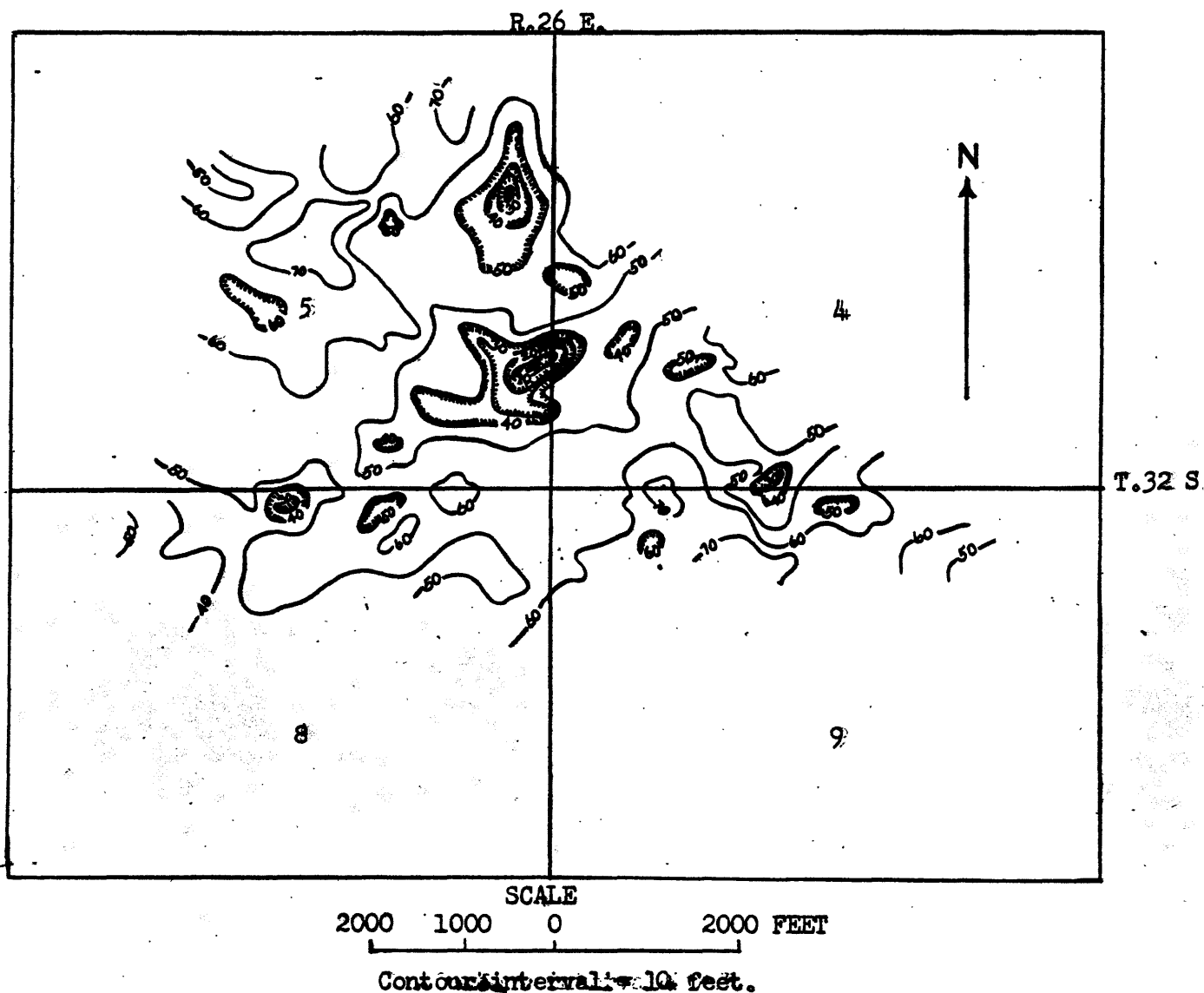


Figure 3. The surface of the Hawthorn formation, Old Colony Mine, American Cyanamid Company, land-pebble phosphate field, Florida. (Data furnished by the American Cyanamid Company).

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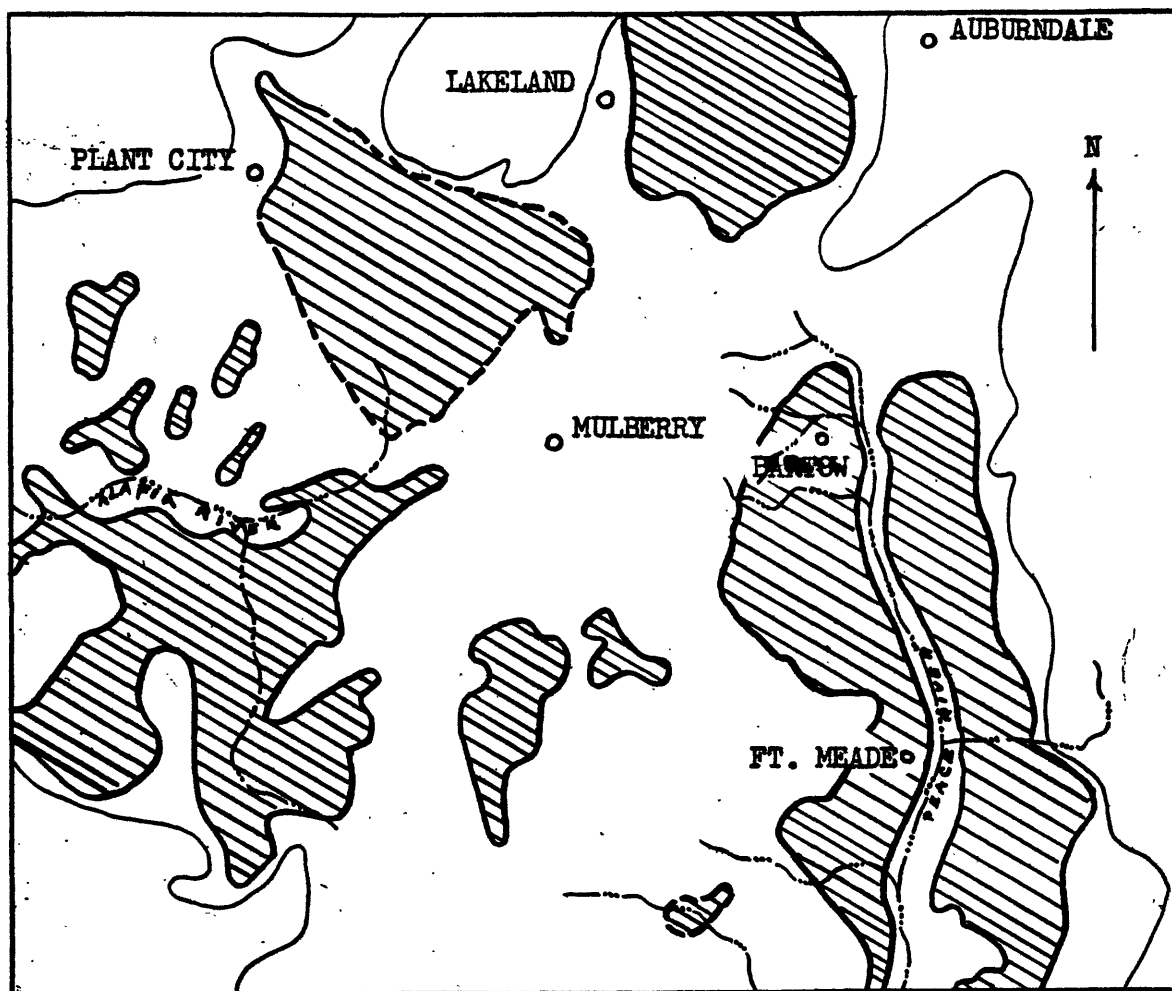
finer and the P_2O_5 content of the particles is 33 to 36 percent (Fig. 4). W. F. Davidson and F. N. Heuser (unpublished U. S. Geological Survey reports) have shown that the coarser particles are found on highs on the Hawthorn formation.

Mining, at present restricted to the northern part of the field, is entirely by large-scale, low-cost open-pit methods. The phosphorite particles are separated from the matrix by washing, screening, and flotation.

The upper part of the Bone Valley has been irregularly leached and altered. This irregular leached zone generally ranges from 1 to 15 feet in thickness; however it may be as thick as 50 feet. The leached zone is generally thickest on topographic highs. From 70 to 80 percent of the leached-zone material is medium to coarse quartz sand and the remainder is minus 150 mesh particles. The fines consist mainly of the aluminum phosphate wavellite and the calcium aluminum phosphate pseudowavellite; minor amounts of carbonate-fluorapatite, and kaolin are also present. The leached-zone material is stripped and discarded. The minus 150 mesh fraction is easily separated from the quartz sand, and contains 15 to 30 percent P_2O_5 and a similar amount of Al_2O_3 . It is possible that the minus 150 mesh fraction may be utilized eventually as a source of phosphate or alumina.

2. Florida hard-rock field

The hard-rock deposits in northwestern peninsular Florida have



6 5 4 3 2 1 0 6 MILES

EXPLANATION



Limits of economic phosphate deposit.



Areas where the ratio of coarse ($+1.2$ mm) to fine ($-1.2+0.1$ mm) phosphate is less than one. The remainder of the area within the limits of the economic phosphate deposit has a ratio of coarse to fine phosphate greater than one.



Line dashed where uncertain.

Figure 4. Distribution of coarse ($+1.2$ mm) and fine ($-1.2+0.1$ mm) phosphate in the land-pebble phosphate district, Florida.

produced about 13.5 million long tons of phosphate rock from 1889, when mining began, to 1949. Production in recent years, however, has dropped to a rate of 25,000 to 50,000 tons a year.

The hard-rock deposits are in the Alachua formation of Pliocene age which outcrops within a belt 5 to 30 miles wide extending about 150 miles southeastward from Tallahassee to the northern part of Pasco County (Mansfield, 1940, 1942a). The Alachua formation rests on the eroded surfaces of parts of the Ocala and Suwanee limestones of Eocene and Oligocene age respectively (Sellards, 1915). It is probably the nonmarine equivalent, in both age and source, of the Bone Valley formation and consists mostly of the collapsed and compacted residue of the Hawthorn formation of Miocene age (Mansfield, 1940; Cooke, 1945). The phosphate present originally as nodules in the Hawthorn formation has been largely dissolved and redistributed as replacements of limestone blocks and clay. Some of the immediately underlying limestones of the Ocala and Suwanee have also been phosphatized.

Most of the hard-rock deposits occur in the lower part of the Alachua (Fig. 2), and are associated with fragments of chert and silicified limestone in a matrix of fuller's earth, quartz sand, and phosphatic clay (Vernon, 1951). The phosphate is in the form of phosphatic clay, detrital pebbles of phosphorite, phosphatized fragments or blocks of limestone, and irregular masses or plates. Individual deposits are characteristically small and irregular in shape, but they contain 33 to 36 percent P_2O_5 or more.

The hard-rock deposits are mined by cheap open-pit methods, and the rock is concentrated by washing, and screening. Because of the small size and irregular distribution of the remaining deposits, prospecting costs are much higher than in the land-pebble field. The coarse size and high phosphate content of the hard-rock make it an ideal furnace feed and a small continuing production may be expected for that purpose from the Dunellen area.

The upper part of the Alachua formation consists of phosphatic clay and fine-grained quartz sand. This zone has been little studied but it is possible that it is a leached-zone analogous to that in the land-pebble field. This zone, together with slime derived from the washing of the hard-rock deposits, yields what is known in the industry as soft-rock phosphate. About a million tons of soft-rock has been produced from this field.

3. Tennessee brown-rock field

The Tennessee brown-rock field produced 33.3 million long tons of phosphate rock from 1896, when mining began, through 1949. Its production in 1949 was about 1.4 million tons. It thus ranks second to the Florida land-pebble field in total as well as current annual production.

The brown-rock deposits are composed of residual phosphorite particles, quartz sand, and clay derived from the chemical decomposition of platform-type phosphatic limestones of Ordovician age (Hayes and Ulrich, 1903; Smith and Whitlatch, 1940; Burwell, 1950).

These phosphatic limestones, deposited in shallow, platform seas, have been gently uplifted, arched, and exposed by erosion in the central (Nashville) basin. The phosphatic formations are of wide extent--the Kentucky brown-rock deposits are derived from the same formations--but residual concentrations of present commercial value are found mainly in the vicinity of Columbia and Mount Pleasant, Maury County, Tenn.

The local distribution of the deposits conforms in a general way to the outcrops of the limestones from which they were derived. The thickest are found as fillings in corroded joints or "cutters" lying between limestone horizons. The most extensive (blanket) deposits occur on flat ground underlain by the Hermitage, Bigby and Leipers limestones. Less extensive deposits are found as rims on hillside outcrops (Fig. 5).

Although most of the phosphate particles are physical residues from the limestones, in areas of deeper weathering the phosphatic particles in the upper parts of the deposits have been dissolved and redeposited as cement or as plate-like replacements of other materials in the lower parts. Such plate-rock is rich in P_2O_5 and has been selectively mined in many places. The uncemented rock as mined contains about 15 to 30 percent P_2O_5 . Most of it is concentrated by washing, screening, and, in some places, by flotation, to a product containing 30 to 36 percent P_2O_5 , but some of the rock is used without beneficiation as electric furnace feed. All of the brown-rock is mined by open-cut methods.

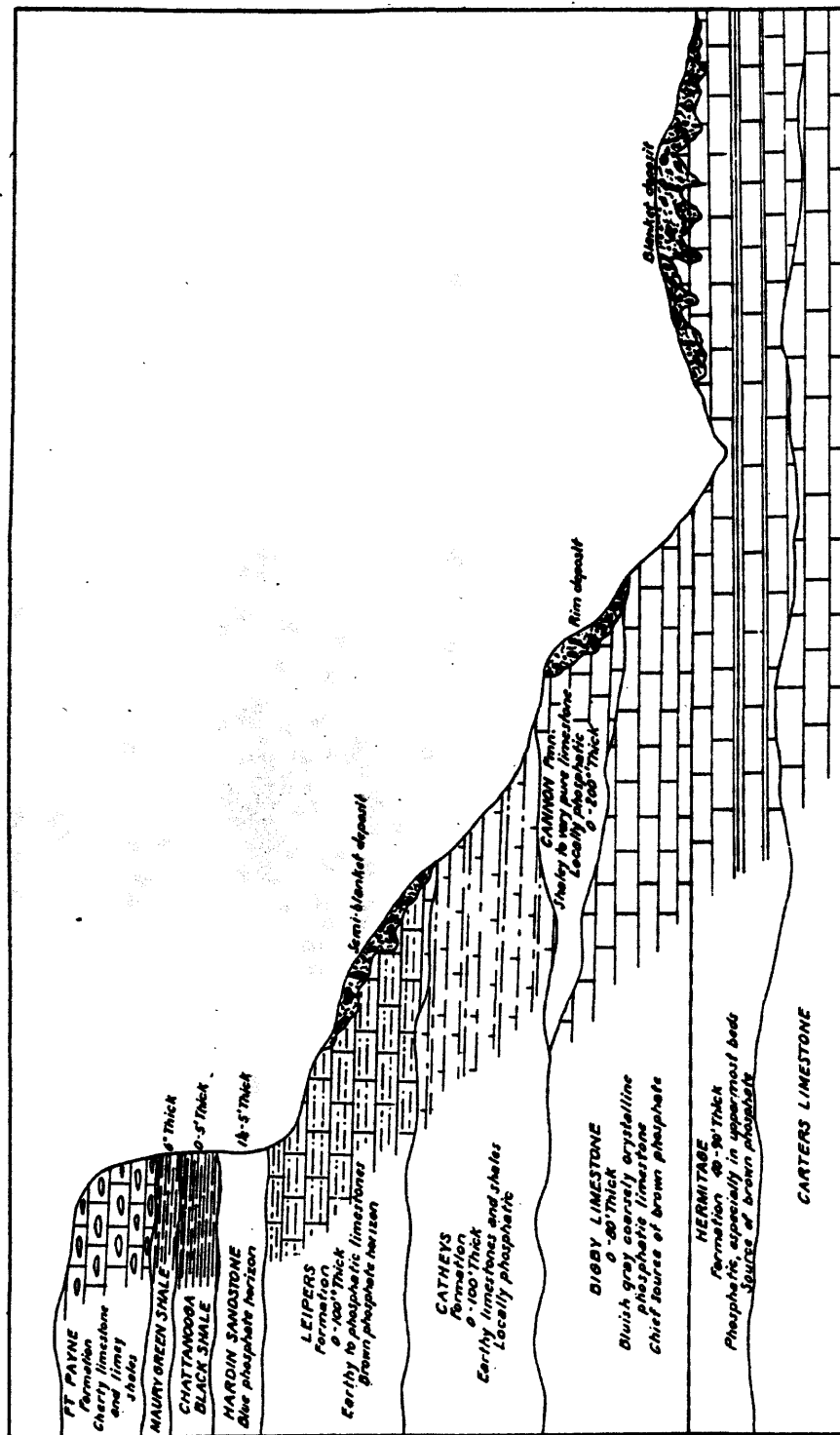


Figure 5. Mode of occurrence of Tennessee blue and brown phosphate deposits (from Smith and Whitlatch 1940).

A. The western field

The western phosphate field is one of the largest in the world, both in size and in reserves (Mansfield, 1927; McKelvey, 1949). Mining operations date back to 1906 but only about 6 million long tons were produced through 1949. The growing importance of the field, however, is indicated by the fact that 55 percent of the total production came during the 1946-1949 period.

The western deposits are marine. Some are found in the Brazos limestone of Carboniferous age but the most extensive, and the only ones we shall consider here, occur in the Phosphoria formation of Permian age and its partial stratigraphic equivalent in Utah, the Park City formation. These formations crop out over an area of about 135,000 square miles in Montana, Idaho, Wyoming, Utah, and Nevada (Fig. 6). The deposits in the eastern part of the field are ^{of} the platform type and those in the western part are of the geosynclinal type (McKelvey et al., 1952).

The rocks of Permian age and the overlying and underlying sediments have been compressed, folded, uplifted, and exposed by erosion since their widespread deposition on the sea floor. Although deformation affected the whole area, it was more intense in the western part. The field may thus be divided into an eastern part of simple structure and a western part of complex structure (Fig. 6). In the eastern part, the folds are of the dome and basin

type; The beds generally dip less than 30 degrees, and closely spaced faults of large displacement are uncommon. The folds are randomly oriented and the outcrop belts of the phosphatic rocks are widely separated. In the western area, on the other hand, the folds are tightly compressed and the beds generally dip at high angles, commonly more than 45° . The folds have a parallel orientation. Many are masked and are broken by faults of both large and small displacement. Because of the close, intense folding and repetition by faulting, outcrop belts of the phosphatic rocks are close together.

Many layers of these formations of Permian age are phosphatic, but the most important ones are found in the lower, phosphatic shale member of the Phosphoria formation (Fig. 7). These layers range widely in thickness and P_2O_5 content over the field, but the variation for the most part is systematic. As shown in Figures 8 and 9, the thickness and quality of the phosphatic rocks increase westward to a maximum in southeastern Idaho. Information is sparse for areas further west in Idaho, but the thickness and quality appear to decrease.

Rocks of two qualities are mined in the western field. The principal production in the past has been of acid-grade rock, which contains 31 percent or more P_2O_5 in layers about 3 feet in thickness. Rocks of this quality and thickness are found in northern Utah, westernmost Wyoming, southeastern Idaho, and southwestern Montana (Fig. 8); although acid-grade rock is mined at only five localities, many others contain minable deposits. The second type of rock, furnace-

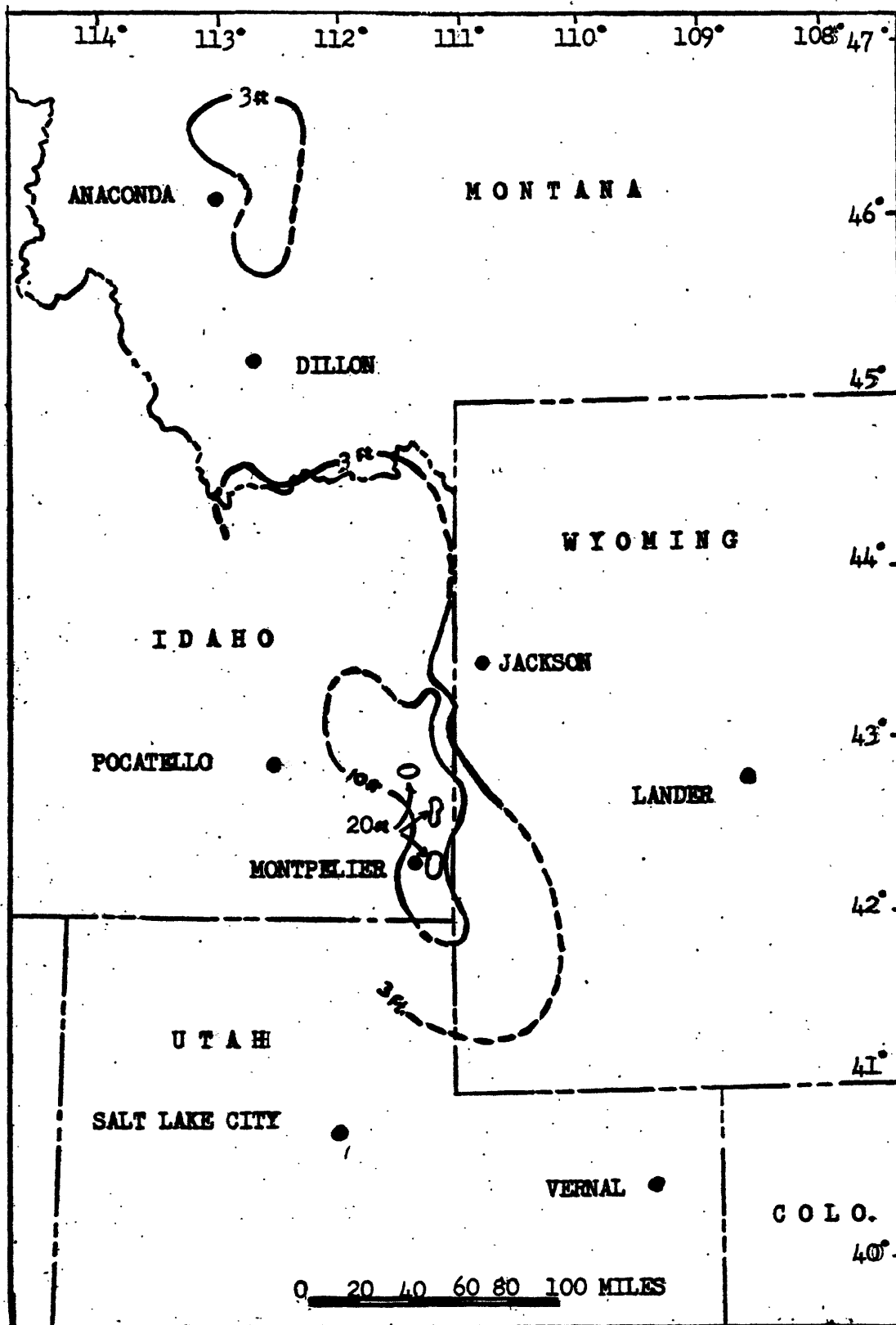


Figure 3. Thickness in feet of beds in the Phosphoria and Park City formations containing more than 31 percent P_2O_5 .

grade, has been produced in important quantities only since 1949, when the first of the eight electric furnaces now in operation (or construction) in the field was built at Pocatello, Idaho, by the West Vaca Co. Furnace-grade rock contains about 24 percent or more P_2O_5 and occurs in beds 8 feet or more thick. Such deposits are found in essentially the same areas where acid-grade rocks are found, but present production is restricted to two localities in southeastern Idaho and one in western Montana. For the most part, rocks of both qualities must meet the specified P_2O_5 content as mined. Their high degree of cementation and hardness does not recommend them for low-cost beneficiation.

Most rich and thick deposits can be mined only by underground methods because of the structural complexities already described. There are a few high-grade deposits amenable to strip-mining in southeastern Idaho and western Wyoming, but most of these are found in the eastern part of the field (Fig. 6) where the thickness and quality are too low to make this mining profitable now. Some of these deposits, such as those near Vernal, Utah, may, however, be important producers in the future.

5. Other deposits

None of the other phosphate deposits in this country is apt to be an important producer in the foreseeable future but a few remarks on distribution may serve as background for appreciation of our phosphate resource potential. A more complete summary of information

on these deposits may be found in papers by Jacob (1952); Jacob et al. (1933); and Mansfield (1940).

a. Atlantic and Gulf Coastal Plain

Phosphate deposits are found in rocks of Cretaceous or Tertiary age on the Atlantic and Gulf Coastal Plain in nearly every state from Massachusetts to Texas. The most widespread are those of the marine platform type associated with glauconite sand, quartz sand, and limestone. The most important deposit to be mined in the far distant future is the Hawthorn formation of Miocene age which contains phosphorite particles over nearly its whole extent in Florida, Georgia, and South Carolina. The most productive deposits on the Coastal Plain, aside from current producers already described, are the river-pebble and land-rock phosphate deposits in South Carolina (Rogers, G. S., 1915) and the river-pebble deposits in Florida (Mansfield, 1942a). The South Carolina land-rock deposits, which consist of phosphatized rock in the Hawthorn formation, produced 9.3 million tons between 1867 and 1925. The South Carolina and Florida river-pebble deposits, both derived directly or indirectly through erosion of the Hawthorn formation, produced 4.1 and 1.3 million tons prior to 1910 and 1914 respectively.

Other deposits on the Coastal Plain are found in Massachusetts (Shaler, 1888); New Jersey (Mansfield, 1922); North Carolina (Brown, 1905); Georgia (McCallie, 1896); Alabama (Smith, 1892); Monroe, 1941); Mississippi (Stephenson and Monroe, 1940; Day, 1886); Arkansas (Brammer and Newson, 1902); and Texas (Stephenson,

1929; Gardner, 1933). Only the deposits in South Carolina, Georgia, and Alabama have been mined and their production has been negligible.

b. Continental interior and western mountain regions

Igneous apatite deposits associated with ilmenite in Virginia (Stese, 1914; Watson and Taber, 1913) yielded small production until 1947 when mining ceased (Johnson and Tucker, 1950). Wilbur (1883) reports that small amounts of apatite associated with magnetite were recovered in New York and New Jersey. Similar deposits are found in Massachusetts (Wilbur, 1883), and Missouri (Blake, 1893).

The most widespread deposits in the continental interior are the marine platform-type, associated with limestones of Paleozoic age, glauconite sands, or black shales. Examples include deposits in the Oriskany formation of Devonian age in New York (Hopkins, 1914), Pennsylvania (Ihlseng, 1896), and Virginia (Stese, 1914); the Hardin sandstone member of the Mississippian Chattanooga shale in Tennessee (Smith and Whitlatch, 1940) and Georgia (Hayes, 1895); the Maquoketa shale of Ordovician age in Illinois (Waller, 1907), Iowa (Bain, 1906), and Wisconsin (Grant and Burchard, 1907); several formations of Ordovician horizons in eastern Minnesota (Pettijohn) and Arkansas (Branner and Newson, 1902; Waggoner, 1912); black shales in the Pennsylvanian of Kansas (Bunnels, 1949) and Oklahoma (Oakes, 1936); and limestones in the Permian in El Paso and Hudspeth

Counties, Texas (A. L. Slaughter, written communication). Only the deposits in Tennessee and Arkansas have been mined. The Tennessee deposits, known as the blue-rock phosphates, produced 1.3 million tons; the Arkansas deposits produced about 32,000 tons.

Secondary deposits, concentrated during the weathering of the platform-type rocks, occur in north-central Kentucky (Phalen, 1915); Tennessee (Smith and Whitlatch, 1940); northern (Ross, B. B., 1900) and north-central (Phalen, 1912) Alabama; and Pennsylvania (Stose, 1907). The Kentucky and northern Alabama deposits are similar to the brown-rock phosphates of Tennessee and are derived from the same limestones which are Ordovician in age. The Tennessee white-rock deposits are phosphatized limestones formed from the leaching of the overlying blue-rock deposits. The north-central Alabama and the Pennsylvania deposits are composed mainly of the aluminum phosphate wavellite formed through weathering of the phosphatic rocks of Ordovician and Devonian age in those areas. The Kentucky brown-rock, the Tennessee white-rock, and Pennsylvania wavellite deposits have produced a few thousand tons each.

Numerous deposits of bat guano in caves in central Texas and New Mexico have been reported (Phillips, 1901; Schoch, 1918). Small quantities of the material have been mined from some of them.

c. Western states

In addition to the previously described extensive phosphate deposits in the Phosphoria Formation, marine phosphates are found in the Swan Peak quartzite of the Ordovician (Marshall),

1927) and the Brazer limestone of the Mississippian in northern Utah (Blackwelder, 1910) and southeastern Idaho (Manafield, 1927); the Desert limestone of the Mississippian in Utah (Gilluly, 1932); scattered localities in eastern Nevada (possibly equivalents of the Phosphoria formation); and at numerous localities in the rocks of Tertiary age in California (Rogers, A. F., 1944; Emery and Dietz, 1950; Reed, 1933; Heets, 1931; Woodring et al., 1946). None of these deposits has ever been mined.

Igneous apatite deposits are found in Colorado (Jacob et al., 1933); Utah (Blake, 1893); and Nevada (Stone, 1920). None of these deposits has been mined either.

IV. RESERVES

Reserves of domestic deposits are listed in Table 2. Most of these estimates were published earlier by Manafield (1942b) and Jacob (1952). The estimates for the Florida land-pebble field and the western field, however, are revised, preliminary estimates, based on recent, unpublished results of the U. S. Geological Survey investigations. Because the synthesis of our Florida data is well advanced, the estimates presented here are nearly final. As the compilation of new data on western deposits is not complete, the estimates presented are by no means final, but they do indicate order of magnitude.

An effort has been made in this compilation to separate minable reserves from resources too low in quality or too deep to be

TABLE 2. Representative analyses of principal types of phosphate deposits

	A	B	C	D	E	F	G	H	I	J
P ₂ O ₅	52.85	55.10	52.40	42.30	41.87	50.19	46.35	54.42	33.73	36.5
P ₂ O ₃	40.62	41.24	40.98	28.60	30.17	35.33	44.28	36.92	4.31	5.0(5)
Al ₂ O ₃		0.12		1.40	2.72	1.19	0.11	0.30	33.40	7.4
Fe ₂ O ₃	0.29		0.00	0.70	3.43	0.88				
Y ₂ O ₃		0.36	0.21							
K ₂ O	0.01	0.23	0.54	0.60	0.16	0.03	2.17	0.00	0.08	
Na ₂ O	0.07	0.12	1.32		0.23	0.036				
SiO ₂ (1)	0.96									
SiO ₂	2.57									
TiO ₂				0.10	0.16	0.03			5.42	
Mn ₂ O	1.10		0.00	0.90	0.27	0.42	0.005	0.45		
K ₂ O	0.21		0.00	0.88	0.64	0.26		0.45		
Ca ₂ O ₃					0.003	0.01				
V ₂ O ₃				0.07		0.02				
SiO ₂	0.26				14.38	4.38	2.80(3)	0.30	4.11	25.9
ZnO							1.99			
CaO		0.73		3.30	1.05	2.78	0.02	2.04	0.00	
SO ₃				2.80	0.63	0.12	0.73	0.00		
F	3.56	3.65	1.15	2.60	3.24	3.76	0.02	2.62	0.00	
Cl			3.74		0.01					
H ₂ O			0.06	0.87			1.61	2.78	14.90	2.30
H ₂ O -							0.10		3.80	
L.O.I.										
Insol.				4.50(2)	1.75	1.32				
	100.75	0.22		10.50						
		101.77	100.60	100.12	100.71	100.70				
Loss 0-2	1.90									
Loss 0-1		1.54	0.49	1.09	1.36	1.58				
Total	99.25	100.23	99.27	99.03	99.35	99.12	100.23(4)	100.63	99.77	99.8

(1) Total rare earths.

(2) Exclusive of CO₂ and H₂O(3) Insol. in 1:1 HCl plus SiO₂ liberated by dehydration.

(4) Also present traces of Mn, Cu, V, Sr, K, Ba.

(5) Includes insoluble residues.

(6) Totals as corrected in original publication.

Table 3. (cont'd) Descriptions and references

- A. Igneous apatite intrusion, Kola Peninsula, U.S.S.R. (composite of 110 apatite separates); Volodchenkova, A.I. and Malentiev, B. N., 1938.
- B. Apatite pegmatite, Hastings Co., Ontario; Walker, T. L. and Parsons, A. L., 1926.
- C. Hydrothermal chlorapatite, Kanawaga Pref., Japan; Harada, S., 1938.
- D. Marine geosynclinal phosphorite, Phosphoria formation, Coal Canyon, Wyoming (Bed 24, sample #2077); unpublished analysis, U. S. Geological Survey.
- E. Residual phosphorite, high-grade brown-rock phosphate, Wales, Tennessee; Jacob, K. D., Hill, W. L., Marshall, H. L. and Reynolds, D. S., 1933.
- F. Phosphatized limestone (hard rock), Dunnellon, Florida, (sample #434); Jacob, K. D., Hill, W. L., Marshall, H. L., and Reynolds, D. S., 1933.
- G. Phosphatized limestone, beta tricalcium phosphate, Nueva Leon, Mexico; Gady, J. G., Hill, W. L., Miller, E. V., and Magnus, 1952.
- H. Phosphatized limestone, Nauru Island; Jacob, K. D., Hill, W. L., Marshall, H. L., and Reynolds, D. S., 1933.
- I. Phosphatized augite-andesite, Malpelo Island; McConnell, D., 1943.
- J. Phosphatized trachyte, Clipperton Atoll; Hutchinson, G. E., 1950.

mined economically at the present time. Some of the reserves included in the second category are not much less valuable than these in the first. For example, the tennages in the western field listed as not minable now are of the same thickness and quality as those considered minable but lie at greater depths below the surface. A much larger volume of material of lower quality is not reported. Others, such as the Hawthorn deposits and Tennessee limestone, are of much lower quality than these which are mined in this country. It is safe to assume, however, that many of these deposits as well as tremendous reserves in other leaner deposits not reported will be mined later when the currently minable deposits are exhausted. The separation between minable and unminable deposits shown here is thus not of long-term significance, but emphasizes the fact that some of our deposits cost more to mine than others.

The estimates presented show that our reserves of minable phosphates (measured, indicated, and inferred categories) total about 5 billion tons of rock containing about 1.5 billion tons of P_2O_5 . Known deposits available for mining when these are exhausted total nearly 50 billion tons of rock containing 12 billion tons of P_2O_5 . At the present rate of consumption these resources will supply our needs for about 4,500 years. It is common knowledge that present consumption of phosphate is not adequate to replace the phosphate annually removed from the soil by crops and erosion. These estimated reserves indicate that our resources will support

a much increased production.

This picture of large reserves is made even brighter by the probability that, despite the long history of prospecting in this country, new discoveries of phosphate deposits will be made. Particularly promising are possibilities for discovering high-grade igneous apatite deposits in areas such as Magnet Cove, Arkansas; southwest-central Montana; central Colorado; southern California; and other alkalic igneous rock provinces. It seems likely, too, that geosynclinal phosphorites may be found, particularly at depth on the Gulf Coastal Plain. We thus may consider our resources of this critical element as relatively inexhaustible.

V. ACKNOWLEDGMENTS

Many of our colleagues on the U. S. Geological Survey are participating in current phosphate investigations in the western and Florida fields. It is a pleasure to acknowledge their contributions to the fund of new information drawn on in this summary, even though it is not possible to mention them all by name. The recent investigations of domestic deposits have been supported partly by the Atomic Energy Commission and the Bureau of Reclamation. The support of these agencies is gratefully acknowledged.

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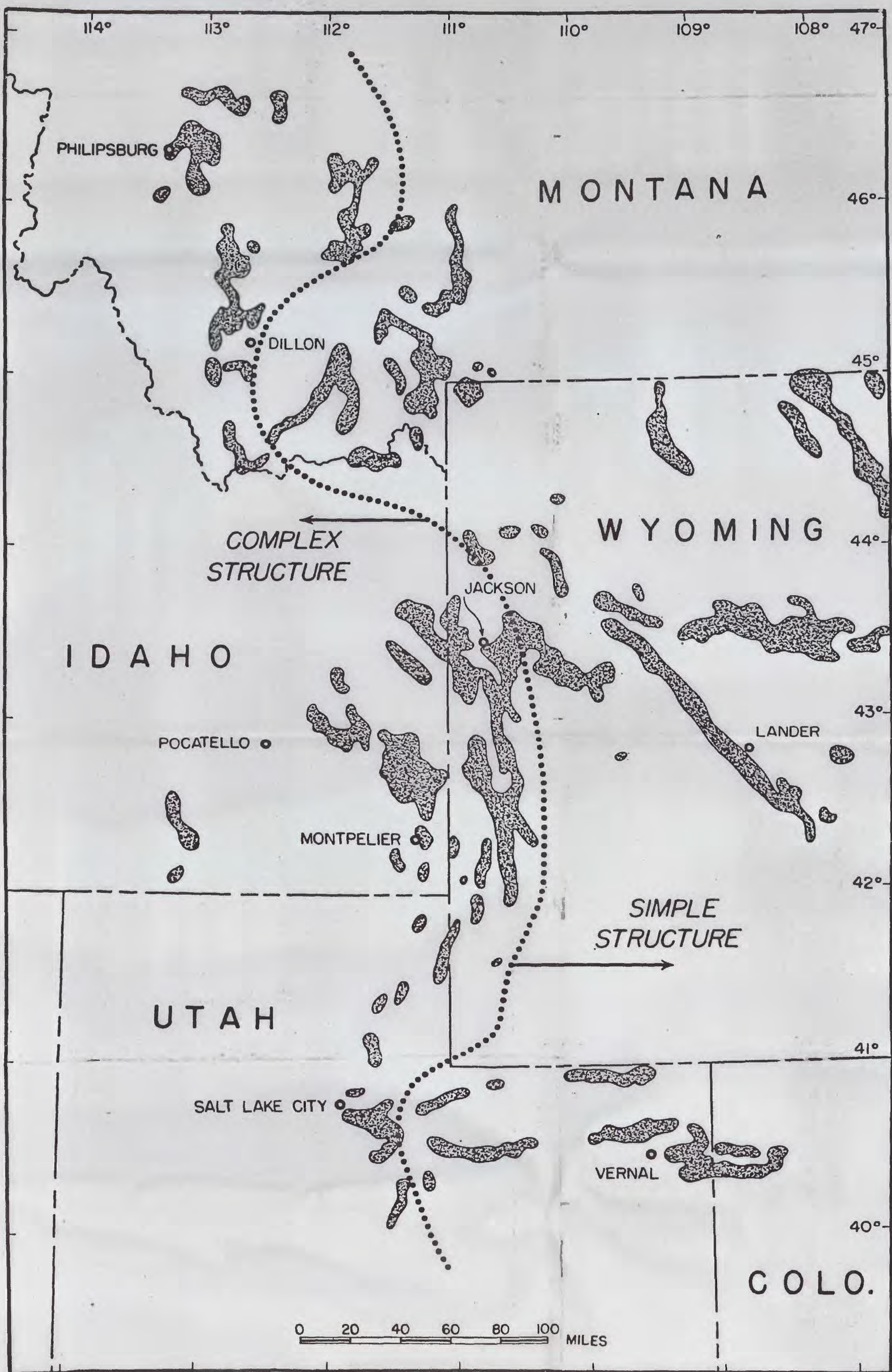
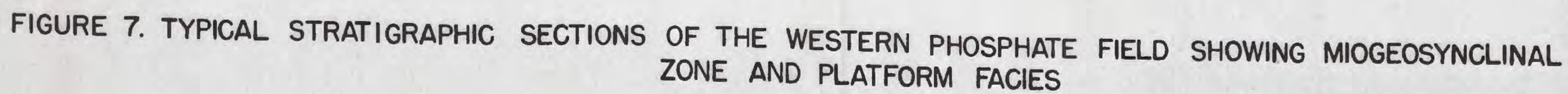


FIGURE 6. DISTRIBUTION OF OUTCROPS OF PERMIAN PHOSPHATIC ROCKS IN THE WESTERN FIELD. DOTTED LINE MARKS THE APPROXIMATE BOUNDARY BETWEEN AREAS OF SIMPLE AND COMPLEX STRUCTURE.



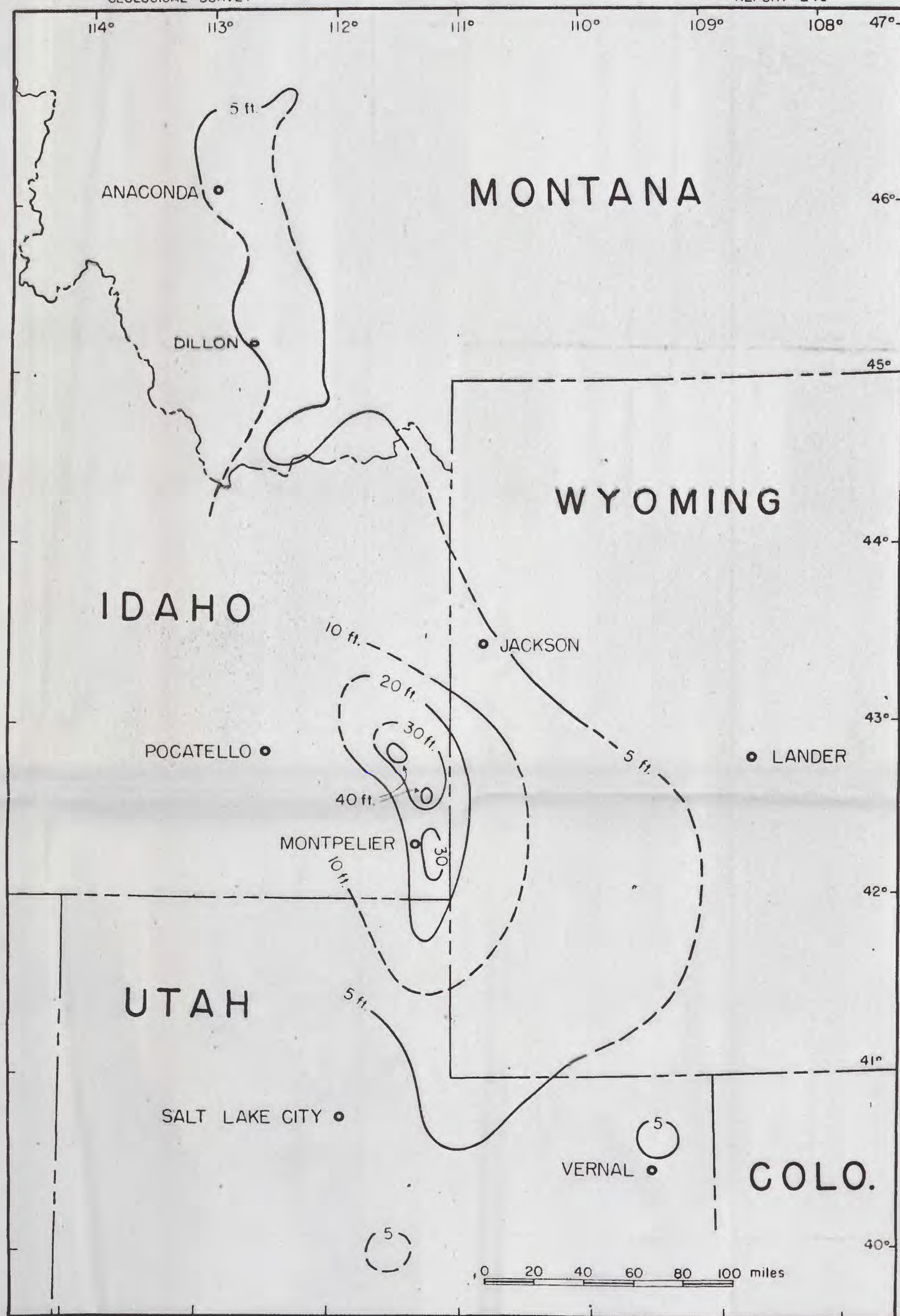


FIGURE 9. TOTAL THICKNESS (IN FEET) OF ROCKS IN THE PHOSPHORIA AND PARK CITY FORMATIONS CONTAINING MORE THAN 25 PERCENT P_2O_5