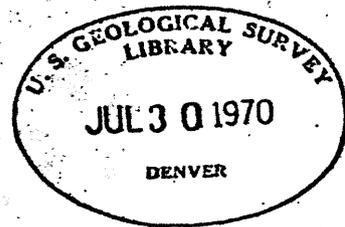UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Saudi Arabia Investigation Report

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PHOSPHATE DEPOSITS IN THE JAWF-SAKAKAH BASIN,
KINGDOM OF SAUDI ARABIA. PART III.
PRELIMINARY OBSERVATIONS ON THE TEXTURE AND COMPOSITION

by

James B. Cathcart
U.S. Geological Survey

U.S. Geological Survey
   OPEN FILE REPORT
This report is preliminary and has
not been edited or reviewed for
conformity with Geological Survey
standards or nomenclature.

1970

70-60

PREFACE

In 1963, in response to a request from the Ministry of Petroleum and Mineral Resources, the Saudi Arabian Government and the U. S. Geological Survey, U. S. Department of the Interior, with the approval of the U. S. Department of State, undertook a joint and cooperative effort to map and evaluate the mineral potential of central and western Saudi Arabia. The results of this program are being released in USGS open files in the United States and are also available in the Library of the Ministry of Petroleum and Mineral Resources. Also on open file in that office is a large amount of material, in the form of unpublished manuscripts, maps, field notes, drill logs, annotated aerial photographs, etc., that has resulted from other previous geologic work by Saudi Arabian government agencies. The Government of Saudi Arabia makes this information available to interested persons, and has set up a liberal mining code which is included in "Mineral Resources of Saudi Arabia, a Guide for Investment and Development," published in 1965 as Bulletin 1 of the Ministry of Petroleum and Mineral Resources, Directorate General of Mineral Resources, Jiddah, Saudi Arabia.

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INTRODUCTION

The present report is a preliminary description of the texture, composition, and other characteristics of one hundred phosphorite samples from the Kingdom of Saudi Arabia, which were collected by James W. Mytton, U. S. Geological Survey, and were examined by the writer in 1966. The geology of the area has been discussed by Bramkamp and others (1963), Sheldon (1967), and Mytton (1966, 1967). The samples are of three types: calcareous, siliceous, and unconsolidated. The calcareous and siliceous types make up about 90 percent of the samples collected and are more or less randomly distributed throughout the area where samples were collected (fig. 1). Where more than one sample was taken at a single locality, both calcareous and siliceous types are represented. The unconsolidated samples in this collection are grouped in the area just south of latitude 29°45'N., and between longitudes 38°00' and 38°15'E. However, sample cuttings from wells drilled by ARAMCO for tests of structure in the northern area of calcareous and siliceous phosphate rock are reported by R. P. Sheldon, J. W. Mytton, and C. R. Meissner (oral communication, 1966), of the U.S.G.S. to disclose unconsolidated phosphorite in the subsurface. The possibility of high-grade phosphate in pods or lentils in the subsurface, or at least friable rock that can be easily beneficiated, is the reason for a proposed drilling program in that area. Samples of this material are not included in the present study.

Calcareous phosphorite

Half of the samples collected (51 percent) are hard, calcareous phosphorite, in which the apatite pellets are cemented by brown to clear calcite. The rock is white, light-tan, or light-brown. The amount of phosphate pellets ranges from minor to abundant, and in a few samples, the phosphate pellets are so abundant that they are crowded together and are separated by only a thin film of calcite.

Attempts to crumble the calcareous phosphorite by gentle grinding in a mortar and pestle were unsuccessful. Grinding to a size necessary to free the phosphate particles from the matrix caused the phosphate pellets and the calcareous matrix
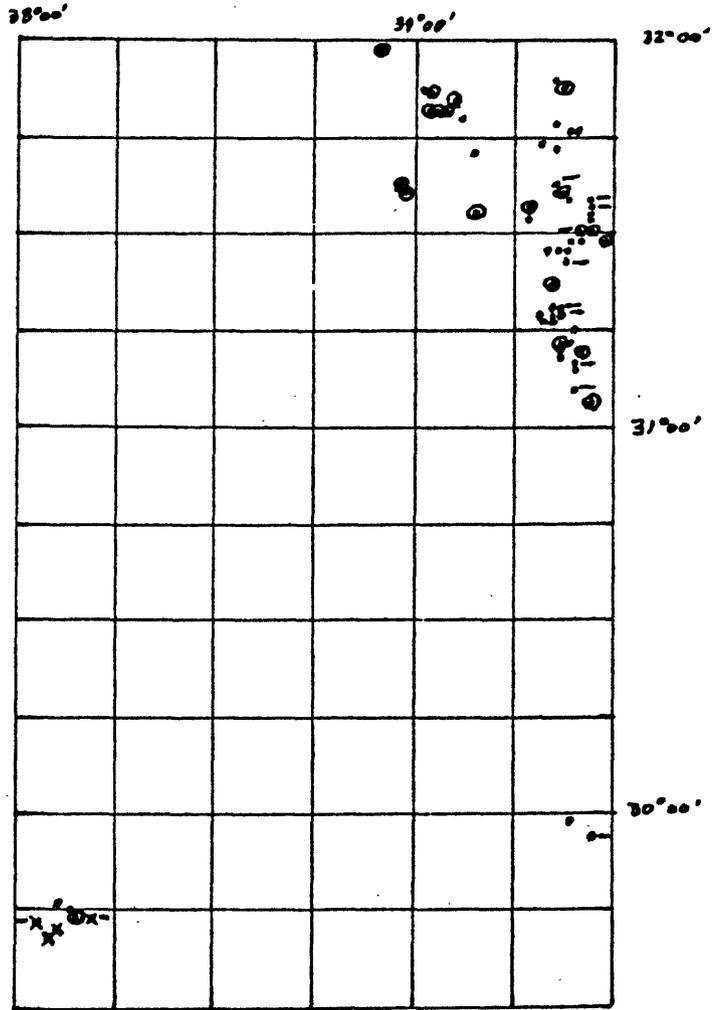
Figure 1. Location and distribution of phosphorite samples, Saudi Arabia

EXPLANATION

x

Unconsolidated samples

•   ◉   ✕—

Calcareous samples   Siliceous samples   Mixed samples

to disintegrate into a more or less uniformly sized material of about 200 mesh. This size material is too fine for successful commercial separation of phosphate and calcite by flotation.

Calcining at elevated temperatures to cause the $CaCO_3$ to break down into CaO and CO_2 probably would free the phosphate particles, and screening and flotation after calcining might result in a phosphate concentrate of a commercial grade, but costs would probably be excessive if the phosphate product is to be competitive on the world market.

Siliceous phosphorite

Somewhat less than half (39 percent) of the samples are light-gray to light-brown, very hard, siliceous phosphorite. The phosphate particles range in amount from minor to abundant, but in general, are less abundant than are the phosphate pellets in the calcareous samples. The silica cement may be a replacement of the calcite cement, but with hand specimens only, all that can be said is that the siliceous cement in some samples is secondary, replacing phosphorite pellets, fossil fragments, and the groundmass.

The phosphate particles cannot be easily separated from the siliceous matrix. Although the phosphate particles are softer than the siliceous cement, the cement is so friable that grinding pulverizes both mineral phases.

The phosphate particles are completely surrounded by the siliceous cement, even in those samples that contained the most abundant phosphate. Acidulation, which might be a practical method of separating the phosphate particles from the silica, was not successful. One sample, broken into coarse sand size, was treated with hydrochloric acid, and only a small percentage of the phosphate was dissolved. The silica cement surrounding the particles of phosphate effectively armored the particles and stopped acidulation. Fine grinding of this material would be necessary prior to acidulation, and it is likely that this cost would make the final product too high priced to compete in the world market.

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Unconsolidated phosphorite

The most interesting of these samples, from the economic view, is the small group (about 10 percent of the samples) of unconsolidated or nearly unconsolidated phosphatic rocks from the area between 38°00' and 38°15'E., and just to the south of 29°45'N. As noted above, this type of material has been seen in well cuttings from the northern area.

The samples were easily disaggregated by gentle agitation and grinding under water, and the screened products (table 1) were fairly clean separates. The +20 mesh fraction consists principally of phosphate particles, but there are some quartz grains present. The -200 mesh fraction (discarded as "slime" in current commercial practice) consists of clay, apatite, quartz, and an iron oxide mineral, and the other fractions consist of apatite pellets and varying amounts of quartz grains. These fractions could easily be separated by flotation into a phosphate concentrate and a sand "tailings". The concentrate fraction should be a commercial product.

PHOSPHATE PARTICLES

The phosphate particles in the siliceous and calcareous phosphorite are identical in all respects, except that, in general, the siliceous phosphorite contains fewer phosphate particles than the calcareous phosphorite. The phosphate particles range in size from about 0.1 mm to about 10 mm in diameter (from very fine sand to fine pebble size). The particles are all light-colored. White particles are most abundant but light-tan, gray, and light-brown pellets are also present. The finer size pellets are much more abundant than the coarser (pebble) size particles. Only about 25 percent of the samples contained abundant fine pebble size phosphate particles, and the coarse phosphate was more abundant than the fine phosphate in only about 5 percent of the samples. Most of the samples contain well-sorted, fine to very fine sand size phosphate particles.

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Table 1. Sieve fractions, in weight percent, samples of unconsolidated phosphorite.

Saudi Arabia

Mesh size	Sample number								
	21220 AA	21220 BB	21220 DD	21220 FF	21220 GG	21220 HH	21221	21229 [3/]	Average
+20	28.1	2.4	2.4	0.9	4.8	2.2	4.6	5.5	6.4
-20+35	9.6	1.2	23.1	8.9	9.3 [1/]	12.0	8.4	10.3	12.4
-35+200	55.4	89.3	62.2	73.4	68.1 [2/]	77.4	63.9	65.5	69.3
-200	6.9	7.2	12.3	16.8	17.8	8.4	23.1	18.7	13.9

1/ The -20+35 mesh fraction contained 2.7 percent apatite concentrate and 6.6 percent quartz tailings.

2/ The -35+200 mesh fraction contained 14.7 percent apatite concentrate and 53.4 percent quartz tailings.

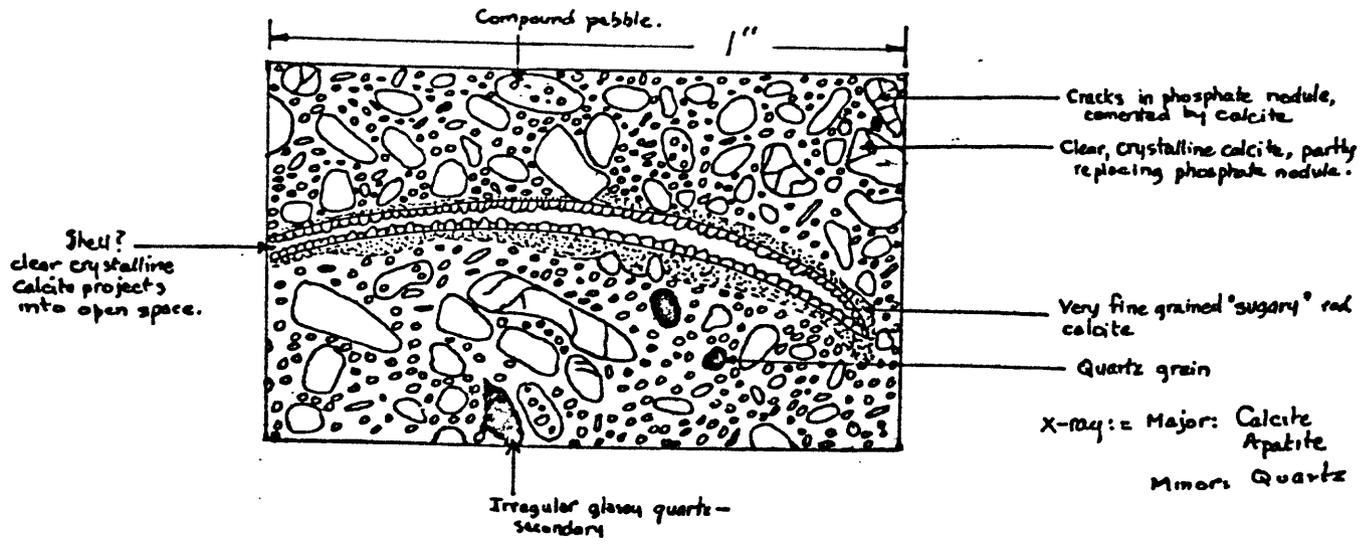3/ All fractions contained apatite as the only major mineral phase.

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lmost no difference in the X-ray patterns for the sized fractions. The sample

The coarser phosphate particles (fine pebble size) are dull, white, and consist of massive, extremely fine-grained to amorphous apatite. The grains are rounded, but are irregular in shape; a very few are subangular (fig. 2). Some of the coarser pebble size particles are compound - they contain smaller rounded phosphate grains and silt size quartz grains (fig. 2A). A few of the larger grains in some of the calcareous samples are cracked, and the cracks are filled with clear calcite.

The fine grained phosphate particles are all well rounded, they are generally ovoid, and some are spherical (fig. 2B). The particles are white, tan, light-brown, and gray, and are highly polished, in contrast to the dull luster of the coarser particles. Oolitic particles occur in many of the samples, and in most of the samples, the finer particles have at least a thin outer rim of contrasting color. Phosphatized fossil fragments are common (fig. 2C); most of them seem to be phosphatized foraminiferal tests, but some are phosphatized molds and casts of pelecypods and gastropods.

The phosphate particles in the unconsolidated phosphorite are rounded, highly polished, white, gray, tan, and light-brown, and range in size from less than 0.1 mm to about 2 mm in diameter. Many of the coarser particles (+20 mesh) are compound - they consist of fine-grained quartz and phosphate grains cemented by phosphate, and the whole grain is rounded and polished. In each of the screened samples, some of the coarser particles are phosphatized molds or casts of gastropods or pelecypods. These molds or casts consist of quartz silt and fine phosphate cemented by phosphate.

The separated phosphate particles contain about the same content of P_2O_5 in all size fractions, as indicated by X-ray diffractometer patterns, except that there is more quartz in the coarser fraction of some of the samples. The more abundant quartz is present where many of the particles are compound. The finer fractions may contain abundant quartz grains as well as phosphate grains - these could be easily separated by flotation. In at least one sample (21229) there was almost no difference in the X-ray patterns for the sized fractions. The sample

Compound pebble.

1"

Cracks in phosphate nodule, cemented by calcite.

Clear, crystalline calcite, partly replacing phosphate nodule.

Shell? clear crystalline calcite projects into open space.

Very fine grained "sugary" red calcite

Quartz grain

X-ray:= Major: Calcite
Apatite
Minor: Quartz

Irregular glassy quartz — secondary

A. Sample 21232. Coarse grained calcitic phosphorite

X-ray: MAJOR
Calcite
Apatite
Trace
Quartz
21.7 percent P_2O_5

1"

Clastic quartz grain

Very thin film of brown, "sugary" calcite on surface of sample.
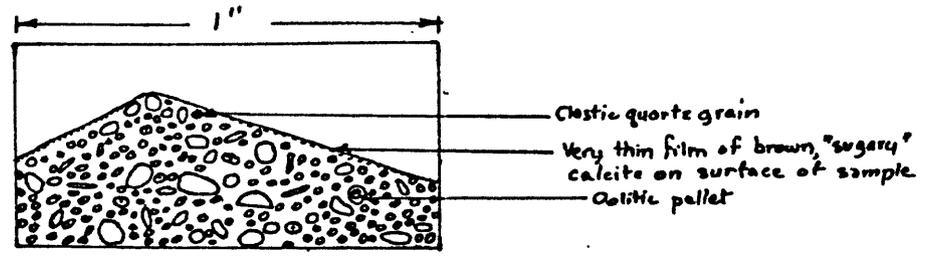
Oolitic pellet

B. Sample 21311C

Fine grained calcitic phosphorite

X-ray: MAJOR
Calcite
Apatite
18.6 percent P_2O_5

½"

phosphatized fossil (foraminifer?)
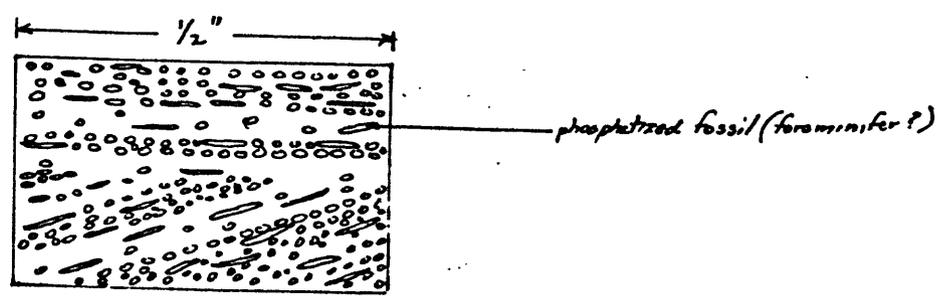
C. Sample 21309

Very fine-grained calcitic phosphorite

Figure 2. Sketches of textural relations of phosphate pellets in calcareous phosphorites. The groundmass is crystalline calcite, quartz grains are black, phosphate pellets and pebbles are uncolored.

7a

consisted almost entirely of phosphate grains of varying size in which only the finer fractions contained clay. This sample had 32.4 percent P_2O_5, and there was no apparent beneficiation by screening. This is, however, a minable sample. .

BEDDING

Bedding is indicated by orientation of flat phosphatized fossil fragments and ovoid phosphate particles, by irregular, subparallel beds that contain varying amounts of phosphate particles, by particle sizing, and, in the siliceous samples, by subparallel, lenticular areas of brown or gray "chert" replacing both the groundmass and the phosphate particles. Some samples are cross-bedded on a micro scale (fig. 2C). The bedding in the calcareous samples is best shown on the weathered surface where the phosphate particles tend to stand out in relief.

One sample of silica-cemented phosphorite showed a suggestion of graded bedding by the distribution of the phosphate particles. Coarser particles, more abundant at the base, gave way upward to finer grained particles, and the amount of the microcrystalline cementing material increased from bottom to top.

In general, the silica cemented phosphorites show less bedding than the calcareous samples. Most of the siliceous phosphorites are massive.

Bedding in the unconsolidated samples was not evident because of the nature of the samples. It is probable that the unconsolidated phosphorite is bedded in the same way as the more thoroughly cemented samples.

CEMENT

Siliceous phosphorite

The cementing material is brown or gray silica that resembles chert under the hand lens. The siliceous cement completely surrounds the phosphate pellets, even in the most highly phosphatic samples. The X-ray pattern is clearly quartz; only a few samples showed even a trace of an amorphous pattern. In several samples the cherty looking cementing material was recrystallized. In most samples the

siliceous material has replaced both the groundmass and the phosphate and fossils, and this replacement probably accounts for the lower average P_2O_5 content of the siliceous samples. In two samples the replacement was virtually complete. Both samples have abundant rounded pellets, oolites, and fossil fragments, separated by only thin films of the cherty looking groundmass. However, the X-ray patterns indicate that quartz is the only major constituent of these samples, and the chemical analysis showed that the samples contained 0.6 and 1.9 percent P_2O_5 (samples 21228 and 21249).

Calcareous phosphorite

The cementing material of the calcareous phosphorite samples is calcite. Only one sample contained dolomite as a major mineral phase, although dolomite was a minor or trace constituent of several samples. The calcite cement is brown or tan to clear, and completely surrounds the phosphate grains (fig. 2). Some of the calcite cement is secondary - fossils are replaced by clear, crystalline calcite (fig. 2) and cracks in some of the larger phosphate grains are filled with calcite. In two or three samples, the calcite groundmass is optically oriented to form large calcite crystals, up to 5 cm in diameter, poikilitically enclosing abundant phosphate pellets. The phosphate pellets within the large calcite crystals are oriented in the same fashion as the phosphate pellets outside the crystals.

Unconsolidated phosphorite

The cementing material of the unconsolidated phosphorite is a mixture of a clay mineral, apatite, and in one or two samples, calcite. Plate-like areas of white, very finely laminated apatite are present in a few samples. These areas are probably secondary apatite precipitates, filling cracks or joints or as coatings on what seems to be the surface of the sample.

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FOSSILS

Microfossils (foraminifera) and fragments of megafossils (pelecypods and gastropods) are present in many samples, and flat or slightly curved, rounded fragments found in many samples may be fossil fragments that have been phosphatized. Many megafossils in the siliceous samples tend to be replaced by silica, and in the calcareous samples, by calcite, but most fossil fragments are phosphatized. For example, in the unconsolidated samples, many of the coarse fragments are phosphatized molds and casts of gastropods or pelecypods, and similar fragments in the calcareous and siliceous phosphorites are believed to be phosphatized, although the grains could not be separated for analysis. Microfossils are abundant in only one sample (21228). In this sample the phosphate grains and the microfossils are almost completely replaced by silica.

MINERALOGY

The mineralogy, as determined by X-ray diffractometer, is basically simple. The phosphate mineral is a carbonate fluorapatite, and is present as a major mineral phase in most samples, or as a minor or trace constituent in a few samples. Good determinations of the amount of apatite can be made from X-ray·patterns, and these determinations agree very closely with the P_2O_5 determinations.

The calcareous phosphorites contain calcite as a major mineral phase in all samples. Dolomite is present only in a few samples, and is a major mineral phase in only one sample. Quartz as a minor or trace constituent is present in most samples of calcareous phosphorite. A clay mineral may be present in trace amounts in some samples, but the lines on the diffractometer pattern are too faint to make identification positive. Typical X-ray patterns of calcareous phosphorite are shown in figure 3. Number 21288H is a pattern of a sample containing abundant apatite, and number 21289B is a pattern of a calcareous rock containing minor apatite. Quartz is present in both of these samples, but only in trace amounts, and a trace amount of dolomite is present in sample 21289B.

The siliceous phosphorite always contains quartz as a major mineral phase (samples 21284, 21228, and 21249, fig. 3). The cementing material under the hand lens looks like brown or gray chert, although there are areas that appear to be microcrystalline quartz. Apatite is present in all samples and ranges from a trace constituent (sample 21228) to a major constituent (sample 21284). Calcite is present in many samples, but usually only in trace amounts where it may be contained as an impurity in the phosphate particle. Calcite is a minor mineral phase in some samples (21249) where it is a part of the groundmass or is present in fossil fragments. Dolomite is present in a few samples, always as a trace constituent (21228). Clay minerals may be present in trace amounts but no distinct clay mineral phase could be determined.

The unconsolidated phosphorite contains apatite as a major constituent in all samples. Quartz is present as a major constituent in four samples, as a minor constituent in four samples, and as a trace constituent in the remaining two samples. Dolomite is a minor constituent in one sample. A clay mineral, attapulgite, is present as a minor constituent in several of the samples and as a trace constituent in the rest (sample 21220 FF, fig. 3). Only the unconsolidated phosphorite contains a clay mineral in amounts that are abundant enough for identification. Halite is present as a major mineral phase in one sample and as a minor phase in three other samples. Calcite is present in trace amounts in several samples, probably as fossil fragments or as a constituent of the phosphate nodules. One sample (21229) contained apatite as the only major mineral phase, attapulgite as a minor phase, and a trace amount of quartz. Screened fractions of this sample showed no appreciable differences in mineral content in any of the fractions.

An iron mineral, probably goethite, was present in the very fine fractions of one sample, and chlorite is present in trace amounts in a few samples.

WEATHERING

Many of the samples have extremely thin brown crusts at the surface. Quartz and phosphate grains stand out in relief on the surfaces of the calcareous ... phosphorite, and bedding is emphasized. In the siliceous samples, the groundmass

stands out in relief, the phosphate grains have been removed by solution. Crusts of secondary apatite are present in a few samples of the unconsolidated phosphorite. Such crusts are evidence of solution and redeposition of the phosphate particles. The effects of weathering are very minor.

CHEMISTRY

The partial chemical analyses (table 2) of 9 samples of raw phosphorite from Saudi Arabia, made in the laboratory of the U.S.G.S., Denver, Colorado, confirm that the phosphate mineral is a carbonate fluorapatite. The samples contain an excess of fluorine and CO_2. In the carbonate fluorapatite, $(CO_3)^{-2}$ substitutes for $(PO_4)^{-3}$ and fluorine is added to balance the charge difference that is created. The ratio of F/P_2O_5 is about the same as is this ratio in phosphate samples from North Carolina, U.S.A., and is slightly higher than is the ratio in phosphate rocks from Florida, U.S.A. The ratio of CaO/P_2O_5 is about the same as is this ratio in both North Carolina and Florida, and is very high in the calcareous phosphorites. The ratio of CO_2/P_2O_5 again, is about the same as this ratio in phosphate particles from Florida and North Carolina, and is extremely high in the calcareous phosphorite.

K_2O and Na_2O contents are somewhat lower than in phosphorite samples from other parts of the world (Jacob and others, 1933), except for sample 21223, which is very high in Na_2O. This sample contained halite as a major mineral phase.

MgO is present in about average amounts, except in sample 21220CC, and this sample contained dolomite rather than calcite as the major carbonate mineral phase.

Al_2O_3, Fe_2O_3 and MnO are present in amounts that are somewhat lower than in phosphate particles from other deposits (Jacob and others, 1933).

Phosphate content

Analyses of P_2O_5 in the raw phosphorite samples were made by W. C. Goss and L. F. Rader of the U. S. Geological Survey laboratories, Denver, Colorado. The distribution of P_2O_5 in the three groups of samples is shown in figure 4. The distribution in the siliceous rocks is normal, the average P_2O_5 content is 11.8 percent, and most samples fall in the two groups from 10.0 to 15.0 percent P_2O_5.
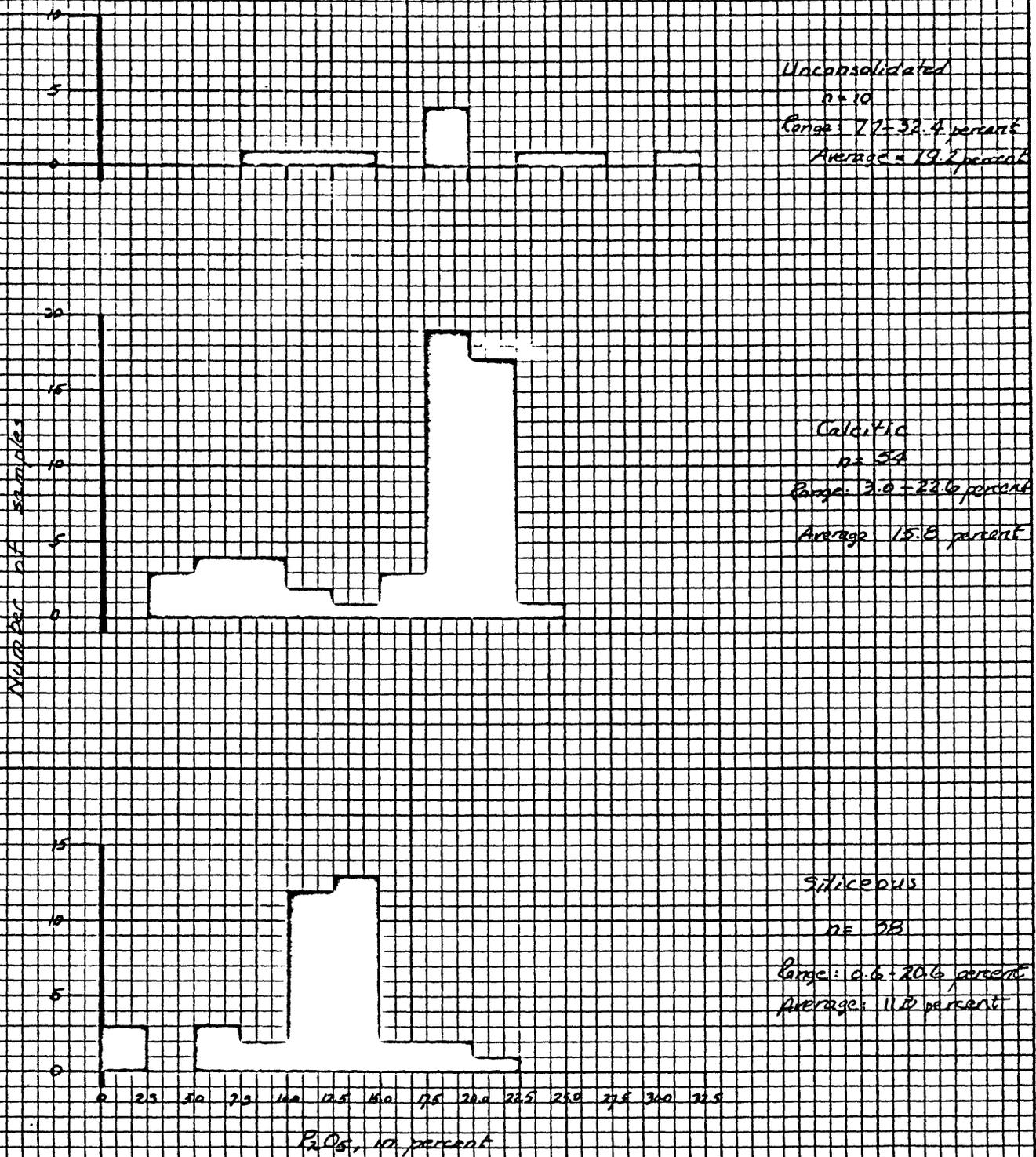
FIGURE 4. Bar graphs of distribution of P_2O_5, phosphate rock, Saudi Arabia.

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Table 2. - Partial chemical analyses of selected samples of phosphorite, Saudi Arabia

Lab. No.	Sample number	Chemical analysis, in percent										Remarks
		P_2O_5	CaO	SiO_2	Acid insoluble	MgO	Al_2O_3	Fe_2O_3 [1/]	Na_2O	K_2O	TiO_2	
D121890	21223	18.1	26.2	1.67	2.36	2.28	0.68	0.17	17.5	0.05	0.03	Unconsolidated phosphorite
D121883	21220DD	25.8	37.9	10.5	12.52	.78	.69	.27	1.70	.20	.04	
D121893	21229	32.4	50.0	.62	2.86	.82	.85	.21	.28	.08	.05	
D121906	21243	6.9	13.2	69.4	74.60	.08	.27	.12	.16	<.05	.03	Siliceous phosphorite
D121907	21244	14.6	22.4	55.1	56.87	.11	.22	.12	.11	<.05	.02	
D121902	21239	20.6	30.0	36.6	45.20	.07	.07	.06	.14	<.05	.02	
D121882	21220CC	5.0	26.2	6.98	9.21	14.3	.82	1.66	1.14	.17	.06	Calcareous phosphorite
D121798	21289A	13.6	53.8	.51	.61	.20	.21	.10	.24	<.05	.02	
D121903	21240	22.6	53.7	.17	.17	.12	.09	.03	.13	<.05	.02	

1/ Total iron as percent Fe_2O_3.

SiO_2, Al_2O_3 and TiO_2 determined colorimetrically by G. T. Burrow. Acid insoluble in 1+1 hydrochloric acid, determined by G. T. Burrow. CaO, total iron as Fe_2O_3, MnO and MgO determined by atomic absorption by H. H. Lipp. Total S determined gravimetrically by H. H. Lipp. CO_2 determined gasometrically by Dorothy Kouba. F determined volumetrically by W. D. Goss and G. D. Shipley, eU determined by beta-gamma scaler by E. J. Fennelly. U determined fluorometrically by E. J. Fennelly. Na_2O and K_2O determined by flame photometer using internal standards by Wayne Mountjoy. P_2O_5 (sample 21289A) determined by A.O.A.C. volumetric method by L. F. Rader. P_2O_5 (all other samples) determined volumetrically by W. D. Goss.

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Table 2. - Partial chemical analyses of selected samples of phosphorite, Saudi Arabia (contd)

Lab. No.	Sample number	Chemical analysis, in percent						Ratios			Remarks
		MnO	CO_2	F	Total S	eU	U	F/P_2O_5	CaO/P_2O_5	CO_2/P_2O_5	
D121890	21223	<0.01	4.54	1.91	0.49	0.003	-	0.106	1.45	0.250	Unconsolidated phosphorite
D121883	21220DD	.01	2.03	2.69	.25	.006	0.006	.104	1.47	.079	
D121893	21229	<.01	2.82	3.92	.50	.007	.007	.121	1.54	.087	
D121906	21243	.01	3.19	.72	.14	.001	-	.104	1.92	.462	Siliceous phosphorite
D121907	21244	.01	2.33	1.55	.12	.001	-	.106	1.53	.160	
D121902	21239	<.01	1.60	2.34	.07	.001	-	.113	1.46	.078	
D121882	21220CC	.03	31.4	.42	.09	<.001	-	.084	5.04	6.29	Calcareous phosphorite
D121798	21289A	<.01	29.5	1.62	.17	.002	-	.119	3.96	2.17	
D121903	21240	<.01	18.8	2.82	.11	.001	-	.125	2.38	.83	

Total S determined gravimetrically by H. H. Lipp. CO_2 determined gasometrically by Dorothy Kouba. F determined volumetrically by W. D. Goss and G. D. Shipley, eU determined by beta-gamma scaler by E. J. Fennelly. U determined fluorometrically by E. J. Fennelly. Na_2O and K_2O determined by flame photometer using internal standards by Wayne Mountjoy. P_2O_5 (sample 21289A) determined by A.O.A.C. volumetric method by L. F. Rader. P_2O_5 (all other samples) determined volumetrically by W. D. Goss.

1/ Total iron as percent Fe_2O_3.

SiO_2, Al_2O_3 and TiO_2 determined colorimetrically by G. T. Burrow. Acid insoluble in 1+1 hydrochloric acid, determined by G. T. Burrow. CaO, total iron as Fe_2O_3, MnO and MgO determined by atomic absorption by H. H. Lipp.

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The distribution in the calcareous samples is skewed toward the higher P_2O_5 groups, but there is a bimodal distribution. The average is 15.0 percent P_2O_5, and most samples fall in the two groups between 17.5 and 22.5 percent P_2O_5.

The unconsolidated samples are higher in P_2O_5 than the other types. The average P_2O_5 content is 19.2 percent, and the distribution is nearly normal, although there are too few samples to be certain.

Spectrographic analyses

Six-step spectrographic analyses were run on all samples by Barbara Tobin of the U. S. Geological Survey. The analytical results for selected samples are shown on table 3. The distribution of the major elements is predictable on the basis of the mineralogy of the samples - i.e., the siliceous samples all have major amounts of Si; Ca is a major element in all samples; Al is highest in samples that have an identifiable clay mineral phase, Fe is highest in the sample that contained the iron mineral goethite; Mg is highest in the samples of calcareous phosphorite that contain dolomite as a distinct mineral phase.

In addition to the rare earths, eight other metals are present in almost all of the samples in trace to minor amounts. Barium and strontium are present in amounts of 0.01 to about 0.1 percent, and strontium is definitely higher in the calcareous phosphorite, while barium is in about the same amounts in the calcareous and siliceous samples and is in lower amounts in the unconsolidated samples. Chromium, manganese, titanium, and vanadium are present in all samples in amounts ranging from 0.001 to 0.05 percent, and all of these metals are in distinctly higher amounts in the unconsolidated samples. Copper and nickel are present in lesser amounts than the above metals, ranging from 0.0005 to about 0.005 percent and both of these metals are present in somewhat higher amounts in the unconsolidated samples. Cobalt, silver, molybdenum, and zirconium are present in a few samples. In most specimens, these elements are below the limits of detection, and are therefore, present in very minor amounts.

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Table 3. - Semiquantitative spectrographic analyses of selected phosphorite samples, Saudi Arabia. (Analyst: Barabara Tobin. Results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, etc.; which represent approximate midpoints of group data on a geometric scale. The assigned group for 6-step results will include more accurately determined values about 30 percent of the time. Symbols. — M = >10%; 0 = looked for but not detected; — = not looked for; <, with number, = less than number shown - here usual detectabilities do not apply).

Sample and laboratory number

Element	21220 CC D121882	21220 DD D121883	21223 D121890	21229 D121893	21239 D121902	21240 D121903
Si	3.	7.	.7	1.5	M	.15
Al	.7	1.5	1.5	1.5	.05	.03
Fe	2.	.5	.3	.5	.1	.03
Mg	M	.7	2.	1.	.05	.07
Ca	M	M	M	M	M	M
Na	5.	5.	M	.7	.3	.3
Ti	.03	.03	.02	.03	.002	.003
P	1.	M	3.	M	M	7.
Mn	.015	.007	.003	.001	.005	.001
Ag	0	0	.0002	.0002	.0007	0
B	0	0	0	0	0	0
Ba	.007	.015	.003	.005	.007	.05
Ce	<.05	<.05	<.05	<.05	<.05	<.05
Cr	.01	.03	.05	.07	.015	.015
Cu	.003	.001	.002	.003	.002	.001
La	0	0	.01	.015	0	.005
Ni	.01	.0015	.003	.003	.002	.002
Sc	0	0	.0007	.0015	0	.0007
Sr	.02	.1	.15	.1	.03	.07
V	.015	.02	.02	.05	.007	.01
Y	0	.005	.015	.03	.007	.007
Yb	0	.0003	.001	.002	.0005	.0005
Zr	0	0	0	.003	0	0
Nd	0	0	<.05	<.05	—	0

Table 3. - Semiquantitative spectrographic analyses of selected phosphorite samples,
Saudi Arabia. (Analyst: Barbara Tobin. Results are reported in percent
to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1,
etc.; which represent approximate mindpoints of group data on a geometric
scale. The assigned group for 6-step results will include more accurately
determined values about 30 percent of the time. Symbols. -- M =>10%;
0 = looked for but not detected; -- = not looked for;<with number,
= less than number shown - here usual detectabilities do not apply).

Sample and laboratory number

Element	21243 D121906	21244 D121907	21289A D121798	21298 D121808	21309 D121818
Si	M	M	.3	M	.07
Al	.3	.3	.015	.07	.05
Fe	.1	.2	.07	.05	.05
Mg	.07	.1	.1	.1	.07
Ca	M	M	M	M	M
Na	.2	.2	.7	.5	.3
Ti	<.005	.007	.003	.003	.003
P	7.	M	2.	M	7.
Mn	.003	.005	.007	.01	.0007
Ag	.0007	.0007	.00015	.0003	0
B	.007	.01	0	0	0
Ba	.07	.03	.007	.1	.03
Ce	<.05	<.05	<.05	<.05	<.05
Cr	.007	.015	.015	.002	.02
Cu	.01	.002	.002	.0015	.001
La	0	.005	0	.005	0
Ni	.002	.001	.0015	.001	.001
Sc	.0007	.0005	0	0	0
Sr	.05	.05	.07	.15	.5
V	.003	.005	.007	.01	.005
Y	.0015	.003	.002	.007	.005
Yb	0	.0002	.00015	.0005	.0003
Zr	0	0	0	0	.007
Nd	--	--	--	--	--

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The rare earth elements, cerium, yttrium, and ytterbium are present in almost all samples, while lanthanum and neodymium are below the limit of detection in most samples.

RELATIONS OF TEXTURE AND COMPOSITION TO ECONOMICS OF THE PHOSPHORITE

The calcareous and siliceous phosphorites, that make up most of the samples received, are competent, thoroughly cemented rocks that range from less than 1 to about 22 percent P_2O_5. The unconsolidated phosphorites range from about 8 to about 32 percent P_2O_5, and even the lower grade samples could be crumbled and then upgraded by flotation methods. No attempt has been made to compute tonnages, but there are large areas in the Turaif-Sakakah basin that are probably underlain by phosphorites that contain more than 15 percent P_2O_5. If the beds represented by the samples have any thickness the tonnages represented are very large.

It would be possible to produce acceptable superphosphate or triple super-phosphate from the calcareous and siliceous phosphorite, but the costs probably would be excessive. These phosphorites can be upgraded by grinding, calcining, screening, and flotation, but the fine grinding necessary to completely free the fine-grained phosphate particles from the calcareous or siliceous matrix would probably cause excess loss of phosphate by "sliming", and would also be a costly process.

The unconsolidated phosphorites may be economic provided tonnages are large enough and accessible beds are found. Material like the unconsolidated phosphorite represented by sample 21229 is high enough in grade to be mined and shipped without beneficiation or could be converted to super or triple superphosphate. The other samples of unconsolidated phosphorites can be easily upgraded by disaggregation followed by screening and flotation. However, in the area where these samples were found, there is a considerable thickness of overburden which would require underground mining (written communication, C. R. Meissner, 1966).

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Samples of unconsolidated phosphorite consist of quartz and phosphate grains that are weakly cemented by a mixture of apatite and clay. Standard flotation methods of separating quartz and phosphate grains can be used to upgrade the unconsolidated phosphorites. The first steps are disaggregation and sizing. The standard sizes used in the United States (Florida and North Carolina) are approximately 20, 35, and 200 mesh. The +20 mesh fraction is called pebble, the -20+35 mesh is the coarse feed, the -35+200 is the fine feed, and the -200 mesh is the slime fraction. Screen data, in weight percent, are shown on table 1. The +20 mesh or pebble fraction is an economic product in Florida, and this fraction in all of the screened samples from Saudi Arabia consists of grains of phosphate and minor to trace amounts of quartz. +20 mesh fractions were too small to analyze for P_2O_5, but selected samples were X-rayed, and contained apatite as the only major mineral phase. Quartz is the only other recognizable mineral phase, and is present in amounts estimated as less than 10 percent. Thus, this fraction may be an economic product in the samples from Saudi Arabia.

The flotation feed fractions can be separated by the use of heavy liquids (bromoform, sp. g. = 2.86) into a light and a heavy separate. The light fraction corresponds to the flotation tailings and the heavy fraction to the concentrate. The feed fractions of two samples were separated in heavy liquids to determine, at least qualitatively, the economics.

Sample 21220 GG contained 14.1 percent P_2O_5 in the head sample. The +20 mesh fraction, 4.8 percent by weight, consists of apatite, minor (less than 10 percent) quartz, and a trace of an iron oxide mineral, probably goethite.

The coarse feed fraction of this sample (-20+35 mesh) is 9.3 percent by weight, and of this, the concentrate (heavy) fraction was 2.7 percent, the tailing (light) fraction 6.6 percent. The fine feed fraction (-35+200 mesh) is 68.1 percent of the total, and consists of 14.7 percent concentrate and 53.4 percent tailings. The concentrate fractions, as determined by X-ray, contain apatite and a trace (less than 5 percent) quartz. The tailings fractions consist of quartz, minor to trace

amounts of apatite, and a trace of a clay mineral. The clay mineral probably is present as a cement in undisaggregated particles present in both fractions.

The slime fraction (-200 mesh) consists of apatite, minor clay (attapulgite) and a trace of quartz and goethite. This fraction apparently much higher in apatite than the slime fraction in the phosphate deposits of either Florida or North Carolina.

The total sample contains about 22 percent, by weight, of recoverable phosphate particles, 60 percent quartz sand tailings, and 18 percent slime. In terms of recoverable tonnage, this sample contains about 400 tons per acre-foot of phosphate particles, and these particles, based on the X-ray patterns, are probably economic - they certainly contain more than 30 percent P_2O_5. This tonnage is about at the base of what is considered economic to mine in Florida at the present time, therefore all samples of unconsolidated material that contain in excess of about 15 percent P_2O_5 should be considered as potentially economic, and heavy liquid separations should be made on the samples after disaggregation.

RECOMMENDATIONS FOR FURTHER WORK

The area around latitude 29°45'N. and between longitude 28°00' and 38°15'E. from surface indications contains the best phosphorite samples. Samples from this area were easily disaggregated by agitation and gentle crushing under water. Screening after disaggregation produced reasonably clean fractions. The principal diluent is quartz, although several samples also contained halite as a diluent. The quartz and phosphate can be easily separated by standard flotation methods and the halite eliminated by simple washing.

This area offers the best potential for economic phosphorite on the basis of the surface samples viewed here, and it should be examined in detail to determine tonnage and grade of the material. The presence of halite as a diluent in some of the samples from this area is deleterious. Halite must be removed from the product.

Unconsolidated phosphorite reported in subsurface samples from the northern area, but not examined in this study, increases the economic potential of that region, and requires that it be explored by drilling to find suitable sources for this variety of phosphorite.

An effort should be made to determine the economics of treating the calcareous and siliceous phosphorites, particularly to determine the magnitude of differences in the probable cost of beneficiation versus prices current on the world market. The results of such a study will probably show that the siliceous and calcareous phosphorites are not economic on the present world market.

The present analyses of the siliceous and calcareous phosphorites indicate that among these surficial samples there is nothing that approaches the 30 percent P_2O_5 that might be economic. However, all samples are surficial, and additional work should be done to determine thickness of the phosphorite, and also whether the rock at depth is of the same grade and composition. It is evident from the wide geographic distribution of the samples that the total tonnage of phosphorite is very large. For example, the area underlain by calcareous phosphorite that contains more than 15 percent P_2O_5 is about 200 square miles, or 128,000 acres. A bed of phosphorite 1 foot thick, containing an average of 15 percent P_2O_5, contains about 300 tons per acre of P_2O_5, or about 38 million short tons of P_2O_5 in the 200 square miles. The formula used in this calculation is:

$$\frac{43,560 \text{ (square feet per acre)} \times 100 \text{ (weight of rock in pounds per cubic feet)}}{\text{short ton (2000 pounds)}} = 2178 \text{ (constant)}$$

rounding, 2000 (constant) x percent P_2O_5 x thickness in feet = tons of P_2O_5 per acre.

Samples of siliceous and calcareous phosphorites should be analyzed for P_2O_5, and only those samples that contain more than 24 percent P_2O_5 should be submitted for further work. Phosphatic shales are mined for electric furnace feed when the grade is in excess of 24 percent P_2O_5. Grades in excess of 30 percent are used in fertilizer plants, or can be beneficiated by calcining, screening, and acidulation.

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Unconsolidated material might be economic when grades exceed 15 percent P_2O_5. Certainly this is the case in Florida and North Carolina, particularly where the tonnage is high enough and where mining costs can be kept low. I would recommend that heavy liquid separations (in bromoform) be made on all samples capable of disaggregation that contain 15 percent or more P_2O_5.

Tonnage computations can be made on any basis, but I would recommend that, at least for the unconsolidated material, the tonnages be computed following the practice of the phosphate industry.

The tonnage should be computed for the recoverable phosphate particles, the pebble (+20 mesh) and the total concentrate (-20 +200 mesh). Note here that grades, in percent P_2O_5 must be given for each fraction.

A bed of unconsolidated phosphate particles one foot thick contains about 2000 short tons per acre, so:

2000 (constant) x weight percent of fraction (either pebble or concentrate) x thickness, in feet = short tons of phosphate particles per acre.

The figure of tons per acre is used throughout the industry as a standard, and is, I believe, a useful figure, particularly for reconnaissance work.

Beneficiation by flotation requires large amounts of water. For example, a recovery plant in Florida that produces 1-2 millions tons of product uses 5 to 10,000 gallons of water per minute. Water, particularly in this desert area might be an extreme problem.

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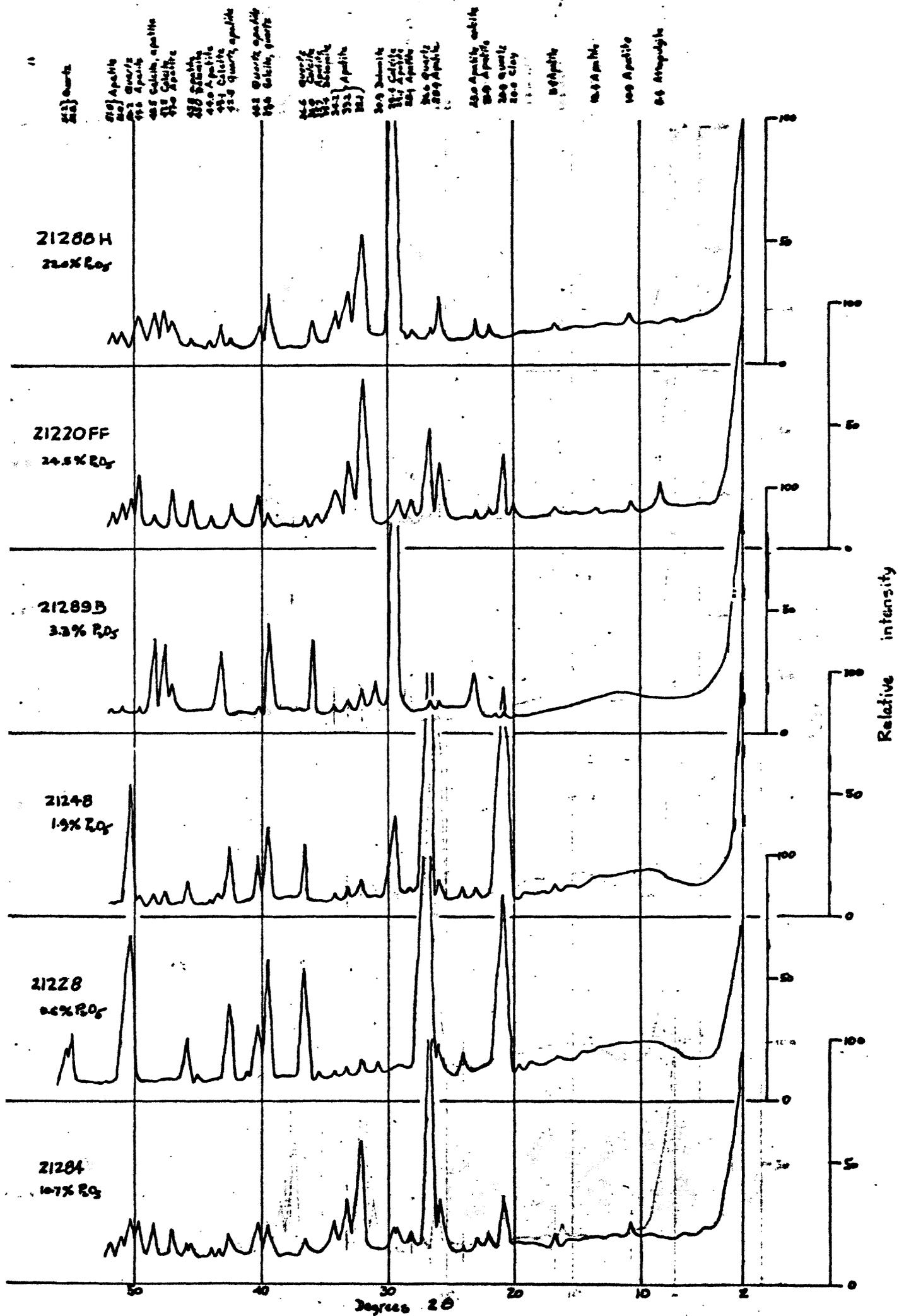
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FIGURE 3   Selected X-ray diffractometer patterns, Saudi Arabian phosphorites.