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# GEOLOGY OF PHOSPHATE DEPOSITS IN THE SIRHAN-TURAYF BASIN, KINGDOM OF SAUDI ARABIA

by


Charles R. Meissner, Jr.
U.S. Geological Survey

and

Abdullah Ankary
Directorale General of Mineral Resources


with

# DRY BENEFICIATION OF PHOSPHATE ORE FROM WEST THANIYAT, SAUDI ARABIA

by


Tennessee Valley Authority





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

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## 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 Also on open file in that office is a large amount of material, in the form of unpublished manuscripts, maps, field notes, drill logs, annotated aerial photographs, etc., that has resulted from other previous geologic work by Saudi Arabian government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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ABSTRACT

The Sirhan-Turayf sedimentary basin in northern Saudi Arabia contains two widely separated phosphate bearing areas: the Thaniyat area along the southwestern rim of the basin and the Turayf area in the northeastern desert plains. Phosphate in the Thaniyat area is in two zones, one in the lower part of the Hibr Formation and another at the top of the Upper Cretaceous Aruma Formation. The Turayf phosphate is in three numbered zones, all of which are in the Eocene phosphate member of the Paleocene and Eocene Hibr Formation. The zone in the Aruma Formation at Thaniyat contains the most potentially economic phosphate if an efficient technique can be developed to upgrade the ore. The best phosphate-bearing beds in the zone is in the area referred to as "West Thaniyat."

At West Thaniyat the zone contains two beds of phosphate. The upper bed of the zone is too thin to mine (underground) alone, but is valuable if the whole zone is mined. However, the lower bed at the bottom of the zone, is thick enough to mine alone by underground methods (overburden ranges from 20 to 100 meters).

The lower bed of West Thaniyat crops out along an irregular, east-west trending cliff for a distance of about 10 kilometers and, as learned from core drilling, it is nearly flat-lying and extends in the subsurface northward from the outcrop for about 10 kilometers. The bed ranges in thickness from 1 to 2.50 meters, averaging 1.65 meters,

and in grade from 20 to 26 percent $P_2O_5$, averaging 23 percent $P_2O_5$. The phosphate is soft and friable consisting of apatite pellets, quartz sand, and clay. Reserves are approximately 200,000,000 metric tons of ore (30,000,000 metric tons of $P_2O_5$). A preliminary mining-milling, transportation-marketing feasibility survey by phosphate experts with the U.S. Tennessee Valley Authority had suggested on the basis of adit samples that the lower bed at West Thaniyat possibly could be economically mined and beneficiated to produce a marketable rock suitable for use in phosphate fertilizer processes. However, upon examination of core samples resulting from a subsequent drilling program it was found that the ore is more argillaceous than expected and that the large amounts of clay interferes with the beneficiation processes.

Mapping and core drilling in the Turayf area have shown that the three phosphate zones are in an area of about 2000 square kilometers. The upper zone is the most important because it contains the most phosphate, 3 to 5 or more beds, and is at the shallowest depth, averaging about 12 meters. The average aggregate thickness and $P_2O_5$ content of beds with at least 10 percent $P_2O_5$ is 2.5 meters and 16 percent. The tonnage of $P_2O_5$ concentrate in upper zone is about 1 billion metric tons. The best phosphate found in the zone is along the western end of the "TB" line of core holes between TB-1 and TB-11 where the average aggregate thickness is 3.9 meters, and $P_2O_5$ content is 18 percent.

Here the phosphate beds are estimated to contain about 80,000,000 metric tons of $P_2O_5$.

Most phosphate rock in the Turayf area is hard and solid consisting of apatite pellets firmly bound and cemented by calcite or silica, although soft, friable, calcareous phosphate has been found locally. CERPHOS, a French phosphate research company, has shown that the hard, calcareous, phosphate rock can be upgraded to 37 percent $P_2O_5$ by calcining, screening, and washing out the lime.

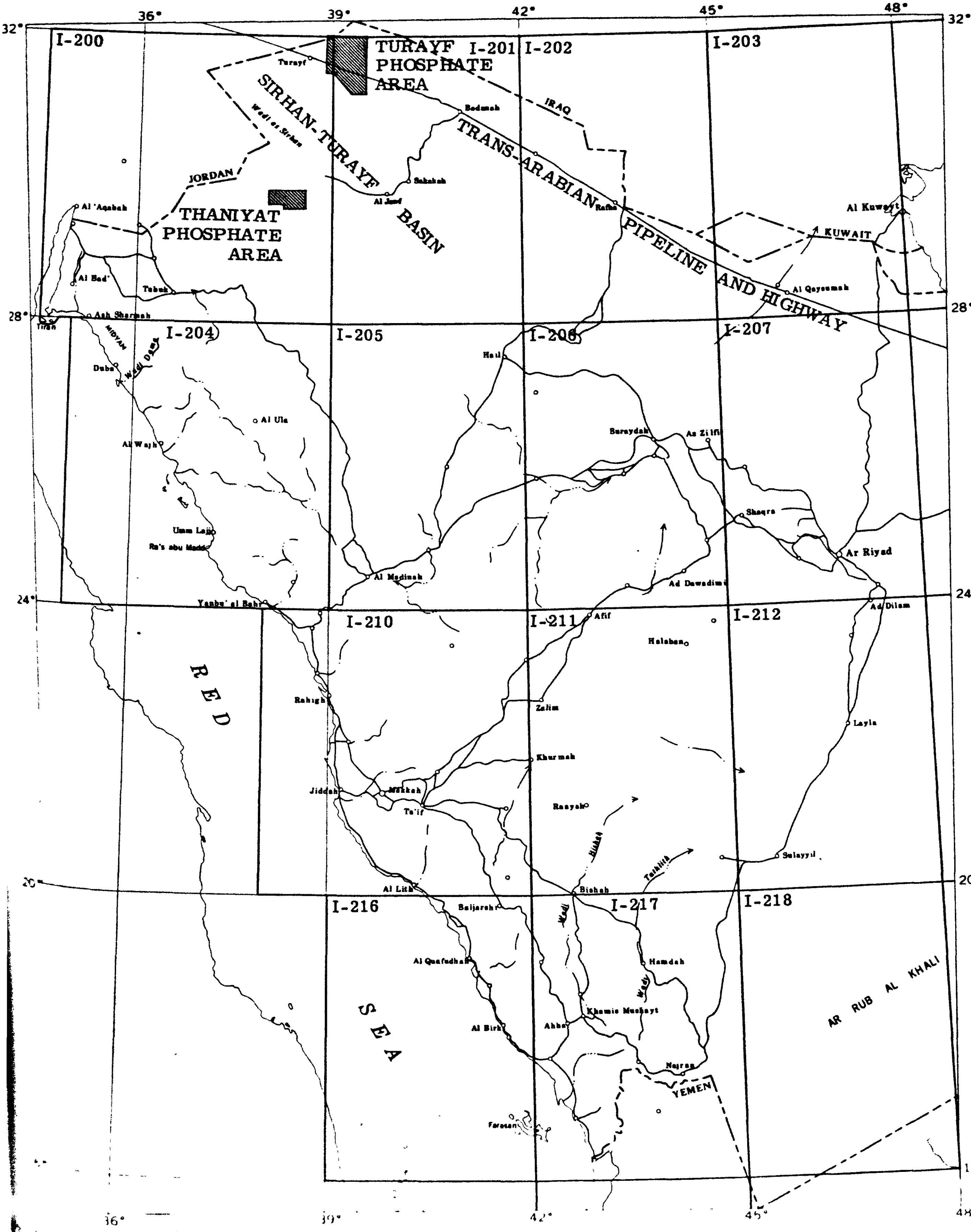
# INTRODUCTION

## Purpose and scope of the report

This report summarizes activities since phosphate rock float originally was discovered in the desert plains of the northeastern part of the Sirhan-Turayf sedimentary basin in northern Saudi Arabia, to the completion of core drilling of potentially economic phosphate deposits discovered later along the southwestern rim of the basin. A brief description of the geology of the basin is given to illustrate its relationship to the phosphate-bearing formations. Current information has been obtained through field and laboratory studies during the period April 1966 to May 1969.

## Location and extent of the area

The Sirhan-Turayf basin is in the northernmost part of Saudi Arabia between lat 29°15' and 32°00'N., and long 37°00' and 40°00'E. (pl.1 and fig.1). The name Sirhan-Turayf is from Powers and others




RE 1. - Index map of western Saudi Arabia showing the location of the Turayf and Thaniyat phosphate areas

(1966); it has been less correctly called Jauf-Sakaka in reports by Cathcart (1970), Mytton (1966, 1967), and Sheldon (1967). The basin is bordered on the north by Iraq and Jordan and mostly on the west by Jordan. The Trans-Arabian oil pipeline and highway extend across the northeastern part of the basin and the Turayf pump station is located about 42 kilometers east of the Jordan border. Wadi Sirhan extends diagonally across the western side of the basin area.

The basin has two widely spaced phosphate-bearing areas. The Thaniyat area lies along the southwestern rim of the basin and the Turayf area lies in the northeastern desert plains about 250 kilometers north-northeast of Thaniyat.

The Topographic Division of the U.S. Geological Survey has prepared sixteen 7½'-quadrangle maps of the Thaniyat area and is now preparing twenty 7½'-quadrangle maps of the Turayf area, all to a scale of 1:25,000 and a contour interval of 5 meters. Orthophotomosaics also have been prepared of six selected quadrangles (1:25,000) in the Thaniyat area which include West Thaniyat. These orthophotomosaics are the base maps upon which we plotted geologic contacts directly from field photo prints (1:30,000). Controlled photomosaics of all Turayf quadrangles have been prepared and geologic contacts are plotted on the mosaics in the process of preparing geologic maps of the selected area of Turayf. These maps will be subsequently printed separately from this report.

## History of discovery

Potentially commercial phosphate rock was first discovered in the Turayf area in northern Saudi Arabia during a reconnaissance of the region by R.P. Sheldon (1967) between August 12 and September 3, 1965. James W. Mytton (1966, 1967) did the original follow-up field reconnaissance during the period October 19 to December 11, 1965, at which time he traced out the surface extent of the Turayf phosphate and in a general reconnaissance of the Sirhan-Turayf basin discovered phosphate in the Thaniyat area. Phosphate surface samples collected by him were shipped to Denver and analyzed by James B. Cathcart (1970). About 90 percent of the samples consist of hard, calcareous or siliceous phosphate from the Turayf area, whereas all but a few of the remaining samples were of the unconsolidated phosphate from a small limited part of the Thaniyat area. Cathcart (1970) concluded that it would be possible to produce superphosphate or triple superphosphate from the calcareous and siliceous phosphate rock (surface float samples), but that the cost probably would be excessive to compete in the world market. He (1970) believed that the unconsolidated phosphate was the most promising because it was easily upgraded and might be economic provided the tonnages were large enough and the beds were accessible. The possibility of finding pods or lentils of friable phosphate in the subsurface at Turayf was disclosed upon the detection of loose phosphate pellets by Sheldon (1967) and Mytton (1966, 1967) in sample cuttings from structure test holes drilled in the area years ago by the Arabian American Oil Company.

In April 1966, I was assigned, and joined later by Abdullah Ankary, to work out in detail the geology of phosphate in the Sirhan-Turayf basin in order to explore for a phosphate ore body, and to determine the thickness, grade, and tonnage of the phosphate deposits.


## Acknowledgements

Ahmed Zaki Yamani, Minister, Fadil Kabbani, Deputy Minister, Ghazi Sultan, Director General for Mineral Resources, and others of the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, were constant benefactors of the U.S. Geological Survey exploration program.

Glen F. Brown, Chief of the U.S. Geological Survey Saudi Arabian Project, enthusiastically supported the phosphate exploration effort and helped guide and support day-to-day work. Conrad Martin assisted in ore beneficiation studies and development considerations. V. E. McKelvey, U.S. Geological Survey Staff Geologist, Washington, D.C., visited the project twice and offered valuable and timely advice. Jean Ebrard, mining engineer, advisor to the Ministry of Petroleum and Mineral Resources, advised on sampling and ore-dressing procedures.

The Arabian-American Oil Company (Aramco) provided a set of samples from structure and stratigraphic test wells they drilled in the basin years ago. These gave the first subsurface information.

R.B. Burt and S. Ingle of the Tennessee Valley Authority, Muscle Shoals, Alabama, visited the project, evaluated the data, and completed a preliminary feasibility report on the economic aspects of the West Thaniyat phosphate.

The Parsons and Basil Company provided well logs of water well tests drilled in Wadi Sirhan.

## GEOLOGIC SETTING

The Sirhan-Turayf sedimentary basin consists of rocks ranging in age from Ordovician to Quaternary (Bramkamp and others, 1963). The older rocks are along the southern rim, whereas most of the surface elsewhere is composed of Tertiary or Quaternary rocks. The phosphate rock deposits exist as thin beds in the Upper Cretaceous Aruma Formation and the Paleocene and Eocene Hibr Formation.

The Tabuk Formation, given an Early Ordovician to Early Devonian age range by Powers and others(1966), is at least 1000 meters thick and crops out in the southwestern corner of the basin. It lies disconformably beneath bluff and cliff-forming Cretaceous (Aruma) and Tertiary (Hibr) formations. The Tabuk Formation consists of sandstone that has been weathered black or dark brown by "desert varnish," and forms bare, low, rounded hills. Eastward along the southern rim of the basin, the Lower Devonian Tawil Sandstone Member (upper member of the Tabuk Formation) and younger Devonian Jauf Formation disconformably underlie the Cretaceous (Aruma) and Tertiary (Hibr) rocks. The Tawil

Sandstone Member forms very dark-colored hills similar to middle and lower parts of the Tabuk Formation; the softer less resistant Jauf Formation, about 300 meters thick, forms valleys and low sandy areas.

In the southeastern corner of the basin the Sakaka Sandstone of possible Middle Cretaceous age lies above the Jauf Formation and beneath the Upper Cretaceous Aruma Formation. The Sakaka Sandstone, which is about 285 meters thick, weathers into dark-colored bare, rough, irregular terrain with numerous wadis.

Rocks of the Aruma Formation form the eastern limit of the basin and are in bluffs along the southern rim underlying rocks of the Hibr Formation. The Aruma Formation consists of light-colored limestone, marl, sandstone, and shale. The sandstone in places is very friable and along parts of the southern rim forms a steep slope of loose sand. The Aruma Formation along the southern rim ranges in thickness from about 8 to 67 meters; it thins at the southern tip of the basin and thickens to the east and west. Aramco structure test S-459 drilled in the northeastern desert plains penetrated at least 170 meters of Aruma. Aruma phosphate rock was detected by the senior author in drill cuttings from this structure test in a 6-meter zone at a depth of about 100 meters. Thin beds of phosphate and phosphatic rock are in the bluffs northwest of Al Jauf in the southeastern part of the basin. They are traceable intermittently along the southern rim to southwestern part of the basin. At Thaniyat the phosphate is in a zone

(zone 5) at the top of the Aruma, in contact with the overlying Hibr Formation.

The Hibr Formation ranges in thickness from a meter or so in outcrop at the southern tip of the basin to over 600 meters in the subsurface at the northern end of the structural axis of the basin which apparently coincides with Wadi Sirhan. The formation is composed mostly of alternating limestone, marl, clay, and chert with phosphate units containing beds of phosphate rock. Where phosphate is present in the northern part of the basin, the formation is divided into the upper, phosphate, and lower members. The maximum known thickness of the phosphate member is about 120 meters, deep in the subsurface in Aramco structure test S-451 in the Khawr-umm-Wual graben. However, in the Turayf phosphate area the phosphate member ranges in thickness from a featheredge to 71 meters. Commonly near the top of the member, are several beds of hard, calcareous or siliceous, phosphate rock with individual beds that rarely exceed 2 meters thick.

Unnamed Miocene and Pliocene sandstone, marl, and limestone overlie the Hibr Formation along Wadi Sirhan and in the Khawr-umm-Wual graben below the surficial sediments. The unnamed rocks are 143 meters thick in a well in the graben. The sandstone is red, brown, and gray, marly to calcareous, with conglomerate lenses. The marl is sandy with minor amounts of red, sandy shale. The limestone is white, gray, and brown, and also sandy. The nearly flat-lying beds are eroded and weathered into very light-colored, low, rounded hills. Near the village of Kaf, at the north end of Wadi Sirhan, the Miocene and Pliocene rocks are interbedded with Tertiary and Quaternary basalt sills and flows.

Deposits of Tertiary and Quaternary basalt cover much of the central part of the basin. Basalt flows, sills, dikes, and plugs form the highest hills in the basin, and cones form peaks up to 1125 meters above sea level. A complete section of the basalt sequence is not exposed, but the estimated thickness is about 150 meters.

Quaternary silt and gravel is locally in undrained depressions. Quaternary gravel covers a very large area along the southwestern flank of the basin. Small patches of windblown sand are common everywhere in the basin, and large amounts of dune sand are in the southern part. The Great Nefud, the second largest dune sand area in Saudi Arabia, lies just to the south-southeast of the Sirhan-Turayf basin.

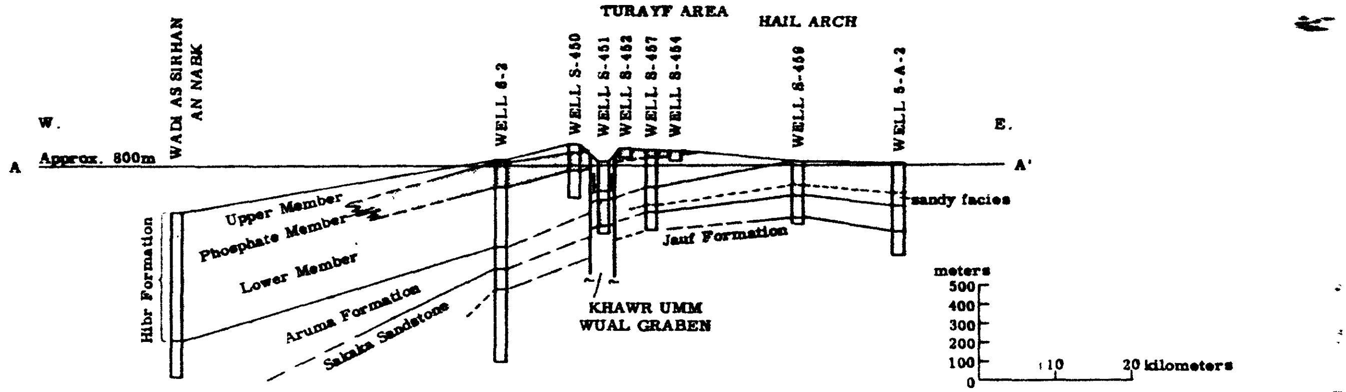
## STRATIGRAPHY

The stratigraphy described herein is largely that of the phosphate-bearing Upper Cretaceous Aruma and Paleocene and Eocene Hibr Formations. For the stratigraphy of other formations in the basin and additional information on the Aruma and Hibr Formations, the reader is referred to a study by Powers and others (1966).

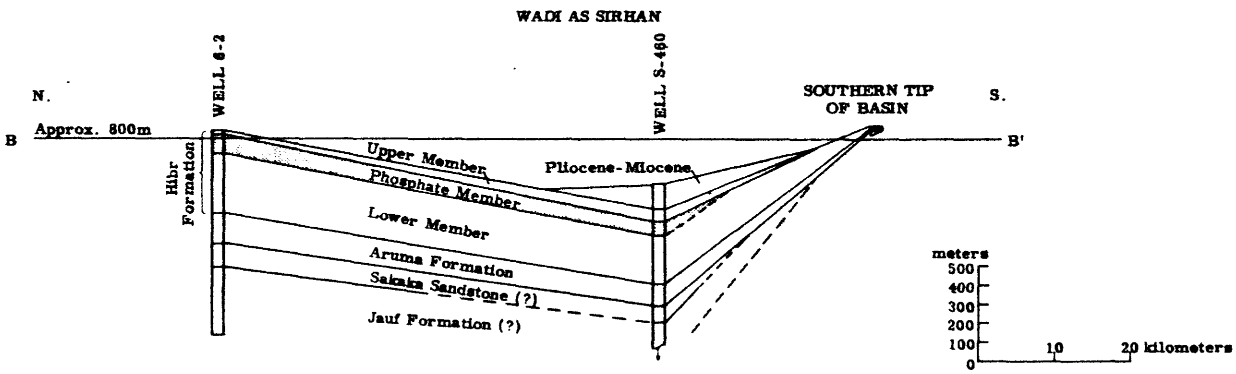
Aruma Formation

The Aruma Formation was named for its exposure on the Al Aramah plateau, a broad upland surface related to the easternmost of the Najd escarpments. Limits of the formation are essentially as they were originally described by Burchfiel and Hoover (Powers and others 1966, p. D79). First formal reference to the Aruma appears in Steineke and Bramkamp (1952). The composite type section is from several sections measured along a traverse from Khashm Khanasir (lat 25°38'12"N., long 46°22'39"E.) northeast to a point on the back slope of the Al Aramah escarpment (lat 25°39'18"N, long 46°23'30"E.), thence northeast to a promontory (lat 25°44'35"N., long 46°30'41"E.) where the top of the formation is exposed.

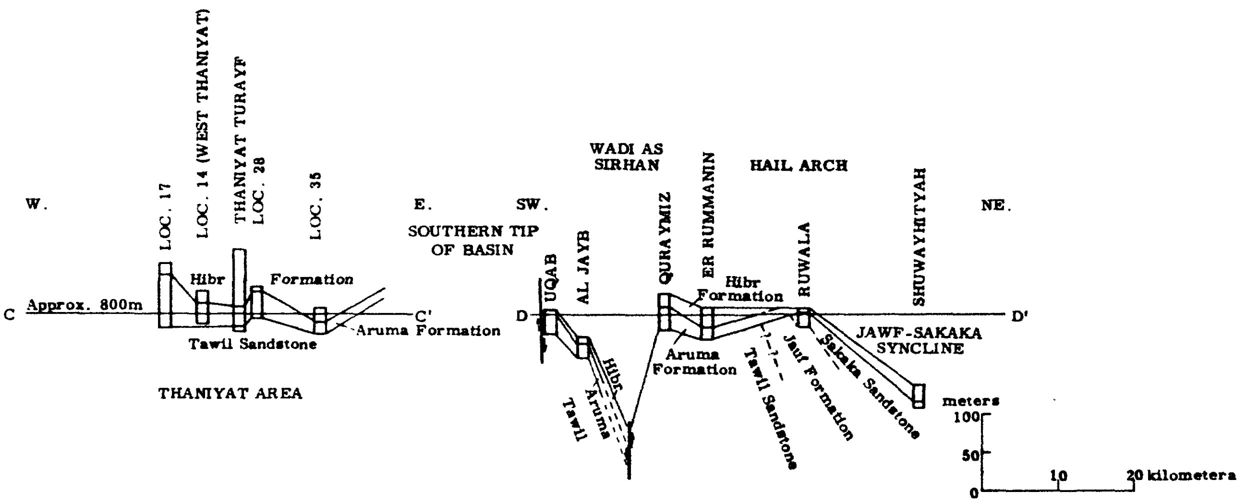
The Aruma Formation in the subsurface of the northern part of the Sirhan-Turayf basin appears to rest upon the Sakaka Sandstone which in turn overlies the Jauf Formation (fig.2, A-A[1]). At Al Jalamid, east of the basin, the Aruma is 213 meters thick in the Trans-Arabian Pipeline Company's (Tapline) water well 5-A-2. The upper two-thirds of the formation is composed of light-colored limestone with a sandstone bed near the center of the unit and sandy limestone near the bottom. The lower one-third of the formation is mostly white sandstone with interbeds of sandy limestone. The Aruma thins slightly westward over a distance of about 40 kilometers to the crest of the Hail Arch. The Aramco structure test well, S-459, on the crest of




CROSS SECTION OF THE NORTHERN PART OF THE SIRHAN-TURAYF BASIN




NORTH-SOUTH CROSS SECTION OF THE SIRHAN-TURAYF BASIN




CROSS SECTIONS OF THE SOUTHERN RIM OF THE SIRHAN-TURAYF BASIN

FIGURE 2.- Cross sections of the Sirhan-Turayf basin.

the Arch, contained a bed of phosphate identified from sample cuttings between 98 and 104 meters deep. The zone was not found in other wells in the northern area, but it may be equivalent to zone 5 phosphate at Thaniyat farther to the south.

The Sirhan-Turayf basin begins west of the crest of the Hail Arch where the Aruma Formation dips very gently to the west into the subsurface beneath the Hibr Formation. The top of the Aruma Formation is cherty in places on the flank of the basin, and the basal sandy unit changes basinward into limestone, marl, and shale. In the An Nabk water well test located in Wadi Sirhan, in the axial region of the basin, the formation (over 180 meters thick) is composed of chert, marl, and argillaceous limestone.

Southward, the Aruma gradually thins to several meters at the southern tip of the basin (fig.2, B-B$^{1}$) and the basal beds again become sandy. The Aruma lies disconformably on the Sakaka and Jauf Formations and at the southern rim it rests upon the Tawil Sandstone Member of the Tabuk Formation.

Complete exposures of what remains of the Aruma Formation are along much of the southeastern rim. At Shuwayhitiyah, slightly east of the rim, the Aruma consists of about 23 meters of light-colored partly sandy limestone and marl. (fig.2, C-C$^{1}$). It thins southwestward for about 40 kilometers to Ruwala where it is only 6 meters thick. The thinning of the unit may be due to erosion. Southwestward from

Ruwala along the southeastern part of the basin rim the formation overlies the Tawil Sandstone. Also along the rim the Aruma is overlain by the Hibr Formation. Thickness of the Aruma along the southeastern rim ranges from 18 to 30 meters and decreases to only a few meters at the southern tip. In the upper part it is mostly sandy or argillaceous limestone, in places phosphatic. In the lower part it contains interbeds of sandstone and shale that are partly phosphatic and cherty. At Quarymiz there are several thin, 30 to 60 centimeter, beds of very shaly phosphate near the base of the formation that contain 14 to 18 percent $P_2O_5$. The sand content increases near the southern tip of the basin where the Aruma consists of light yellowish-brown, marly or sandy limestone and light yellow sandstone. Near Uqab a 5.5 meter bed of sandy limestone, near the top of the formation, has many pelecypod shells. The shells were examined by Erle Kauffman (written commun., 1967) of the U.S. National Museum, Washington, D.C., who identified in one specimen the probable hingeline and partial external mold of an _Inoceramus_. The range of _Inoceramus_ is from Jurassic through Cretaceous, especially Middle and Upper Cretaceous. According to Kauffman (written commun. 1967), this is the "first Near-Eastern _Inoceramus_ ever found."

The Aruma is poorly exposed for 90 kilometers westward from the southern tip of the basin but again is readily traceable in the Thaniyat area along the southwestern rim of the basin (fig.2, $D-D^1$).

At Thaniyat the formation is mostly a very loose, friable, soft, yellow sandstone, which in places near its base is mottled brownish-red and lavendar. It ranges in thickness from about 9 meters on the east side of Thaniyat, thickening westward to over 60 meters on the west side. At the top of the Aruma, in transitional contact with the overlying Hibr Formation, is a zone of sandy phosphate with interbeds of limestone, chert, and shale. This phosphate zone has been designated zone 5 and at West Thaniyat the potentially valuable bed 2 phosphate is at the base of the zone.

The Aruma Formation, northwestward from Thaniyat to the Jordan border, grades from loose sand to limestone, marl, and shale with interbeds of sandstone. The formation is partly phosphatic but does not contain the zone 5 phosphate beds found at Thaniyat nor any other beds of phosphate thick or rich enough to be valuable.

## Hibr Formation

The name Hibr Formation has been defined as an informal term for undivided Paleocene and Eocene rocks in an area of northern Saudi Arabia which includes the Sirhan-Turayf basin (Powers and others, 1966, p. D85). The name is established in the literature and should be regarded as a formal name. Berg and Owens (Powers and others, 1946, p. D85) measured 150 meters of beds from near Al Jalamid (lat 31°18'N.; long 39°54'E.) to Tall al Hibr (lat 31°51'N.; long 38°08'E.). Tall al Hibr is just across the border along the Tapline in Jordan. About

450 meters of the Hibr was penetrated in the Turayf Tapline pump station water well (6-2) east of Tall al Hibr.

The Hibr Formation was divided into three members originally by Mytton (1966) in the Turayf phosphate area, which are the lower phosphate, and upper members. Detailed lithologic description of the members is given in figure 3.

Lower member.-- In the northern part of the Sirhan-Turayf basin the eastern edge of the lower member (and base of the Hibr Formation) is just west of Aramco structure test well S-459 (fig.2, A-A[1]). From this point the member dips very gently westward toward the basin axis along Wadi Sirhan, even though it is down-faulted in the Khawr-umm-Wual graben. Only the lower member remains along the eastern border of the basin, probably because the upper members have been eroded. It ranges in thickness from 120 meters at the surface to over 300 meters in the Turayf water well nearly 80 kilometers west. It is not recognized in the An Nabk water well test in Wadi Sirhan because of the absence of phosphate. The member on the east is composed of white, pink to brownish-red, or yellowish-brown to brown limestone, which is dense to coarsely crystalline, in part sandy and argillaceous, porous and vuggy, and contains chert nodules. There are thin beds of white and yellow-layered, or grayish-brown or black chert. A few beds of calcareous, argillaceous, siltstone, and sandstone are also present. To the west in Aramco structure test well, S-457, there is one bed of friable,

| AGE | FORMATION | MEMBER | THICKNESS (meters) | CHARACTER |
|---|---|---|---|---|
| EOCENE | HIBR FORMATION | UPPER | 0-24 | SUBSURFACE<br>Limestone, white, buff, tan, light-brown, light-gray, pale-yellow, or pink, dense to fine crystalline, rarely coarse crystalline, thin-bedded to massive, partly argillaceous and chalky, in places porous and vugular; in places slightly phosphatic. Thin interbeds of chert, dark-brownish-gray; in places contains fine- to coarse-grained light-colored phosphate grains. Foraminiferal in part.<br>SURFACE<br>Small blocks of light-colored limestone scattered with numerous pieces of dark-weathered tabular chert which breaks into very sharp edges, partly phosphatic.<br>In southern part of area member contains white and light-brown marl and calcareous claystone. |
| | | PHOSPHATE | 0-71 | SUBSURFACE<br>Limestone, white, pale-white, buff, tan, light-brown, yellowish-brown, light-yellow, yellow, pink, mottled white and pink, pale-pink, red, brownish-red, pale-gray, and gray, dense to coarse crystalline to conglomeratic, in places sucrosic; detrital, porous, vugular; in part argillaceous, phosphatic, chalky, fossiliferous (casts and molds), also a few siliceous beds; becomes sandy to the east and south; calcite crystals in vugs; contains thin layers of chert, chert nodules, and chert chips.<br>Marl, clay, claystone, shale, and rarely argillaceous sandstone are found mostly in the lower part of the member, especially in the southern half of the area.<br>Marl, white, cream, pink, mottled-white and yellowish-brown, gray; dense with chert nodules; in places sandy<br>Clay, claystone, and shale, white, buff, yellowish-brown, pink, red, brick-red, reddish-brown; in most places sandy, chalky, calcareous; in a few places shale contains calcite crystals.<br>Chert, white, layered pale-pink and pale-gray, light-gray, gray, grayish-brown, lavendar, pale-gray, gray-banded, dark-brown, phosphatic.<br>Phosphate rock, white, buff, cream, tan, pale- to light-brown to brown, pink, light-gray to gray, fine-grained to conglomeratic or pebbly; calcareous, hard, locally soft and friable, minor amounts of calcareous phosphate with chert nodules or chips and cherty (siliceous) phosphate rock.<br>The number of phosphate beds in the member ranges from 1 to 15, although 3 to 5 beds are most common and most beds are concentrated in zone 1 in the upper part of the member. The thickness of beds ranges from .03 to 3.65 m, but thicknesses of 2 m or more are uncommon and the maximum thickness of 3.65 m was noted in only one core hole.<br>SURFACE<br>Coquinal (pelecypod) chert, weathered dark, rounded stones up to 30cm in diameter scattered in belts and patches on the surface mark the top of the member.<br>Chert, gray, black, black with white coating; small rounded pieces.<br>Phosphatic chert, dark-gray or brown with light-colored grains of phosphate, irregular shaped slabs, chips, and pieces.<br>Cherty phosphate rock, dark-gray, grayish-brown; irregular small slabs.<br>Limestone, white, light-brown, light-gray, reddish-brown, purple; dense to crystalline, in part sandy, argillaceous, phosphatic, chalky; small blocky pieces.<br>Phosphate rock, white, light-brown, calcareous, hard, with close packed oolites and pellets of phosphate; small rounded pieces.<br>The resistant cherty material abundant on the surface is a minor part of the member. |
| PALEOCENE | | LOWER | 174 | SUBSURFACE<br>Limestone, white, pink, red, brownish-red, light- to yellowish-brown, brown; dense to coarse crystalline, silty, sandy, argillaceous, in part porous and vugular; contains chert nodules; detrital and friable in part, rarely slightly phosphatic, veins and crystals of clear calcite in upper part of member.<br>Chert, white and yellow to grayish-brown or black. Foraminiferal in places.<br>Few interbeds of white siltstone and a bed of gray sandstone, fine-grained, calcareous, argillaceous, containing black chert.<br>One friable, calcareous phosphorite bed approximately 1.5 m thick near top of Paleocene(?)<br>SURFACE<br>Chert, yellow, laminated, tabular.<br>Limestone, purple, lavendar, yellow, mottled white, reddish-brown, and light-green; laminated, pock-marked, argillaceous and sandy, chunks and pieces. |
| CRETACEOUS | ARUMA FORMATION | | | Top of formation is limestone, white to light-brown, dense to fine-crystalline. |

FIGURE 3.- Generalized section of strata in the Turayf phosphate area.

calcareous phosphate, about 1½ meters thiick. It is at a depth of 175 meters and near the top of the lower one-third of the member. This bed may be near the top of the Paleocene according to J. F. Mello (written commun., 1967) who identified two Paleocene Eponides from the phosphatic interval. The phosphate was not found elsewhere in the northern area. It lies far below the base of the phosphate member and may be related to phosphatic beds in the lower member along the southern rim of the basin. The lower member grades laterally in the subsurface into mostly dolomite and chert in the Turayf water well, and into the lower part of the Hibr Formation in Wadi Sirhan which is mostly marl with some chert. Southward from the northern area the member is identified in Aramco structure test S-460, which is near the southern end of Wadi Sirhan (fig.2, B-B[1]). In this well it consists of limestone and chert with interbedded marl, about 260 meters thick. The lower part of the member contains beds of dolomite and chert which are underlain by fossiliferous limestone and shale. The basal shale contains Globigerina triloculinodes and Globorotalia, that are believed to be of Paleocene age by Mello (written commun., 1967). The member apparently continues southward in the subsurface for some distance until it outcrops and forms the surface along the southern part of the basin. Here it is the only part of the Hibr Formation that remains, which is only a few meters thick at the southern tip of the basin.

Complete exposures of the remaining part of the member are found along the southern rim of the basin (fig.2, C-C[1]). The eroded edge of the lower member is between Ruwala and Er Rummanni on the south-eastern rim, and at Er Rummanni it is about 23 meters thick. The member is composed of light-gray and light-brown limestone with gray chert. There is one 30-centimeter thick bed of cherty, calcareous phosphate rock near its base that contains about 14 percent $P_2O_5$. The member thins southwestward along the rim to 6 meters or less at the southern tip of the basin. The low grade, cherty, calcareous phosphate rock apparently is continuous in this area with thicknesses up to 90 centimeters and ore grades ranging from less than 10 to 21 percent $P_2O_5$. This layer of phosphate rock may be related to the bed of Paleocene phosphate previously discussed that is in the lower member deep in the subsurface (Aramco S-457) in the northern area of the basin.

The lower member is difficult to trace around the southern tip of the basin because it is covered by sand and gravel in many places. However, it is well exposed on the southwestern rim in the Thaniyat area and forms most of the surface of that area (fig.2, D-D[1]). At Thaniyat it rests in transitional contact on top of the Aruma Formation, just above the zone 5 phosphate. The maximum continuously exposed vertical thickness of the member in the Thaniyat area is at Thaniyat Turayf where about 100 meters were measured. The lower part of the section consists of limestone that is white, earthy, massive to thick-or medium-bedded, porous, with some slightly sandy layers. The rest of the section is white to very pale yellow, marl and limestone with large chert nodule layers and geodal lenses.

A zone of noteworthy phosphate (zone 4) is from 45 to 65 meters above the base of the member (base of the Hibr Formation) and the top of zone 5 in the Thaniyat area. It is associated with a black chert bed near the middle of the zone that can be easily traced on the surface or on aerial photographs as it forms a noticeable bench mantled with fragments of dark chert. Zone 4 consists of one to three beds above the chert bed and one or two beds below it. The zone is about 5 meters thick and the phosphate beds range in thickness from a few centimeters to 60 centimeters. The thin phosphate beds range in grade from about 21 to 30 percent $P_2O_5$. In many places the upper bed of zone 4 phosphate is very soft and friable, whitish-gray in color, and contains small fish teeth. The lower beds of phosphate are mostly hard, light-colored, and composed of a calcareous or siliceous matrix. This zone of phosphate may be related to the phosphate bed previously described in the lower member along the southern rim of the basin and in the subsurface in the northern area. Zone 4 is an important stratigraphic marker, especially at West Thaniyat where it is widely exposed and serves as a reference plane to estimate drilling depths to the top of zone 5 phosphate.

In Wadi umm-Urta, in the northern part of the Thaniyat area, an outcrop section was measured and sampled which includes most of the upper part of the lower member. Two samples from this section contained Globigerina, and Globorotalia, which, according to Mello (written commun., 1967), may be late Paleocene in age. Thus all of the lower member, i.e., all of the Hibr Formation in the Thaniyat area, is probably Paleocene in age.

Phosphate member.-- The phosphate member of the Hibr Formation overlies the lower member in much of the northern area of the Sirhan-Turayf basin (fig.2, A-$A^1$). It includes the major beds of phosphate rock located in the Turayf area.

The base of the member crops out about 8 kilometers east of Aramco well S-454 and marks the eastern edge of the Turayf phosphate area. The member has a very gentle westerly regional dip. It is down-faulted in the Khawr-umm-Wual graben, and warped along the east side of the graben where there are some local easterly dips. The member forms most of the surface along the eastern side of the Turayf phosphate area and in other parts of the phosphate area where the upper member is absent. Maximum thickness of the phosphate member in the Turayf phosphate area to the east of the Khawr-umm-Wual graben is 71 meters as obtained from core drilling data. The member is composed of limestone that is white to yellow to brown, and pink to brownish-red or gray, dense to conglomeratic, porous and vuggy, in part argillaceous, chalky, and phosphatic. The limestone also has thin layers of chert, chert nodules, and chert chips. Marl and clay are in the lower part of the member. The marl ranges in color from white to pink to yellowish-brown and gray. It is sandy in places. The chert is vari-colored, including white, pink, lavendar, gray, and dark brown. It is locally phosphatic. The number of phosphate beds varies from 1 to 15, but 3 to 5 beds are most common; most of them are concentrated near the top of the member (zone 1). In addition, phosphate zones 2 and 3 are in the area. The phosphate beds are described in detail in the chapter on phosphate deposits.

The phosphate member is probably Eocene in age inasmuch as J.F. Mello (written commun., 1967) described the phosphate bed in the lower member of Aramco S-457 well as probably uppermost Paleocene in age. The base of the phosphate member is 150 meters above this bed. The member is abnormally thick (over 120 meters) in the Khawr-umm-Wual graben where deposition may have been contemporaneous with down-faulting. In Turayf pump station water well (6-2) it is about 107 meters thick.

The phosphate member is almost entirely overlain by the upper member west of the Khawr-umm-Wual graben, west of the Turayf phosphate area. The member changes facies in the subsurface west of the Turayf pump station. Phosphate of zone 1 is absent (although zone 2 and zone 3 are present) in the Turayf well where the zone is mostly phosphatic limestone and chert. All phosphate material is absent in the An Nabk well located in the axial region of the Sirhan-Turayf basin. The equivalent interval at An Nabk is marl, chert, and some dolomite.

The member apparently is continuous in the subsurface southward from the northern area of the basin as it is present in Aramco well S-460 (fig.2, B-B[1]). Here it is 76 meters thick and consists of phosphatic and dolomitic limestone, dolomite, cherty limestone, and marl. Some phosphatic layers, with possibly a thin low grade zone 1 phosphate bed, are at a depth of 210 meters. The member pinches out south of well S-460 in the area north of the southern rim of the basin.

The phosphate member is not recorded in water well tests drilled in Wadi Sirhan. Its lithologies are unknown on the west flank of the basin in Saudi Arabia as it is covered by Quaternary deposits. Most of the member on the west flank of the basin is in Jordan.

Upper member.-- The upper member of the Hibr Formation in the northern area of the basin overlies the phosphate member in part of the Turayf phosphate area. The upper member forms the surface from the top of the west bank of the Khawr-umm-Wual graben, westward past the Turayf pump station, up to the basalt fields about 30 kilometers west of the station (fig.2, A-A[1]). The basalt fields cover the area up to Wadi Sirhan near where the top of the undifferentiated Hibr Formation is exposed along the part of the west flank of the basin that is not in Jordan. The member ranges in thickness from a few meters, where heavily eroded, to possibly 100 meters or more basinward. The surface of the member forms a broad, flat, monotonous, gravel-strewn desert plain. The upper member is buried in the Khawr-umm-Wual graben by as much as 150 meters of the Miocene and Pliocene sediments.

The member consists of limestone, chert, and in places, marl and calcareous claystone. The limestone is white to light brown or light gray, pale yellow, or pink. It is dense to finely crystalline, (rarely coarsely crystalline), thin bedded to massive, and partly argillaceous and chalky. The limestone is slightly phosphatic in places. The chert is in the form of thin interbeds, nodular lenses and geodal lenses. It is dark brownish-gray, and in part contains fine-to coarse-grained, light-colored phosphate grains and foraminfera tests. Locally there are beds of white to light-brown marl and claystone.

The upper member forms the surface southward from the Turayf pump station to where it is buried by basalt flows, or covered by large thicknesses of Miocene and Pliocene sediments in Wadi Sirhan as revealed in Aramco S-460 well (fig.2, B-B[1]). In this well the member is 60 meters thick and it is mostly limestone, chert, and marl, with a 6-meter thick gypsum bed at the top. The member pinches out north of the southern rim area of the basin.

## STRUCTURE

The Sirhan-Turayf sedimentary basin is bounded on the east by the Hail Arch, on the south by Paleozoic rocks associated with the

Arabian Shield uplift, and on the west by the Dead Sea rift area. To the north it apparently opens into the Mediterranean basin of Jordan. The axis of the basin trends northwest along Wadi Sirhan, which has the lowest elevation and in general the thickest sedimentary section. In most places the dip of the beds is very low, ranging from ½ to 3°. At a few places, adjacent to faults, the dip is as much as 29°. The strike differs around the basin. It trends north on the east flank, but deviates around the southern area to a northwesterly strike on the west flank where the beds form a long gentle dip-slope. Most of the west flank is in Jordan.

The basin is criss-crossed with faults or fractures and grabens which are probably related to the Dead Sea rift belt of Jordan. Most faults strike due north to 30°W. or N.70° to 90°W. In places there are three sets of faults oriented north-south, northwest-southeast, and east-west. These faults intersect each other and are readily visible on aerial photographs but very difficult to distinguish on the ground. Displacement of most of them cannot be measured because of the lack of exposure, but it is probably slight. Small grabens are inferred on the surface by long narrow slightly depressed areas. The Khawr-umm-Wual graben in the northeastern part of the basin is formed by a complex of faults oriented about N.30°W., which has resulted in a displacement of more than 200 meters in the subsurface (fig.2, A-A$^{1}$). Surface relief, however, is as much as 60 meters between the floor of

Khawr-umm-Wual and the top of the flanking hills; it is a result of sedimentary fill. Subsurface evidence has revealed thickening of the Hibr Formation in the graben, which suggests that deposition was contemporaneous with down-faulting during Paleocene-Eocene time. About 150 meters of Miocene and Pliocene rocks are also in the graben. Khawr-umm-Wual is from 5 to 7 kilometers wide and about 100 kilometers long; the displacement on the faults decreases markedly to the north and presumably to the south according to subsurface data. This long, broad depression is the approximate western boundary of the Turayf phosphate area. A major fault with a displacement of about 150 meters is along the southeastern end of Wadi Sirhan and it bisects the southeastern flank of the basin (fig.2, C-C$^1$). Jabal Quarymiz, which contains some phosphate, is in the upthrown block north of the fault, and the Hibr Formation is in the downthrown block on the south side of the fault. A small northwesterly trending fault is south of Al Jayb, and it is downthrown to the north with an estimated vertical displacement of 75 meters. The displacement at the rim of the basin may be coupled with horizontal movement, resulting in a 5-kilometer lateral offset in the exposed rocks. In the northern part of the Thaniyat area, near the southwestern rim of the basin, several parallel grabens have been identified from their surface expression in the Hibr Formation. The grabens are oriented N.22$^{\circ}$W., up to 1 kilometer wide, several kilometers long, and have a maximum vertical displacement of 50 meters from the graben floor to flanking hill tops.

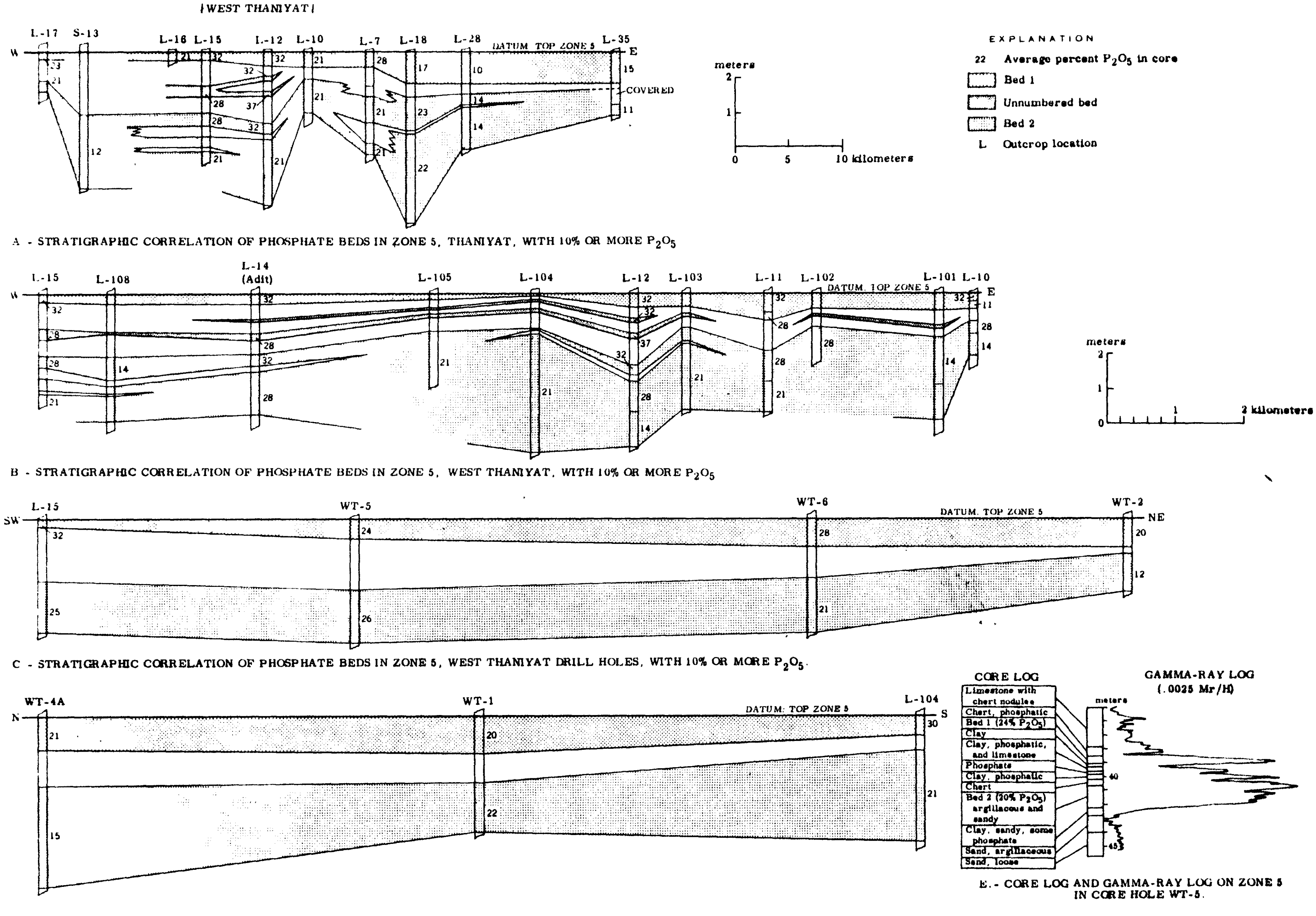
The Hail Arch, which originates south of the Great Nefud, probably extends in the subsurface along the eastern side of the Sirhan-Turayf basin. The crest of the Arch may extend in the vicinity of Aramco well S-459 (fig.2, A-A[1]). The Sakaka Sandstone and Jauf Formation are truncated in the structurally high area of Ruwala, but to the north they dip both east and west from well S-459. The westerly dip persists into the Sirhan-Turayf basin except for local reversals noted in the Turayf phosphate area due to folding along the east flank of the Khawr-umm-Wual graben. The cross-section along the southern rim of the basin is complicated by faulting and tilting in the lower part of the basin (fig.2, C-C[1]). On the southwestern rim, in the Thaniyat area, the beds have a very gentle northeasterly dip of about one-half degree. The north-south cross-section, which trends diagonally across the basin axis (fig.2, B-B[1]), shows opposing dips toward the axis.

## PHOSPHATE DEPOSITS

### Thaniyat phosphate deposits (West Thaniyat)

The Thaniyat phosphate area includes the southwestern rim of the Sirhan-Turayf sedimentary basin between 29°22½'N.- 30°07½'N., and long 37°43'E.- 38°22½'E. The part of the Thaniyat area described herein includes the phosphate outcrops and the area of core drilling at West Thaniyat, and lies between lat 29°35'N. and 29°50'N., and long 37°43'E.- 38°17'E. (pl.2). The rim of the basin of the Thaniyat area forms an easterly trending bluff or cliff that contains the Aruma and Hibr Formations. At the top of the Aruma, in transitional contact with the overlying Hibr, is a zone of phosphatic material that is designated zone 5. The zone has been traced, sampled, and measured for more than 60 kilometers to where it apparently pinches out east of the Thaniyat area, about 15 kilometers southeast of Thaniyat Rilan, to where it changes laterally into limestone, marl, and chert west of the area near outcrop locality 17.

Much of the zone is partly covered with talus from cliff-forming limestone of the Hibr Formation. However, exposures of zone 5 are adequate to define the thickness and grade of the phosphate beds. A correlation section of zone 5 (fig.4A) extends from locality 17 to locality 35 near Thaniyat Rilan and illustrates the thickness and lateral variation of the zone from west to east across the Thaniyat area. Other sections were sampled but are not included on figure 4. At locality 17 the zone, 1.15 meters thick, has a thin bed of phosphate at the top and bottom separated by limestone and chert. The top bed of phosphate is traceable across the area to locality 35 to the east, a strike distance of about 50 kilometers. It is designated bed 1 and ranges in thickness from 10 to 90 centimeters and in grade from 10 to 32 percent $P_2O_5$. The bed generally thickens eastward where it contains a lower grade phosphate. The thin bed of phosphate at the bottom of zone 5 at locality 17 is also traceable across the area to locality 35. It thickens and is richer in phosphate in the West Thaniyat




A - STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONE 5, THANIYAT, WITH 10% OR MORE $P_2O_5$

B - STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONE 5, WEST THANIYAT, WITH 10% OR MORE $P_2O_5$

C - STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONE 5, WEST THANIYAT DRILL HOLES, WITH 10% OR MORE $P_2O_5$.

D. - STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONE 5, WEST THANIYAT DRILL HOLES, WITH 10% OR MORE $P_2O_5$

E. - CORE LOG AND GAMMA-RAY LOG ON ZONE 5 IN CORE HOLE WT-5.

FIGURE 4 - Stratigraphic correlation of phosphate beds in zone 5 in the Thaniyat phosphate area, includes comparison between core log and gamma-ray log on zone 5 in core hole WT-5

area. This bed, designated bed 2, ranges in thickness from about 30 centimeters to 3.65 meters and in grade from 11 to 25 percent $P_2O_5$. The average grade of bed 2 from locality 17 to locality 35 is about 18 percent $P_2O_5$, and the average thickness (excluding barren beds between the phosphate layers) is about 1.80 meters. Both bed 1 and bed 2 are very soft, friable phosphate with quartz sand and clay impurities. Between bed 1 and bed 2 of zone 5 there are from .30 to 1.65 meters of limestone, shale, and chert which in places are interbedded with thin beds of phosphate containing as much as 37 percent $P_2O_5$. The average thickness of the zone 5 outcrop in the Thaniyat area is about 3.20 meters. The zone dips only about one-half degree northeast from the cliff face under 20 to 100 meters or more of Hibr limestone and chert.

West Thaniyat, which contains the thickest and richest phosphate beds of zone 5, is between 29°40'- 29°50'N. and long 37°52'- 37°59'E. in the west-central part of the area. Here zone 5 is exposed along a 50 to 90-meter or more high, south-facing, steep bluff or cliff with an undulated surface along the east-west strike. The zone is about 30 meters above the base of the bluff, and the higher grade phosphate extends for a distance of about 10 kilometers.

The top of zone 5 at West Thaniyat is at the base of a thin-bedded chert unit 1 to 3 meters thick. This chert is at the base of the Hibr Formation. The zone in the cliff face is not offset by faults;

however, there is some slumping in the zone. The base of the zone is near the top of non-phosphatic, loose, white or yellowish-white, quartz sand that in most places has a yellowish-brown ferruginous layer about 30 centimeters thick at its top.

Bed 1 underlies the basal chert of the Hibr and ranges in thickness from 10 to 80 centimeters, averaging 35 centimeters. Its grade ranges from 11 to 32 percent $P_2O_5$, averaging 28 percent $P_2O_5$ (fig.4). Bed 1 is very soft and friable, contains marl and, in places, quartz sand impurities.

As previously mentioned, between bed 1 and bed 2 there is an interval of limestone shale, siltstone, and chert that in most places at West Thaniyat has one or two thin beds of phosphate. The interval ranges in thickness from about .35 to 1.65 meters; its upper part consists of shale, siltstone or limestone, and phosphate. Between localities 14 and 12, a strike distance of about 3 kilometers, there are two beds of phosphate in the interval. The upper bed ranges in thickness from about 5 to 15 centimeters and contains about 32 percent $P_2O_5$. The lower bed ranges in thickness from 8 to 15 centimeters and in grade from 28 to 37 percent $P_2O_5$. It is almost continuous between locality 15 and 10 across West Thaniyat (fig.4B). Below this thin phosphate there is a persistent chert bed that forms a capping layer of bed 2. The chert bed ranges in thickness from 25 to 75 centimeters.

Phosphate bed 2 comprises the lower one half to two thirds or more of zone 5 at West Thaniyat and in outcrop ranges from 1 to 2.60 meters, averaging 2.00 meters thick; it contains 14 to 25 percent $P_2O_5$, averaging 21 percent $P_2O_5$, including local non-phosphatic partings. A somewhat higher average grade of $P_2O_5$ and lower average thickness was obtained in a core.

Six core holes were drilled north of the bluff to determine the extent of zone 5 in the subsurface at West Thaniyat. The holes ranged in depth from 30 meters to 103 meters due mostly to variations in terrain (table 1).

Zone 5 trends north-northwestward from the outcrop, thickening in that direction and thinning both east and west (fig.5A). Thickness of the zone, according to surface and subsurface information, ranges from 1.80 meters in outcrop at locality 10 to 4.90 meters in core hole WT-4a (fig.4C). Waste-rock to ore ratios range from .24:1 on the east side of the area, to 1.6:1 on the west side. Ore thickness includes only bed 1 and bed 2, whereas the thin phosphate beds interbedded in the intervening waste-rock are included with the waste.

The aggregate thickness of phosphate bed 1 plus bed 2 in zone 5 ranges from about 1.23 to 3.05 meters and grade from about 16 to 28.5 percent $P_2O_5$ (fig.5B). About 50 square kilometers of West Thaniyat is underlain by aggregate zone 5 ore which is 1.50 meters or more thick, and has a grade of 20 percent $P_2O_5$ or more (fig.5B). Here the ore has

Table 1. West Thaniyat phosphate core holes.

| Name | Coordinates | Elev. above sea (meters) | Total depth (meters) | Commenced | Completed | Depth (meters) | Zone 5 Thick-ness (meters) | Aggreg. Thickness Phos. beds | Av. $P_2O_5$ grade | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| WT-1 | lat 29°44'39"N. long 37°54'49"E. | 945 | 103.30 | Nov. 4, 1968 | Dec. 11, 1968 | - | - | - | - | Core barrel stuck at 60.50 m. moved 1 m. and redrilled same location |
| Zone 5 | - | - | - | - | - | 97.90-101.20 | 3.30 | 2.10 | 21% + | |
| Bed 1 | - | - | - | - | - | 97.90-98.95 | 1.05 | .85 | 20% + | |
| Bed 2 | - | - | - | - | - | 99.80-101.20 | 1.40 | 1.25 | 22% + | |
| WT-2 | lat 29°44'40"N. long 37°57'52"E. | 841 | 46.30 | Dec.15, 1968 | Jan. 16, 1969 | - | - | - | - | Mostly chert from surface to Zone 5. Estimated average $P_2O_5$ grade. |
| Zone 5 | - | - | - | - | - | 41.40-43.50 | 2.10 | 1.40(?) | 16% | |
| Bed 1 | - | - | - | - | - | 41.40-42.20 | .80 | .60(?) | 20% + | |
| Bed 2 | - | - | - | - | - | 42.40-43.50 | 1.10 | .80% | 12% | |
| WT-3a | lat 29°44'44"N. long 37°51'46"E. | 947 | 73.60 | Apr. 17, 1969 | Apr. 30, 1969 | - | - | - | - | WT-3 core recovery unsatisfactory. Moved few meters and redrilled same location. |
| Zone 5 | - | - | | - | - | 69.05-72.35 | 3.30 | 2.20 | 19% | |
| Bed 1 | - | - | - | - | - | 69.05-70.75 | 1.20 | .55 | 20% | |
| Bed 2 | - | - | - | - | - | 70.50-72.35 | 1.85 | 1.65 | 18% | |
| WT-4a | lat 29°46'56"N. long 37°53'14"E. | 892 | 68.50 | Apr. 8, 1969 | Apr. 15, 1969 | - | - | - | - | WT-4 core barrel stuck at 77.20 m. shifted 3/4 km. SSW and redrilled. Estimated average $P_2O_5$ grade |
| Zone 5 | - | - | - | - | - | 60.20-65.10 | 4.90 | 3.05 | 18% + | |
| Bed 1 | - | - | - | - | - | 60.20-61.15 | .95 | .95 | 21% + | |
| Bed 2 | - | - | - | - | - | 62.20-65.10 | 2.90 | 2.10 | 15% | |
| WT-5 | lat 29°43'13"N. long 37°53'18"E. | 927 | 45.70 | May 3, 1969 | May 12, 1969 | - | - | - | - | |
| Zone 5 | - | - | - | - | - | 38.55-42.15 | 3.60 | 1.98 | 25% | |
| Bed 1 | - | - | - | - | - | 38.55-39.10 | .55 | .55 | 24% | |
| Bed 2 | - | - | - | - | - | 40.60-42.15 | 1.55 | 1.43 | 26% | |
| WT-6 | lat 29°43'13"N. long 37°56'25"E. | 869 | 30.00 | May 14, 1969 | May 19, 1969 | - | - | - | - | |
| Zone 5 | - | - | - | - | - | 26.25-29.55 | 3.30 | 2.40 | 24% | |
| Bed 1 | - | - | - | - | - | 26.25-27.05 | .80 | .80 | 28 | |
| Bed 2 | - | - | - | - | - | 27.95-29.55 | 1.60 | 1.60 | 21 | |



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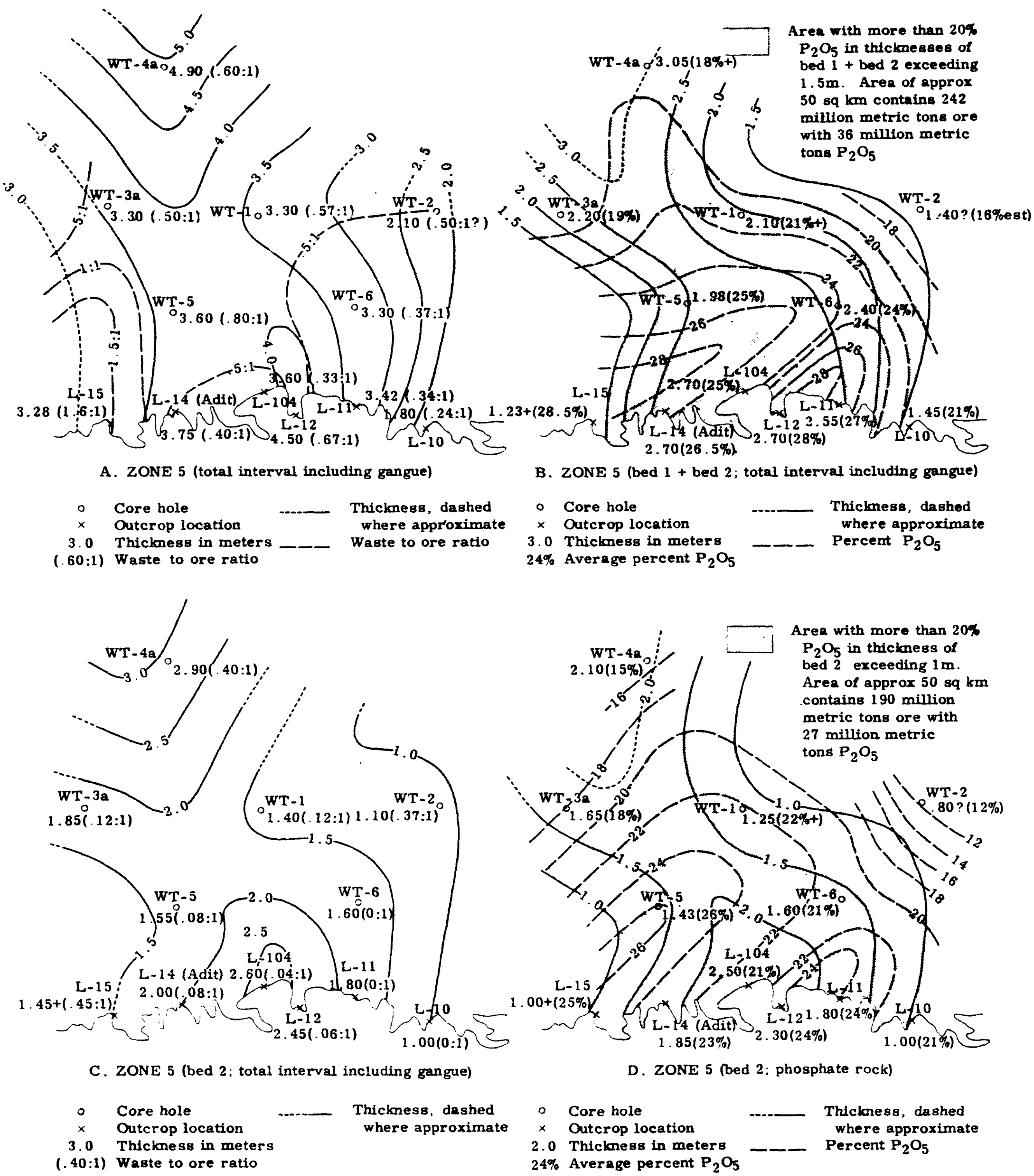



FIGURE 5.- Isopach maps of phosphate zone 5, West Thaniyat, with percent $P_2O_5$ and waste to ore ratios.

an average thickness of 2.10 meters, and average grade of 24 percent $P_2O_5$. Calculated tonnage of $P_2O_5$ concentrate in the 50 square kilometer area is about 36,000,000 metric tons, or roughly 242,000,000 metric tons of ore (specific gravity 2.3).

Bed 1 alone is too thin to mine in most places as it ranges in thickness from 20 to 95 centimeters, but it would be possible to mine bed 2 alone. In fact the original preliminary economic feasibility report by Burt and Ingle (1968) was for bed 2 at West Thaniyat.

Bed 2 trends north-northwestward from the outcrop and thins to the east and west (fig.5C). The bed, according to surface and subsurface data, ranges in thickness from 1 to 2.90 meters. The waste-rock to ore ratio is very low, ranging from no waste rock in the bed, to a maximum of .45:1 (fig.5C). The total thickness of bed 2 increases northwestward but the grade decreases to less than 20 percent $P_2O_5$.

Aggregate thickness of phosphate bed 2 ranges from .80 to 2.50 meters, and grade from 12 to 26 percent $P_2O_5$ (fig.5D). About 50 square kilometers of West Thaniyat is underlain by aggregate bed 2 ore, which is 1 meter or more thick and has a grade of 20 percent $P_2O_5$ or more. In this area the ore has an average thickness of 1.65 meters and average grade of 23 percent $P_2O_5$. Calculated tonnage of $P_2O_5$ concentrate in the 50 square kilometer area is 27,000,000 metric tons, or about 190,000,000 metric tons of ore (specific gravity - 2.3).

Faults were not detected by core drilling at West Thaniyat where, in fact, structure contours drawn on top of zone 5 show a uniform regional dip of 37' NE. North of the bluff, however, there is a normal fault in the western part of the area, to the southeast of core hole WT-3a. It strikes about N.17°W. and is downthrown on the west with a displacement of about 20 meters. A graben is in the central part of the area west of core hole WT-1. It also strikes about N.17°W., is about 3 kilometers long, one-half kilometer wide, and the downthrown block has a maximum displacement of 25 meters.

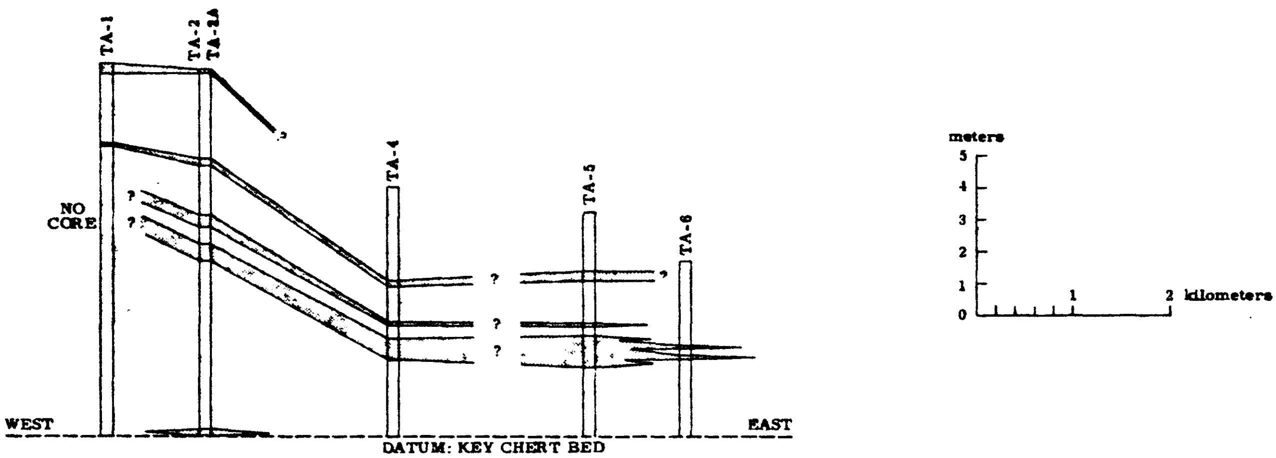
## Turayf phosphate deposits

The Turayf phosphate area is in the northeastern part of the Sirhan-Turayf basin between 31°10'N.- 32°00'N., and long 38°56'E.- 39°30'E. (pl.3). In this area the Hibr Formation forms a flat, monotonous, desert plain except for gentle hills along the west side adjacent to the Khawr-umm-Wual graben. Volcanic basalt rock form low peaks at several places on the west side of the graben. Most phosphate beds are in a triangular-shaped area about 2,000 square kilometers in size east of the Khawr-umm-Wual graben.

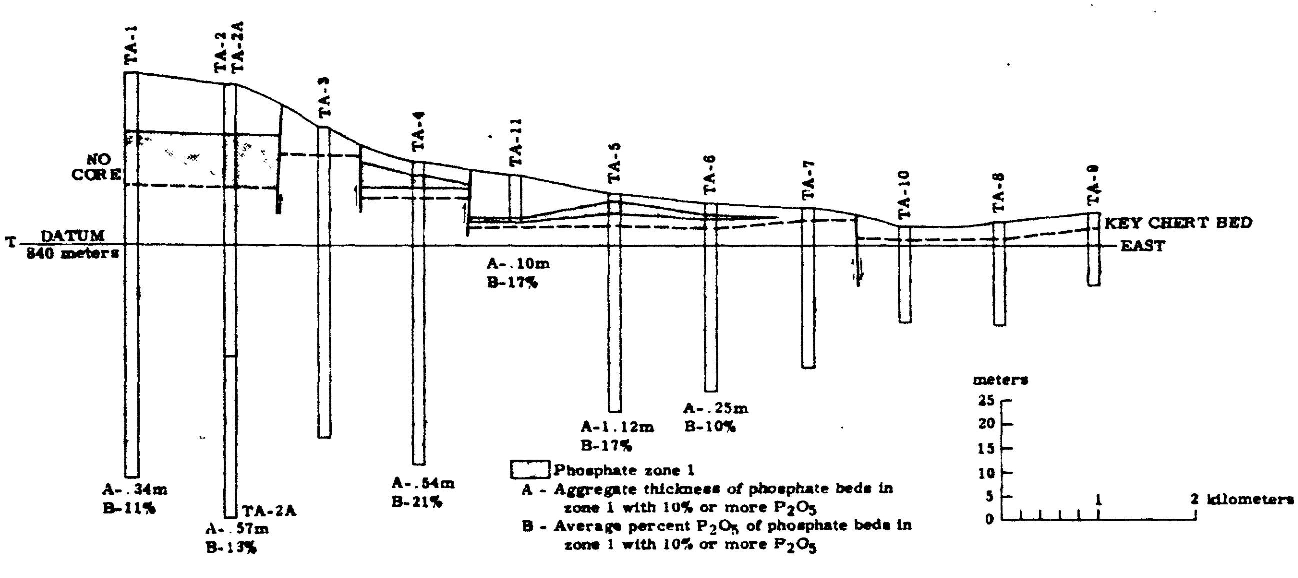
Fifty-two core holes were drilled to evaluate the phosphate rock in the Turayf area where in most places the rock is found only as float in the desert residium. Forty holes are along two lines. The first line of eleven core holes, designated TA, was drilled 500 meters north and parallel to the Trans-Arabian pipeline beginning north of Trans-Arabian pipeline kilometer marker 752 on the west, and ending north of pipeline kilometer marker 742 on the east (lat 31°31'06"N.; long 39°18'11"E. to lat 31°28'54"; long 39°24'19"E.). The holes, spaced at 1 kilometer intervals, are alined across the Turayf phosphate discovery area. The holes range in depth from about 15 meters to 90 meters; the deep holes are at the west end of the line, near where the top of the phosphate member is in contect with the upper member of the Hibr Formation. The phosphate member thins eastward, mostly by erosion, to where its base is in contact with the top of the lower member.

Along line TA there are several thin layers of low grade phosphate rock between core holes TA-1 and TA-6 (fig.6). The maximum thickness of any one layer of phosphate was 97 centimeters penetrated at depths between 3.87 and 4.84 meters in hole TA-5. This bed is a hard, calcareous, partly cherty phosphate with an average content of 16 percent $P_2O_5$. It thins to one-half meter or less about 1 kilometer east and west of the hole.

The phosphate beds along line TA are in a flat-lying zone designated zone 1 near the top of the phosphate member at depths ranging from 1½ to 12 meters; Zone 1 ranges in thickness from less than 1 meter to 11 meters; it pinches out between core holes TA-6 and TA-7. Aggregate thickness of phosphate rock in the zone ranges from .25 to 1.12 meters, excluding limestone and chert interbeds and any rock




STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONE 1 WITH 10% OR MORE $P_2O_5$




STRUCTURAL CROSS SECTION OF PHOSPHATE ZONE 1

FIGURE 6.- Stratigraphic correlation and structural cross sections of phosphate zone 1 along TA line of core holes.

with less than 10 percent $P_2O_5$. Average grade of the phosphate rock ranges from 10 to 21 percent $P_2O_5$. Several faults intersect this line which offset zone 1 as much as 7 meters.

The second line of core holes, designated TB, is about 17 kilometers north of the TA line. The line begins near the Khawr-umm-Wual graben on the west and extends eastward for about 28 kilometers (lat 31°39'17"N.; long 39°06'31"E. to lat 31°39'24"N.; long 39°23'59"E.). This line of 29 holes, spaced at about 1 kilometer intervals, extends across the widest exposure of the phosphate member in the Turayf area. The holes range in depth from 10 meters to 30 meters; the deep holes are at the west end of the line where the top of the phosphate member is in contact with, or overlain by, the upper member of the Hibr Formation. From 1 to 6 layers of phosphate are between core holes TB-1 and TB-23 (fig.7). All phosphate is in zone 1, ranging in depth from the surface on the east to 30 meters or more on the west where the top of the holes are in the upper member of the Hibr Formation. The nearly flat-lying zone ranges in thickness from 1 to 10 meters, and pinches out east of core hole TB-23. Aggregate thickness of phosphate rock ranges from .38 to 7.75 meters, and the average grade ranges from 11 to 23 percent $P_2O_5$. These data do not include limestone and chert interbeds and any rock with less than 10 percent $P_2O_5$. Most phosphate beds are calcareous, firmly cemented, hard, and locally with cherty and siliceous material. However, soft, friable, marly phosphate was encountered at the base of zone 1, first in TB-2, within what subsequently was found to be the highest grade phosphate of the Turayf phosphate area. Five block faults intersect the TB line and they displace zone I phosphate as much as 15 meters.

Drilling of the TA and TB lines of core holes showed the continuity of the phosphate zone so that core drilling exploration in the Turayf area was adequately completed with six widely spaced wildcat holes (table 2). These holes verified that zone 1 phosphate is continuous from north to south along the Turayf area, and that there are two other discontinuous phosphate zones below zone 1 (fig.8). Zone 1 extends over a distance of about 90 kilometers from the northernmost core hole TD-2 to the southernmost core hole TE-1, and farther south to the south end of the Turayf area where it was exposed by trenching at locality 86. Along this line zone 1 ranges in thickness from 1.95 meters to 8.30 meters and contains 3 to 6 beds of phosphate with aggregate thicknesses (excluding rock with less than 10 percent $P_2O_5$) ranging from 40 centimeters to 3.87 meters. Average grade of phosphate ranges from 13 to 20 percent $P_2O_5$. Most of the phosphate is hard, calcareous, and in places cherty.

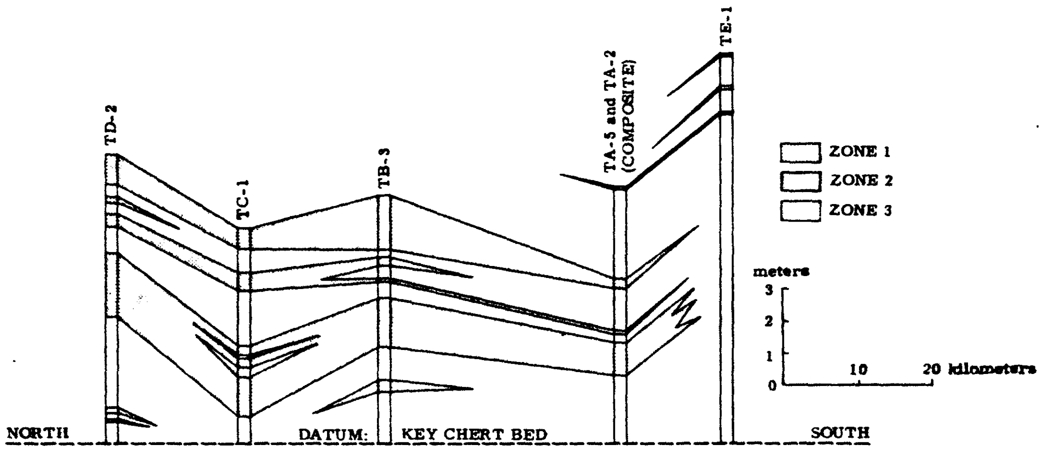
Core hole TB-1W was drilled to the west of the Khawr-umm-Wual graben, in line with the TB line of core holes, to test the western extent of the phosphate beds. Zone 1 in this hole is at a depth of

Table 2. Turayf widely spaced (Wildcat) Phosphate Core Holes.

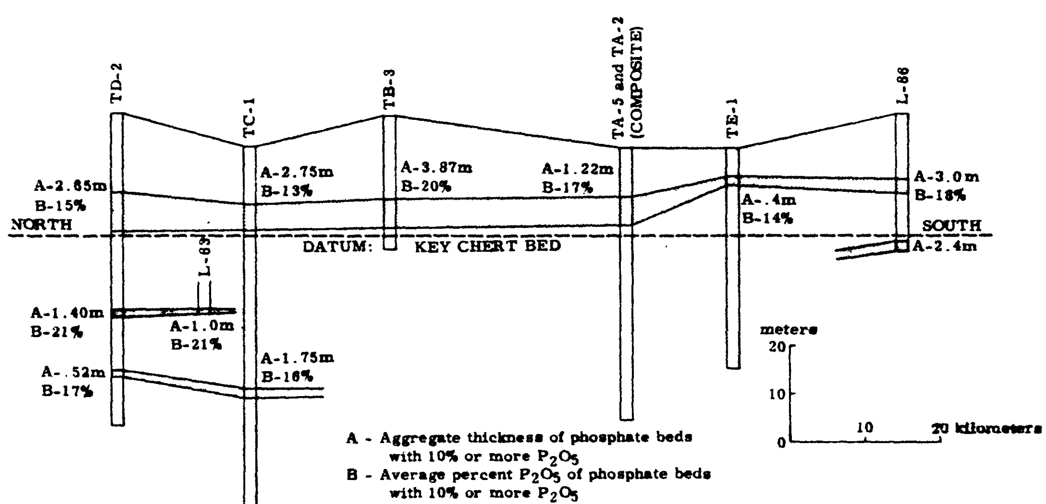
| Name | Coordinates | Total depth (meters) | Completed | Depth (meters) | Zone Thickness (meters) | Aggregate thickness phosphate beds(m.) | Av. % $P_2O_5$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| TB-1W | lat 31°39'16"N. long 38°58'53"E. | 79.80 | Oct. 2, 1967 | - | - | - | - | |
| Zone 1 | - | - | - | 47.45-66.85 | 19.40 | 3.37 | 20% | |
| Zone 2 | - | - | - | 106 | 1.0/ | 1.0 / | - | Detected in Aramco S-450 drill cuttings drilled to 274 meters at same location |
| Zone 3 | - | - | - | 118 | 1.0/ | 1.0 / | - | |
| TC-1 | lat 31°48'03"N. long 39°04'49"E. | 80.00 | Nov. 9, 1967 | - | - | - | - | |
| Zone 1 | - | - | - | 12.10-17.60 | 5.50 | 1.75 | 13% | |
| Zone 2 | - | - | - | - | - | - | - | Zone 2 absent? poor core recovery. |
| Zone 3 | - | - | - | 50.80-52.55 | 1.75 | 1.75 | 16% | |
| TC-7 | lat 31°47'35"N. long 39°09'53"E. | 65.00 | Dec.2, 1967 | - | - | - | - | TC-2 thru TC-6 not drilled. |
| Zone 1 | - | - | - | 20.40-25.80 | 5.45 | 2.85 | 14% | |
| Zone 2 | - | - | - | - | - | - | - | |
| Zone 3 | - | - | - | - | - | - | - | |

Table 2. Turayf widely spaced (Wildcat) Phosphate Core Holes.

| Name | Coordinates | Total depth (meters) | Completed | Depth (meters) | Zone Thickness (meters) | Aggregate thickness phosphate beds (m.) | Av. % $P_2O_5$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| TD-1 | lat 31°56'03"N. long 39°09'43"E. | 65.00 | Dec. 2, 1967 | - | - | - | - | |
| Zone 1 | - | - | - | 12.00-15.25 | 3.25 | 2.48 | 16% | |
| Zone 2 | - | - | - | 34.75-37.85 | 3.10 | .35 | 24% | |
| Zone 3 | - | - | - | - | - | - | - | Equivalent interval is phosphatic, cherty limestone |
| TD-2 | lat 31°56'44"N. long 39°02'15"E. | 65.00 | Jan. 6, 1968 | - | - | - | - | |
| Zone 1 | - | - | - | 16.50-24.80 | 8.30 | 2.65(?) | 15% | Core recovery poor |
| Zone 2 | - | - | - | 40.95-42.73 | 1.78 | 1.40 | 21% | |
| Zone 3 | - | - | - | 53.73-55.25 | 1.52 | .52 | 17% | |
| TE-1 | lat 31°22'44"N. long 39°18'19"E. | 56.00 | Jan. 24, 1968 | - | - | - | - | |
| Zone 1 | - | - | - | 5.90-7.85 | 1.95 | .40 | 14% | |
| Zone 2 | - | - | - | - | - | - | - | Zone 2 and Zone 3 absent ? core recovery poor |
| Zone 3 | - | - | - | - | - | - | - | |




STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONE 1 WITH 10% OR MORE $P_2O_5$




STRATIGRAPHIC CORRELATION OF PHOSPHATE BEDS IN ZONES 1, 2, AND 3 WITH 10% OR MORE $P_2O_5$

FIGURE 8.- Stratigraphic correlation of phosphate zones in the Turayf phosphate area.

about 47 meters, and it is 19.40 meters thick which is much thicker than it is east of the graben. It contains seven beds of phosphate, but aggregate thickness of the well-spaced beds is only 3.37 meters, averaging 20 percent $P_2O_5$. The thickest bed of about 1½ meters is at the base of the zone.

Zone 2 phosphate is from 9 to 16 meters below the base of zone 1, east of the Khawr-umm-Wual graben, and possibly as much as 39 meters below the zone west of the graben as interpreted from drill cuttings of Aramco S-450 structure test. The zone was penetrated in the TD-1 and TD-2 core holes. It may be present in TC-1, but the core recovery was too poor through the equivalent depths to confirm this. Zone 2 forms a small outcrop at locality 63, and was exposed by trenching at locality 86. The zone ranges in thickness from about 2 to 3.10 meters; it has an aggregate thickness of phosphate rock that ranges from .35 to possibly 2.40 meters. The grade of the phosphate ranges from 20 to 24 percent.

The small outcrop of zone 2 phosphate at locality 63 is the best and practically only complete exposure of this rock in the Turayf area. It is at the base of the bank of a large wadi, and consists of a hard, calcareous bed of phosphate about 1 meter thick. It is fine-to very coarse-grained with rounded to angular phosphate pellets and a few chips of chert. About 60 kilograms of this zone 2 phosphate bed were shipped for analyses to CERPHOS. They upgraded the raw phosphate rock from 20 to 21 percent $P_2O_5$ to 37 percent $P_2O_5$ with a recovery of 88 percent by calcination followed by washing and screening to eliminate the lime (Pouther and Grassart, written commun., 1968).

Zone 3 phosphate is about 10 to 12 meters below zone 2 and in the TC-1 and TD-2 core holes, and interpreted from drill cuttings in Aramco S-450. It ranges in thickness from about 1 to 1.75 meters in the holes, with an aggregate thickness of phosphate ranging from .52 to 1.75 meters. The grade is 16 or 17 percent $P_2O_5$.

To summarize, according to surface and subsurface data, zone 1 phosphate underlies an area of roughly 2000 square kilometers east of the Khawr-umm-Wual graben. The eastern limit of this area is an imaginary line drawn from locality 86 in the south, northward through the TA line core holes, between TA-6 and TA-7, then through the TB line, between TB-23 and TB-24, and north to lat 32°00'N. near the Jordan and Iraq borders. The northern limit is along this line to the Khawr-umm-Wual graben. The western limit is very roughly along the graben south to locality 86. The western limit is well defined southward from about the TB line of core holes, but northward from this line zone 1 crops out along wadi banks in most places before reaching the edge of the graben. In the area the zone averages 3 phosphate beds and has an average thickness of 5.0 meters. Average aggregate thickness of the phosphate beds is 2.5 meters, with an average grade of 16 percent $P_2O_5$. Average depth to the top of zone 1 in the core holes is 12 meters. Estimated tonnage of $P_2O_5$ in zone 1 in the Turayf area is about 1 billion metric tons. Tonnage estimates have not been computed for zone 2 and zone 3.

The highest grade zone 1 phosphate in the Turayf area is along the western end of the TB line of core holes between TB-1 and TB-11 (table 3). Six core holes were drilled offsetting TB-2, TB-3, and TB-4 to partly define the lateral extent of the best area (fig. 9). The average thickness of zone 1 in this area from core hole data is 6.3 meters, and it contains 4 or 5 beds of phosphate in most places. The average aggregate thickness of the beds is 3.9 meters, averaging 18 percent $P_2O_5$. Assuming a circular lens with a diameter of 10 kilometers (distance from TB-1 to TB-11) the phosphate beds contain 80,000,000 metric tons of $P_2O_5$. Limestone and chert overlie zone 1 in this circular area with an average thickness of 15 meters.

The friable phosphate in TB-2 is also in TB-2 (third) 0.7 kilometer to the southeast, but it is absent in the other TB, or offset holes. A pit was dug adjacent to TB-2 to examine zone 1, from which large samples of phosphate were obtained for beneficiation tests.

Although the $P_2O_5$ tonnage is very high in the Turayf area the ore is low grade. In most places the ore is hard and firmly cemented with calcite or silica. Beneficiation tests showed that the hard, calcareous phosphate rock (zone 2) could be upgraded to a marketable product by calcination, but costs of such an operation, coupled with

Table 3. Turayf highest grade Zone-1 Phosphate Core Holes

| Name | Coordinates | Total depth (meters) | Completed | Depth Zone-1 (meters) | Thickness (meters) | No. of Phos. Beds | Aggreg. thickness (meters) | Average % $P_2O_5$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| TB-1 | lat 31°39'16"N., long 39°06'31"E. | 30.00 | June 25, 1967 | 3.53-6.73 | 3.2 | 4 | 1.89 | 16% | |
| TB-2 TB-2bis | 1.00 km. east of TB-1 | 30.20 | July 5, 1967 | 3.65-10.70 | 7.05 | 5 | 4.27 | 23% | Redrilled Zone 1 to improve core recovery. |
| TB-2ter | .7 km SE of TB-2 | 34.10 | Sept. 24, 1967 | 12.71-20.19 | 7.48 | 3 | 3.65 | 14% | Offset hole. |
| TB-2N2 | 2 km N. of TB-2 | 45.00 | Nov. 21, 1967 | 20.60-24.10 | 3.50 | 4 | 1.65 | 19% | Offset hole. |
| TB-3 | 1 km E. of TB-2 | 28.00 | July 15, 1967 | 17.36-23.43 | 6.07 | 5 | 3.87 | 20% | |
| TB-3bis | .6 km NE of TB-3 | 25.00 | Oct. 10, 1967 | 7.08-13.30 | 6.22 | 4 | 3.35 | 18% | Offset hole. |
| TB-3N2 | 2 km N. of TB-3 | 45.00 | Nov. 8, 1967 | 13.72-18.05 | 4.33 | 4 | 3.21 | 16% | Offset hole. |
| TB-4 | 1 km E. of TB-3 | 30.40 | July 23, 1967 | 11.30-18.36 | 7.06 | 5 | 4.64 | 19% | |
| TB-4N1 | 1 km N. of TB-4 | 50.05 | Oct. 18, 1967 | 30.73-37.80 | 7.07 | 4 | 3.80 | 17% | Offset hole. |
| TB-4N2 | 2 km N. of TB-4 | 40.20 | Oct. 19, 1967 | 17.74-23.10 | 5.36 | 4 | 3.88(?) | 17% | Poor core recovery. Offset hole. |
| TB-7 | 1.1 km E. of TB-6 | 30.00 | Aug. 18, 1967 | 17.15-26.61 | 9.46 | 5 | 7.75(?) | 17% | TB-5 & TB-6 not deep enough |
| TB-11 | lat 31°39'20"N., long 39°12'56"E. | 35.05 | Sept. 10, 1967 | 32.75-41.25 | 8.50 | 6 | 5.10 | 18% | TB-8 incomplete TB-9 & TB-10 not deep enough. |

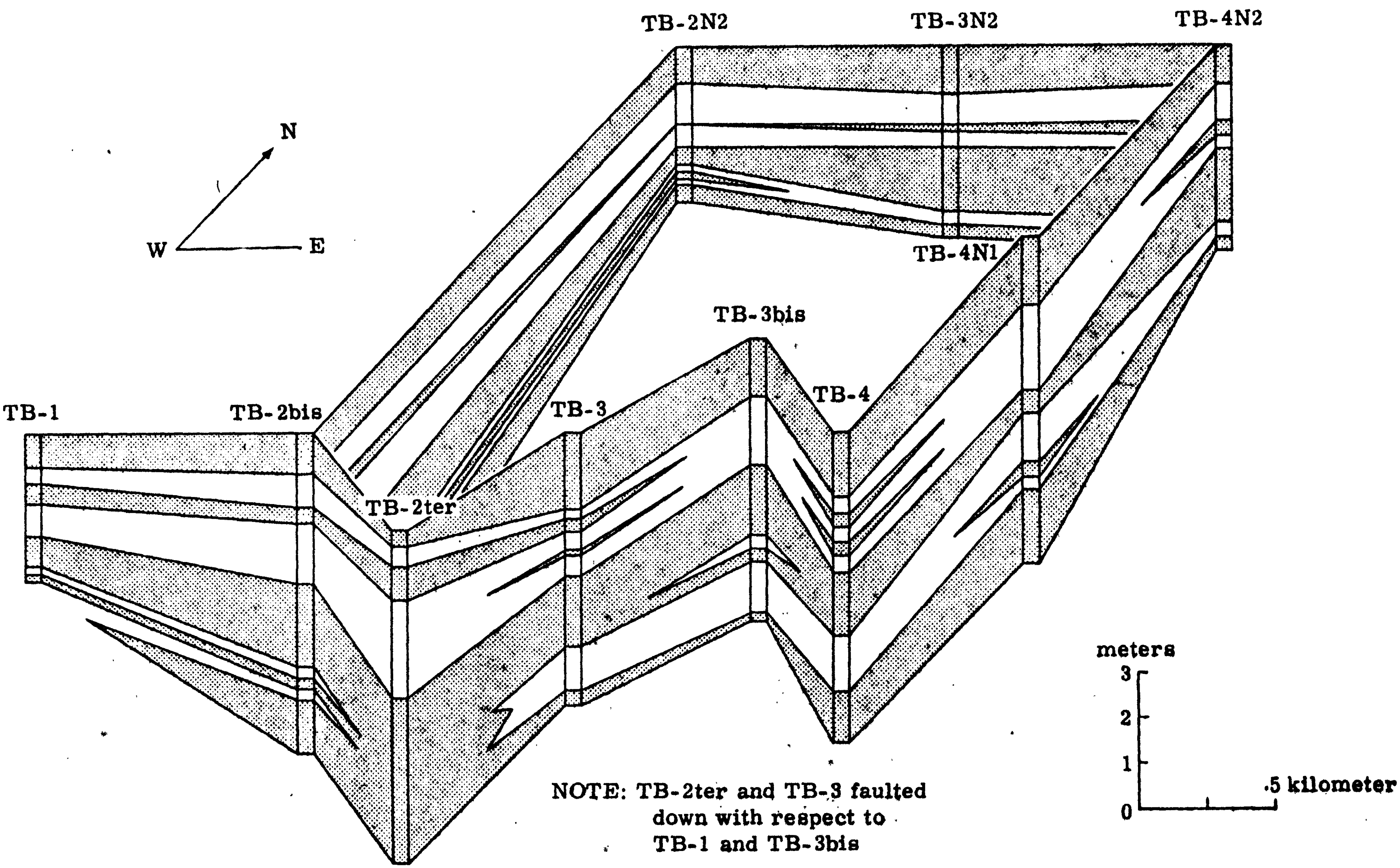



FIGURE 9.- Fence diagram showing the correlation of phosphate zone 1 in offset core holes of TB line of core holes.

the difficulty of supplying the necessarily large quantity of water, have thus far discouraged any consideration of development in the area.

## COMPOSITION AND MINERALOGY OF THE PHOSPHATE

### West Thaniyat area

Prior to the core drilling program at West Thaniyat, a 25-meter adit was driven in zone 5 at locality 14 to determine if fresh phosphate was as soft and friable as the weathered material at the outcrop. The phosphate at the face of the adit is like that at the outcrop. Two samples of bed 1 and two samples of bed 2, one sample from each bed at the weathered outcrop, and one sample from each bed at the face of the adit, were analyzed in laboratories of the Tennessee Valley Authority (Lehr and McClellan, written commun., 1968). Chemical composition of the samples, ground to -80 mesh (U.S. Standard sieve opening of 0.177 mm) on an as-received basis is shown in table 4.

Table 4. - Chemical composition of West Thaniyat phosphate ores.

| | Chemical composition (percent) | | | |
|---|---|---|---|---|
| | Bed 1 | | Bed 2 | |
| | Outcrop | Adit | Outcrop | Adit |
| $P_2O_5$ | 30.2 | 29.2 | 25.2 | 23.5 |
| $Fe_2O_3$ | 0.9 | 0.7 | 1.1 | 1.2 |
| $Al_2O_3$ | 0.7 | 1.0 | 1.0 | 1.3 |
| Acid insol. | 2.4 | 6.6 | 25.9 | 28.4 |

The mineral suite in the samples (raw ore) of the two beds are very similar and include quartz, clay and apatite. The quartz is detrital sand with particle sizes generally in the range 20 (0.841mm) to 100 (0.149mm) mesh. Bed 2 contains much quartz, whereas bed 1 contains very little quartz. Two types of clay are in each bed. A tan-colored clay that is stained by hydrous iron oxide is mainly in the weathered samples, whereas a pale-green (ferrous iron) clay is mainly in the adit samples. The phosphate mineral in both beds is carbonate apatite. It is mainly in oval pellets and as replacement of fossil fragments which include forms of shell, invertebrate cavity fillings, bone fragments, and teeth. The composition of the apathite (in percent) is 55.4 CaO, 0.6 $Na_2O$, 0.2 MgO, 38.2 $P_2O_5$, 3.1 $CO_2$, and 4.4 F.

Physical characteristics of bed 1 samples (raw ore) as determined by dry-screen analysis are shown in table 5.

Dry screen analysis of the bed 1 outcrop sample showed that about one half of the sample was coarser than 10 mesh (2.00mm); blunging and wet screening did not disaggregate most of these coarse agglomerates. The soft agglomerates of oval apatite lightly cemented by clay disaggregate readily, but agglomerates with a much higher clay content and some secondary apatite cement did not. The screen fractions representing the -10 /80 mesh (-2.00mm /0.177mm) material is about 40 percent of the total sample and constitute a high grade

Table 5. Screen analyses of samples from bed 1

| Particle size mesh (U.S. Standard) | Dry screened, wt % | | Blunged coarse fraction of outcrop sample, wt.% |
|---|---|---|---|
| | Adit | Outcrop | |
| +10 (+2.00 mm) | 15.7 | 50.2 | 32.0 |
| -10 +20 (-2.00 mm +0.841 mm) | 7.2 | 11.2 | 3.2 |
| -20 +40 (-0.841 mm +0.420mm) | 13.4 | 10.3 | 2.5 |
| -40 +60 (-0.420 mm +0.250mm) | 27.6 | 12.2 | 2.5 |
| -60 +80 (-0.250 mm +0.177mm) | 13.5 | 4.9 | 1.2 |
| -80 +120 (-0.177 mm +0.125mm) | 8.9 | 3.6 | 0.9 |
| -120 (-0.125 mm) | 13.7 | 7.6 | 7.7 |

apatite concentrate with very little clay, traces of dolomite, and vertually no quartz. Analysis of the bed 1 adit sample showed the coarse agglomerate to be softer so that a much larger fraction of the apatite existed in a liberated state (-10 +80) than in the outcrop sample. The -10 +120 mesh (-2.00 mm +0.125 mm) fractions make up 70 percent by weight of the adit sample constituting a high grade apatite concentrate with only minor quartz and clay impurities.

Bed 2 adit sample had a very weak aggregate structure due in part to the abundance of the pale green clay, which appears to shrink on drying and lose its bonding ability. When the agglomerates disaggregate, the clay readily separates from the phosphate pellets. Quartz, the principal impurity, shows a normal distribution curve in the -20 +120 mesh (-0.841mm +0.125mm) fractions, as does the green clay aggregates. Bed 2 outcrop sample is very similar in texture and mineral composition to the adit material.

Exploratory beneficiation tests were made on a bed 2 adit sample by J. G. Getsinger and others, of the Tennessee Valley Authortiy (written commun., 1968). The ore consists of two distinct phases. One is light-brown sandy phosphate; the other is large lumps of a reddish-brown clay with little phosphate. Therefore, the weak lumps of sandy phosphate were crushed, the ore was screened on a 4-mesh (4.76 mm) screen, and the two phases were analyzed separately (table 6).

Table 6. Analyses of bed 2 phosphate ore, in percent

| Fraction | Solids wt.% | $P_2O_5$ | CaO | $Al_2O_3$ | $Fe_2O_3$ | Acid insol. | F | Ignition loss | $SiO_2$-free phos. $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|
| Phosphate (-4 mesh) (-4.76mm) | 87.5 | 27.3 | 39.9 | 1.0 | 0.9 | 21.3 | 3.0 | 4.9 | 34.7 |
| Clay (+4 mesh) (+4.76mm) | 12.5 | 10.3 | 16.1 | 6.8 | 13.3 | 35.8 | - | - | 19.5 |

The analysis indicate that the phosphatic fraction (-4 mesh) might be used to make wet-process phosphoric acid. The combined percentage of $Al_2O_3$ and $Fe_2O_3$ is 1.9 and $CaO:P_2O_5$ ratio (1.46) are about the same as those of Florida pebble phosphate.

Since the phosphate in the ore is very soft, the feasibility of preferentially grinding the phosphate fine enough to separate it from the quartz by sizing was investigated. In practice, the ore would be ground dry and sized with an air classifier, but to save time the size separation was made in the laboratory by wet screening. The results are shown in table 7.

The screen analysis (test 1) of the minus one-fourth inch (6.35mm) sandy phosphate showed that a concentrate of 27.9 percent phosphate at a grade of 32.3 percent $P_2O_5$ could be separated by sizing the unground ore at 100 mesh (0.149 mm). In test 2, part of the ore was ground in a jar mill for 90 minutes with three-fourth inch (19.05mm) pebbles. About 81 percent of the phosphate was minus 100 mesh, and the grade 31.4 percent $P_2O_5$. Some of the plus 100-mesh phosphate was as coarse as 10 mesh; therefore, another split of the ore was ground for 60 minutes with one-half inch (12.7 mm) steel balls (test 3). Nearly all of the phosphate was ground finer than 35 mesh (0.500 mm), but this had no effect on the minus 100 mesh solids. The grade and recovery of phosphate was nearly identical with those of test 2.

Table 7. Effect of dry grinding on size distribution of phosphate and quartz in bed 2 phosphate adit sample.

| Size traction, mesh | Solid distribution Wt. % | $P_2O_5$ % | | Acid insoluble % | |
|---|---|---|---|---|---|
| | | Content | Distribution | Content | Distribution |
| **Test 1; Crushed to minus ¼ inch (6.35mm)** | | | | | |
| +28 (+.595mm Tyler) | 10.1 | 27.8 | 10.2 | - | - |
| -28 +48 (5mm +.297mm Tyler) | 19.5 | 25.0 | 17.6 | - | - |
| -48 +65 (7mm +.210mm Tyler) | 24.5 | 26.0 | 23.1 | - | - |
| -65 +100 (0mm +0.149mm Tyler) | 22.0 | 26.5 | 21.1 | - | - |
| -100 +200 (9mm +0.074mm Tyler) | 13.0 | 32.3 | 15.2 | - | - |
| -200 (-0.074mm) | 10.9 | 32.3 | 12.7 | - | - |
| **Cummulative head** | 100 | **27.6** | **100** | - | - |
| +100 | 76.1 | 26.1 | 72.1 | - | - |
| -100 (conc) | 23.9 | 32.3 | 27.9 | - | - |
| **Test 2; 400 grams ore ground with 1200 grams 3/4 inch (19.05mm) pebbles for 90 mins.** | | | | | |
| +65 | 10.5 | 14.0 | 5.3 | 60.7 | 30.8 |
| -65 +100 | 17.2 | 21.4 | 13.2 | 42.9 | 35.6 |
| -100 +325 (+.044mm) | 29.5 | 30.5 | 32.3 | 14.9 | 21.3 |
| -325 (-.044mm) | 42.8 | 32.1 | 49.2 | 6.0 | 12.4 |
| Cummulative head | 100 | 27.9 | 100 | 20.7 | 100 |
| -100 (conc) | 72.3 | 31.4 | 81.5 | 9.6 | 33.7 |
| **Test 3; 200 grams ore ground with 600 grams ½ inch (12.7mm) steel balls for 60 mins** | | | | | |
| +65 | 10.9 | 15.1 | 6.0 | 57.5 | 28.2 |
| -65 +100 | 18.8 | 19.6 | 13.4 | 45.0 | 38.1 |
| -100 (conc) | 70.3 | 31.4 | 80.6 | 10.7 | 33.7 |
| Cummulative head | 100 | 27.4 | 100 | 22.2 | 100 |

J.G. Getsinger and others (written commun., 1968) concluded from their tests that dry grinding followed by beneficiation through air would yield a product containing 31.4 percent $P_2O_5$ with 81 percent recovery. A concentrate of higher grade phosphate could be produced by flotation, but recovery would be low because over one half of it is too soft to be floated.

Forty-nine samples of core and cuttings from the six core holes at West Thaniyat were sent to TVA for analyses similar to the ones they completed on the outcrop and adit samples. Eleven samples were of bed 1 and 38 samples of bed 2, most of which were core recovered by a 2 inch (50.8mm) inside diameter (NX) auger-type core bit. Much of the phosphate core contained more clay than the outcrop and adit samples, and responded poorly to beneficiation techniques used on the adit ore samples. The results of the analyses are discussed subsequently in the section by TVA.

A useful aid in drilling at West Thaniyat was the gamma-ray log. Slight radioactivity of the phosphate beds produced a distinct, anomalous curve on the log (fig.4D) which made it easy to correlate zone 5 from one hole to another. Variations in grade of phosphate, as determined from core samples, is reflected in the relative magnitude of the gamma-ray curve, i.e., the curve increases with an increase in grade of phosphate. Present data are not sufficient to calibrate the gamma-ray curve with percent $P_2O_5$.

## Turayf area

Residual surface samples of phosphate rock randomly collected from the Turayf area are hard and firmly cemented by calcite or silica. Most samples were "float" or lag gravel from zone 1, a few are probably from zone 2.

Chemical composition of six select phosphate samples (3 calcareous and 3 siliceous) is shown in table 8, whichhas been adapted from table 2 of a report by Cathcart (1966).

Table 8. Chemical composition of selected phosphate samples, Turayf area. (in percent)

| Type | $P_2O_5$ | CaO | $Al_2O_3$ | $Fe_2O_3$ | $SiO_2$ | Acid insoluble | F |
|---|---|---|---|---|---|---|---|
| Calcareous | | | | | | | |
| 1 | 5.0 | 26.2 | .82 | 1.66 | 6.98 | 9.21 | .42 |
| 2 | 13.6 | 53.8 | .21 | .10 | .51 | .61 | 1.62 |
| 3 | 22.6 | 53.7 | .09 | .03 | .17 | .17 | 2.82 |
| Siliceous | | | | | | | |
| 1 | 6.9 | 13.2 | .27 | .12 | 69.4 | 74.6 | .72 |
| 2 | 14.6 | 22.4 | .22 | .12 | 55.1 | 56.87 | 1.55 |
| 3 | 20.6 | 30.0 | .07 | .06 | 36.6 | 45.20 | 2.34 |

The phosphate mineral in the Turayf samples is carbonate fluorapatite. The calcareous phosphate contains calcite as a major mineral phase, while dolomite is in a few samples. Quartz is a minor or trace constituent in most calcareous samples. The siliceous phosphate always contains chert-like quartz (cement and groundmass) as a major mineral phase, and calcite is a minor constituent. Apatite is in all samples, ranging from small to large amounts. It is mainly oval pellets, and replacement foraminifera and fragments of pelecypods and gastropods.

The phosphate particles in the calcareous and siliceous phosphate beds range in size from about 0.1 to 10 millimeters across (from very-fine sand to fine pebble size); the finer size pellets are more abundant.

Exploratory beneficiation tests were made on the samples. An attempt was made to crumble the calcareous phosphate by gently grinding it in a mortar and pestle, but this procedure was unsuccessful. Grinding to a size necessary to free the phosphate particles from the calcareous matrix caused the phosphate pellets and matrix to disintegrate into a more or less uniformly size material of about 200 mesh. The material is too fine for successful commercial separation of phosphate and calcite by flotation. Calcining at elevated temperatures may cause the $CaCO_3$ to break down into CaO and $CO_2$ and free the phosphate particles. Screening and flotation after calcining might produce phosphate of a commercial grade. The phosphate particles in the siliceous phosphate samples cannot be easily separated from the siliceous matrix. Although the phosphate particles are softer than the cement, they are so friable that grinding pulverizes both minerals. The phosphate particles are surrounded by silceous cement, and acidulation was unsuccessful. One sample, broken into coarse-sand size, was treated with hydrochloric acid, and only a small percentage of the phosphate dissolved. The silica cement surrounding the particles of phosphate effectively armored the particles against acidulation. Fine grinding of this material is necessary prior to acidulation, but the final product is too costly.

To pursue the promising possibility of up-grading calcareous phosphate rock by calcination, about 110 kilograms of the zone 2 calcareous phosphate at locality 63 were collected for analysis. Here the zone 2 outcrop is about the only natural exposure of bed rock phosphate in the Turayf area, and it is fairly representative of the better grade phosphate of zone 1. About 55 kilograms of sample were sent to CERPHOS, and about 55 kilograms were sent for comparison to the U.S. Bureau of Mines metallurgy research center in Albany, Oregon.

The CERPHOS report on the results of their laboratory tests are encouraging (Pouthier and Grassart, written commun., 1968). They stated that they were able to obtain a titrate concentrate of more than 37 percent $P_2O_5$ with excellent recovery of $P_2O_5$, and a very good Ca: $P_2O_5$ ratio. They concluded that the phosphate yields a commercial concentrate of high quality, following a relatively simple test.

A partial chemical analysis of the sample (on an as-received basis) gave the following results (in percent): $P_2O_5$ = 20.5; $CO_2$= 19; CaO=54.5;

$MgO = 0.25$; $Al_2O_3 = .11$; $Fe_2O_3 = .24$; and $SiO_2 = 2$ or less.

Densimetric analyses were run on grounded and washed samples of the phosphate by CERPHOS (written commun., 1968) and the results which are modified and averaged are shown in table 9.

Table 9. Densimetric analyses of calcareous phosphate, Turayf area.

| Density | Weight % | % $P_2O_5$ | % $SiO_2$ | % $CO_2$ |
|---|---|---|---|---|
| d < 2.81 | 33 | 9.6 | 2.60 | 32 |
| 2.81 < d < 2.95 | 22 | 28.6 | .38 | 12 |
| d > 2.95 | 14 | 34.2 | .42 | 7 |
| Cummulative head | 69 | 20.8 | 1.40 | 20.6 |

Indications from previous tests were that physical methods of beneficiation such as gravimetric, flotation, or electrostatic would not produce a product with more than 32 percent $P_2O_5$, and that the phosphate would react best to calcination followed by careful elimination of the lime by washing and screening. The company stressed that they have a special (step-like) process of post-treating calcinated phosphate, but they did not disclose the exact procedure. The results of their tests are shown in table 10:

To summarize, according to Pouthier and Grassart (written commun., 1968), laboratory calcination tests on the calcareous phosphate rock showed a recovery by weight of 49 percent, with post-calcination treatment resulting in a 37 percent $P_2O_5$ concentrate with 88 percent recovery of the $P_2O_5$.

The U.S. Bureau of Mines report on the results of their tests on the same type of calcareous phosphate was not as optimistic (Rule and Clark, written commun., 1968). They concluded, as have the other examiners of this phosphate, that conventional grinding and sizing beneficiation techniques were not effective. However, a possible method for beneficiating of this material consists of a heat treatment, quenching, and attrition grinding followed by sizing at an appropriate size to effect separation of a concentrate.

Table 10. Results of beneficiation tests by calcination, Turayf phosphate.

Mineral ground to 2mm.

1. Calcination in a rotating furnace

   a. Calcination at a maximum temperature of 940°C, for 30 minutes.

   b. Washing of the calcinated mineral and screening at 40 and 80 microns.

| | % $P_2O_5$ | $CO_2$ | % CaO | $\frac{CaO}{P_2O_5}$ |
|---|---|---|---|---|
| >80 microns: | 29.09 | 0.75 | 58.90 | 2.024 |
| 40-80 microns: | 30.16 | 1.15 | 58.20 | 1.930 |

2. Calcination in a muffle furnace

   a. Calcination at 950°C, for 30 minutes

   b. Washing and screening at 40 and 80 microns

| | Wt. % | % $P_2O_5$ | % CaO | $\frac{CaO}{P_2O_5}$ |
|---|---|---|---|---|
| >80 microns: | 44.6 | 32.2 | 58.0 | 1.86 |
| 40-80 microns: | 9.4 | 25.3 | 60.3 | 2.40 |

Table 10. Results of beneficiation tests by calcination, Turayf phosphate (cont'd).

3. Calcination in a stationary furnace

a. Calcination at 950°C for 30 minutes

b. "Treatment" after calcination followed by screening

| | Wt. % | % $P_2O_5$ | % CaO | $\frac{CaO}{P_2O_5}$ | Recovery $P_2O_5$ |
|---|---|---|---|---|---|
| >80 microns: | 33.70 | 36.42 | 54.83 | 1.504 | 59.9 |
| 40-80 microns: | 6.45 | 35.00 | 56.52 | 1.614 | 11.0 |
| >40 microns: | 40.15 | 36.19 | 55.10 | 1.522 | 70.9 |

4. Calcination in a muffle furnace

a. Calcination at 950°C. for 30 minutes

b. Washing and screening.

| | Combined Wt. % | % $P_2O_5$ | % CaO | $\frac{CaO}{P_2O_5}$ |
|---|---|---|---|---|
| >80 microns: | 44.24 | 37.2 | 56.02 | 1.506 |
| >40 microns: | 48.99 | 37.1 | 55.7 | 1.510 |

Best results were obtained when the phosphate rock was heated to calcining temperature (1000°C.) which produced a concentrate analyzing 29 percent $P_2O_5$ at a 78 percent recovery. The concentrate can be considerably improved (up to 35% $P_2O_5$) by selective flotation to remove calcite gangue, but phosphate recovery is reduced.

Because test results differ between CERPHOS and the U.S. Bureau of Mines it seems advisable that further analyses of the Turayf phosphate be made prior to future development considerations.

The gamma-ray logger was not available while core drilling at Turayf. However, three holes that remained open were logged later for test purposes. These holes were TB-1, TB-4, and TB-11 and the phosphate beds in each produced gamma ray "kicks" on the log. To test for the percentage of radioactivity in the phosphate a set of eleven phosphate core samples were sent to the U.S. Geological Survey Laboratory, Washington, D.C. Four samples were in the 10 to 15 percent $P_2O_5$ range; three in the 15 to 20 percent $P_2O_5$ range and four in the 20 to 25 percent $P_2O_5$ range. The average percentage equivalent uranium for the samples in the 10 to 15 percent range was .0023 percent, for those in the 15 to 20 percent percent range .0027 percent; anf for those in the 20 to 25 percent range .0030 percent. Therefore, at least in this one small collection of samples, there was a slight increase (.007%) of percentage equivalent uranium from the lower to the higher grade phosphate samples. Average percent uranium for all the samples was .0023 percent.

# DRY BENEFICIATION OF PHOSPHATE ORE FROM WEST THANIYAT, SAUDI ARABIA

by

Tennessee Valley Authority*

Beneficiation studies were made in 1968 on a sample phosphate ore taken from an adit driven into an outcrop in a desert region of West Thaniyat, Saudi Arabia (June 1968 report). The 25% $P_2O_5$ ore was a mixture of weakly consolidated, light brown, sandy phosphate and massive lumps of reddish brown clay. The tests of this single sample indicated that (1) a large proportion of the clay could be separated from the phosphate as an oversize fraction by sizing the dry ore with a 10-mesh trommel, (2) most of the quartz associated with the phosphate was coarser than 100 mesh, (3) most of the phosphate was soft enough to be ground preferentially finer than the quartz, and (4) air classification of the ground material should recover about 80% of the phosphate as minus 100-mesh concentrate which would contain about 31% $P_2O_5$. Susceptibility of the ore to beneficiation of this dry method was particularly encouraging because of lack of water in the area of the deposit.

Subsequent to the test described above, a field survey was made of the West Thaniyat deposit by representatives of TVA to evaluate other factors that would affect the practicability of development of the deposit. This study indicated that if a sufficiently large deposit

* Division of chemical operations, Muscle Shoals, Alabama, Nov. 1969

of phosphate comparable in quality to that found at the outcrop could be proved, commercial development of the deposit might be warranted. A drilling program to determine the size and characteristics of the deposit and further study of other factors that would affect the development were recommended. Such a drilling program then was conducted by the U.S. Geological Survey in 1968 and early 1969. Six holes were drilled in a pattern behind the face of the outcrop and a total of 49 core samples resulting from this drilling were submitted to TVA for further study and evaluation. The present report covers evaluation of these samples.

Most of the core samples differed in appearance from the adit sample taken previously from the outcrop. The color was a darker brown and the lumps were less friable, both of which suggested a higher clay content. Also, the clay appeared to be intimately associated with the phosphate -- there was little difference in the color of size fractions of a given sample. For preliminary analysis, seven samples, representing a variety in appearance, were selected; results of the analyses are given in table 11. Six of the samples (Nos. 1, 2, 4, 5, 6, and 7) were screened on 10 mesh to determine whether clay might be rejected by discarding the coarser lumps before grinding the ore, as had been successful with the adit sample. The remaining sample (No.3) was a single coherent core with the appearance of reddish brown clay, and there were no granular solids that could be separated

Table 11. - Analysis of selected core samples of Saudi Arabian phosphate ore.

| Sample No. | Sample Hole | Sample Bed | Sample Depth, m. | Size fraction, mesh | Appearance | Analysis, % $P_2O_5$ | Analysis, % Acid insoluble | Approximate mineral content, % Phosphate, 2.76 $P_2O_5$[a] | Approximate mineral content, % Clay,[b] 1.78x | Approximate mineral content, % Quartz,[c] by difference | $P_2O_5$ content of quartz-free[c] ore, % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | WT-2 | 2 | 42.50-42.85 | +10 | Reddish sandstone | 16.1 | 41.3 | 44.4 | 25.5 | 30.1 | 23.0 |
| | | | | -10 | | 15.3 | 46.5 | 42.2 | 20.1 | 37.7 | 24.6 |
| 2 | WT-3a | 2 | 71.25-71.80 | +10 | Lumps of clay, | 16.2 | 32.4 | 44.7 | 40.8 | 14.5 | 18.9 |
| | | | | -10 | brown fines | 15.5 | 27.3 | 42.8 | 53.2 | 4.0 | 16.1 |
| 3 | WT-4a | 2 | 64.00-64.45 | - | Reddish clay core, few fines | 11.5 | 36.2 | 31.7 | 57.1 | 11.2 | 13.0 |
| 4 | WT-5 | 1 | 38.55-38.85 | +10 | Chips of dark gray | 1.0 | 91.3 | 2.8 | 10.5 | 86.7 | 7.5 |
| | | | | -10 | rock, tan granules | 9.8 | 58.7 | 27.0 | 25.5 | 47.5 | 18.7 |
| 5 | WT-5 | 2 | 41.42-41.60 | +10 | Brown granular | 27.7 | 15.4 | 76.5 | 14.4 | 9.1 | 30.5 |
| | | | | -10 | | 27.3 | 16.3 | 75.5 | 14.6 | 9.9 | 30.3 |
| 6 | WT-6 | 2 | 27.95-28.15 | +10 | Brown granular | 29.1 | 13.6 | 80.3 | 10.9 | 8.8 | 31.9 |
| | | | | -10 | | 30.7 | 11.7 | 84.7 | 6.4 | 8.9 | 33.7 |
| 7 | WT-6 | 2 | 28.60-28.85 | +10 | Brown granular | 24.2 | 25.3 | 66.8 | 14.1 | 19.1 | 30.0 |
| | | | | -10 | | 25.2 | 25.1 | 69.6 | 9.4 | 21.0 | 31.9 |

a 2.76 = 100/36.2 (intercept on $P_2O_5$ axis). } See June 1968 progress report.

b x = 100 - (2.76 $P_2O_5$ + acid insoluble) } See June 1968 progress report.

1.78 = 100/100 - 44 (intercept on acid-insoluble axis.

c Includes all forms of silica (chert and flint) other than silicate silica.

by screening. Both the plus 10-mesh and minus 10-mesh fractions of the samples were analyzed for $P_2O_5$ and acid-insoluble content and the approximate mineral contents were calculated using the factors derived in the earlier study of the adit sample. The results of these calculations are included in table 11. The last column in table 11 shows the $P_2O_5$ content of the samples calculated on a quartz-free basis. This value represents the upper limit of $P_2O_5$ content that might be attained by grinding the ore and classifying it at 100 mesh; the values shown could not be fully achieved in a practical operation because some of the phosphate cannot be ground preferentially to minus 100 mesh and some of the quartz is originally finer than this size.

The samples of highest $P_2O_5$ content, 24 to 30% $P_2O_5$, were those (Nos.5, 6, and 7) with a brown granular appearance. Screening these materials at 10 mesh was ineffective in increasing $P_2O_5$ content; the plus 10-mesh fractions had about the same $P_2O_5$ contents as the fine material. The potential maximum $P_2O_5$ contents of these samples, assuming removal of quartz, were calculated to be 30 to 32%. The samples of next highest $P_2O_5$ content (15-16% $P_2O_5$) were No.1, which had a reddish sandstone appearance, and No.2, which consisted of brown fines and large lumps of clay-appearing material. Screening at 10 mesh likewise was of no benefit with these samples; the $P_2O_5$ content of the plus 10-mesh fractions was even higher (16 vs.15%) than that of the minus 10-mesh fractions. By elimination of quartz, the $P_2O_5$ content of sample No.1 would be increased to about 23%, but that of sample No.2 would increase only to about 16 to 18%. Sample No.3, the one that consisted of a single coherent core with the appearance of reddish brown clay, contained only 11% $P_2O_5$. On a quartz-free basis, the $P_2O_5$ content would be 13%. The final sample (No.4) consisted of chips of dark gray rock (chert) and tan granules. The $P_2O_5$ content of the plus 10-mesh fraction was only 1% as compared with about 10% for the minus 10-mesh fraction. On a quartz-free basis, $P_2O_5$ content of the latter fraction would be about 18%.

The results of these preliminary tests indicated that the deposit contains some seams or lenses of clay and chert that probably could be separated from the phosphatic material by selective mining. However, other clay is too intimately associated with the phosphate to be separated from it by sizing of the ore. Although some of the samples may have contained finely divided clay that was originally present as massive clay but was reduced to fines by the coring process, it is not likely that the amount of such action was sufficient to negate the results of the tests.

Since the preliminary tests indicated that a separation could not be made of a significant portion of the clay fraction of the ore by coarse screening as was done on the adit sample, more extensive tests were conducted to determine response of the ore to beneficiation by grinding and screening. Each of the 49 samples was analyzed for $P_2O_5$ and acid insoluble contents and calculations were made of the $P_2O_5$ content on a quartz-free (acid insoluble) basis. The results of these analyses are given in table 12. The samples are listed in the order indicated by the drilling log, so that zones of maximum $P_2O_5$ concentration can be identified by the analyses of sonsecutive samples. The last column of table 12 indicates the groupings of samples, based on analyses and the drilling log, that were used for preparation of composite samples for actual beneficiation tests.

Most of the ore from hole WT-1 was low in $P_2O_5$-- only one sample contained as much as 20%. However, two samples (Nos.6 and 7), which represented a 0.75-meter depth of ore, offered some promise of yielding a useful concentrate (silica-free fraction, so they were composited for grinding and sizing tests (composite C1). The compositing weights were proportional to the thickness of ore represented.

None of the samples from hole WT-2 merited further testing.

In hole WT-3A, sample No.12, which came from the top of bed 1, contained little $P_2O_5$ (2.5%) or acid insoluble (16.5%). Additional analyses showed it to contain 27% CaO and 36% $CO_2$. Since the excess CaO (over that needed to combine with the $P_2O_5$) was equivalent to only about half of the $CO_2$, it was concluded that the sample consisted principally of dolomitic limestone. Samples Nos.13 and 14 from a lower depth in this bed effervesced vigorously when tested with acid; these samples were composited (composite C2) for testing in order to learn how the limestone would behave in the dry beneficiation process. Four samples representing the lower half of bed 2 of hole WT-3A (samples

Table [illegible].—Examination of individual core samples to determine susceptibility to beneficiation by grinding and sizing

| Hole No. | Bed No. | Lab. No. | Core sample | Depth, meters | Thickness, meters | Wt., g. | Analysis, %: $P_2O_5$ | Analysis, %: Acid insol. | Analysis, %: $CO_2$ | Maximum $P_2O_5$ content of potential concentrate,[a] % | Composite No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WT-1 | 1 | 1 | Cuttings | 97.00-98.00 | 1.00 | 301 | 15.2 | 36.2 | | 23.8 | |
| | | 2 | Cuttings | 98.00-98.55 | 0.55 | 204 | 12.8 | 33.1 | | 19.1 | |
| | | 3 | Circ. | 99.25 | - | 35 | 19.2 | 34.6 | | 29.3 | |
| | 2 | 4 | Circ. | 99.95 | - | 34 | 8.6 | 46.0 | | 15.9 | |
| | | 5 | Core | 99.95-100.20 | 0.25 | 128 | 7.8 | 64.8 | | 22.1 | |
| | | 6 | Core | 100.20-100.70 | 0.50 | 470 | 23.0 | 27.3 | | 31.6 | C1 |
| | | 7 | Cuttings | 99.95-100.70 | 0.75 | 412 | 19.0 | 37.3 | | 30.3 | |
| | | 8 | Cuttings | 100.70-100.90 | 0.20 | 283 | 3.3 | 87.6 | | 26.6 | |
| WT-2 | 2 | 9 | Core | 42.50-42.85 | 0.35 | 365 | 15.4 | 44.4 | | 27.6 | |
| | | 10 | Core | 42.85-43.10 | 0.25 | 262 | 6.5 | 56.8 | | 15.0 | |
| | | 11 | Core | 43.10-43.50 | 0.40 | 237 | 5.8 | 56.2 | | 13.2 | |
| WT-3A | 1 | 12[b] | Core | 69.05-69.40 | 0.35 | 365 | 2.5 | 16.5 | 36.1 | 3.0 | |
| | | 13 | Core | 70.00-70.20 | 0.20 | 262 | 16.9 | 25.6 | | 22.7 | C2 |
| | | 14 | Core | 70.20-70.25 | 0.05 | 237 | 21.9 | 17.0 | | 26.3 | |
| | 2 | 15 | Core | 70.70-70.80 | 0.10 | 92 | 13.3 | 41.6 | | 22.7 | |
| | | 16 | Core | 70.80-70.90 | 0.10 | Missing | | - | | - | |
| | | 17 | Core | 70.90-71.00 | 0.10 | 80 | 19.6 | 29.4 | | 27.7 | |
| | | 18 | Core | 71.25-71.80 | 0.55 | 542 | 8.2 | 38.8 | | 13.4 | |
| | | 19 | Core | 71.80-71.93 | 0.13 | 342 | 20.6 | 36.0 | | 32.1 | |
| | | 20 | Core | 71.93-72.06 | 0.13 | 248 | 18.9 | 42.2 | | 32.6 | C3 |
| | | 21 | Core | 72.06-72.21 | 0.15 | 345 | 16.7 | 46.5 | | 31.2 | |
| | | 22 | Core | 72.21-72.35 | 0.14 | 260 | 11.9 | 62.0 | | 31.3 | |
| WT-4A | 1 | 23 | Cuttings | 60.00-61.15 | 1.15 | 215 | 15.4 | 37.7 | | 25.5 | |
| | 2 | 24 | Core | 62.40-62.45 | 0.05 | 165 | 20.1 | 30.5 | 5.1 | 28.9 | |
| | | 25 | Cuttings | 62.45-62.65 | 0.20 | 165 | 19.4 | 21.1 | 8.1 | 24.5 | |
| | | 26 | Cuttings | 62.70-63.70 | 1.00 | 246 | 10.0 | 47.1 | | 18.9 | |
| | | 27 | Core | 64.00-64.45 | 0.45 | 243 | 11.8 | 38.1 | | 19.0 | |
| | | 28 | Core | 64.45-64.90 | 0.45 | 313 | 15.0 | 52.5 | | 31.5 | |
| | | 29 | Cuttings | 64.90-65.10 | 0.20 | 110 | 12.4 | 53.9 | | 26.8 | |
| | | 30 | Core | 65.20-65.30 | 0.10 | 285 | 10.6 | 62.9 | | 28.5 | |
| WT-5 | 1 | 31 | Core | 38.55-38.85 | 0.30 | 583 | 8.9 | 62.5 | | 23.7 | |
| | | 32 | Core | 38.85-39.00 | 0.15 | 424 | 32.8 | 6.1 | | 34.9 | |
| | | 33 | Core | 39.00-39.10 | 0.10 | 425 | 19.6 | 18.0 | 13.1 | 23.9 | |
| | 2 | 34 | Core | 40.70-40.85 | 0.15 | 383 | 29.3 | 14.8 | | 34.3 | |
| | | 35 | Core | 40.85-41.00 | 0.15 | 342 | 28.5 | 14.1 | | 33.1 | |
| | | 36 | Core | 41.12-41.27 | 0.15 | 443 | 24.6 | 21.4 | | 31.2 | |
| | | 37 | Core | 41.27-41.42 | 0.15 | 328 | 29.4 | 12.5 | | 33.6 | C4 |
| | | 38 | Core | 41.42-41.60 | 0.18 | 443 | 27.6 | 17.0 | | 33.2 | |
| | | 39 | Core | 41.60-41.75 | 0.15 | 351 | 22.8 | 32.1 | | 33.5 | |
| | | 40 | Core | 41.75-41.95 | 0.20 | 488 | 22.6 | 32.2 | | 33.3 | |
| | | 41 | Core | 41.95-42.05 | 0.10 | 501 | 23.1 | 29.4 | | 32.7 | |
| WT-6 | 1 | 42 | Core | 26.70-27.00 | 0.30 | 137 | 29.0 | 12.1 | | 32.9 | |
| | 2 | 43 | Core | 27.95-28.15 | 0.20 | 478 | 29.7 | 12.1 | | 33.7 | |
| | | 44 | Core | 28.15-28.30 | 0.15 | 489 | 32.1 | 13.9 | | 37.2 | C5 |
| | | 45 | Core | 28.30-28.45 | 0.15 | 548 | 31.9 | 8.3 | | 34.7 | |
| | 2 | 46 | Core | 28.45-28.60 | 0.15 | 541 | 22.6 | 25.0 | | 30.1 | |
| | | 47 | Core | 28.60-28.85 | 0.25 | 539 | 24.6 | 26.0 | | 33.2 | |
| | | 48 | Core | 28.85-29.05 | 0.20 | 661 | 20.6 | 25.5 | | 27.6 | C6 |
| | | 49 | Core | 29.05-29.40 | 0.35 | 441 | 15.3 | 47.7 | | 29.2 | |
| | | 50 | Core | 29.40-29.55 | 0.15 | 357 | 11.3 | 61.5 | | 29.3 | |

[a] Assuming that all of the acid-insoluble portion was silica which could be separated from the phosphate by grinding and sizing:

$$P_2O_5 \text{ content of concentrate, \%} = \frac{P_2O_5 \text{ content of sample, \%} \times 100}{100 - \text{acid-insoluble content of sample, \%}}$$

[b] CaO, 27.0%.

Nos.19-22) were composited (composite C3) because they showed some promise of response to beneficiation although they contained only 12 to 21% $P_2O_5$ before beneficiation.

From hole WT-4A, only one sample (No.28) showed promise of significant response to beneficiation, and it contained only 15% $P_2O_5$.

The ore from holes WT-5 and WT-6 was of higher grade than that from the other four holes. The high-grade ore in bed 1, however, was considered too thin (0.15-0.30 meter) to be of commercial significance. All of the samples from bed 2 of hole WT-5 were suitable for testing, so they all were included in a single composite (composite C4). The ore from the upper part of bed 2 of hole WT-6 was composited separately (composite C5) from that in the lower part (composite C6) because there were significant differences in quality.

Preliminary grinding and sizing tests indicated that the beneficiation conditions used in treating the adit sample in 1968 were suitable for the drill core composite samples. Pebbles were slightly more effective than steel balls in preferentially grinding the phosphate, and sizing at 100 mesh afforded the best compromise between recovery of phosphate and rejection of quartz. For the beneficiation tests, a 300-gram portion of each composite was ground for 90 minutes with 900 grams of 3/4-inch pebbles, and the ground solids were screened wet on 65- and 100-mesh screens. Wet screening was used only for convenience. In actual practice, a dry air classification would be used.

The resulting size fractions were dried, weighed, and analyzed. The results are given in table 13. A plot of the $P_2O_5$ contents versus the acid-insoluble contents of the fractions (fig.10) gave a relation similar to that obtained for the outcrop ore, and factors derived from this plot were used to estimate the approximate mineral contents of the fractions, which are included in table 13. The degrees of beneficiation achieved by the treatment are evident from table 13 by comparing the $P_2O_5$ concentrations in the head samples with the corresponding $P_2O_5$ concentrations in the minus 100-mesh concentrates. Percent recoveries of the head $P_2O_5$ as minus 100-mesh concentrates are given under the heading "$P_2O_5$ distribution, %,"

Results of the beneficiation tests show that the core samples resembled the outcrop ore in two respects: (1) most of the silica was plus 100 mesh and (2) most of the phosphate could be ground preferentially to minus 100 mesh. However, the core samples contained considerably more clay than the outcrop ore, and as has been discussed, this clay was not removable by initial sizing such as had been effective with the outcrop sample. The clay content of the six core composites was about as great as the silica content. Since the clay was ground along with the phosphate, enrichment was impaired and the iron and aluminum contents of the concentrates (-100 mesh fractions; table 13) were relatively high. The lime content of the core composites also was greater than that of the outcrop ore. The $CaO:P_2O_5$

**Table 13.- Beneficiation of composited core samples of Saudi Arabia Phosphate by dry grinding and wet screening**

| Core samples | | Size fraction, mesh | Solids distribution, % | Analysis, % | | | | | | Ratio, CaO:$P_2O_5$ | $P_2O_5$ distribution, % | Approximate mineral content, % | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Composite No. | Lab. No. | | | $P_2O_5$ | CaO | $Al_2O_3$ | $Fe_2O_3$ | Acid insol. | $CO_2$ | | | Phosphate[a] | Clay[b] | Silica[c] |
| C1 | 6 and 7 | +65 | 16.8 | 10.1 | 14.6 | - | - | 69.8 | 1.4 | 1.45 | 8.1 | 27 | 6 | 67 |
| | | -65 +100 | 11.3 | 18.3 | 26.5 | - | - | 49.6 | 1.5 | 1.45 | 9.8 | 48 | 4 | 48 |
| | | -100 | 71.9 | 24.0 | 35.5 | 3.0 | 3.3 | 22.5 | 3.0 | 1.48 | 82.1 | 63 | 26 | 11 |
| | | Cum. head | 100 | 21.0 | 31.0 | - | - | 33.5 | 2.6 | 1.47 | 100 | 55 | 21 | 24 |
| C2 | 13, 14 | +65 | 14.2 | 26.7 | 40.5 | - | - | 13.3 | 5.5 | 1.52 | 19.3 | 70 | 30 | 0 |
| | | -65 +100 | 7.8 | 31.5 | 46.3 | - | - | 7.0 | 3.4 | 1.47 | 12.5 | 93 | 0 | 7 |
| | | -100 | 78.0 | 17.1 | 27.5 | 7.7 | 4.3 | 28.3 | 3.7 | 1.61 | 68.0 | 45 | 49 | 6 |
| | | Cum. head | 100 | 19.6 | 30.9 | - | - | 24.5 | 3.9 | 1.59 | 100 | 52 | 42 | 6 |
| C3 | 19-22 | +65 | 33.4 | 4.3 | 8.0 | - | - | 87.0 | 0.8 | 1.86 | 8.7 | 11 | 3 | 86 |
| | | -65 +100 | 9.4 | 10.3 | 18.0 | - | - | 69.8 | 1.1 | 1.75 | 5.8 | 27 | 6 | 67 |
| | | -100 | 57.2 | 24.9 | 39.5 | 1.6 | 1.1 | 23.7 | 3.2 | 1.59 | 85.5 | 65 | 20 | 15 |
| | | Cum. head | 100 | 16.7 | 26.9 | - | - | 49.2 | 2.2 | 1.69 | 100 | 44 | 13 | 43 |
| C4 | 34-41 | +65 | 8.7 | 7.9 | 12.0 | - | - | 76.4 | 1.1 | 1.52 | 2.7 | 21 | 5 | 74 |
| | | -65 +100 | 8.7 | 18.9 | 28.7 | - | - | 49.3 | 2.0 | 1.52 | 6.5 | 50 | 2 | 48 |
| | | -100 | 82.6 | 28.0 | 42.7 | 1.6 | 2.1 | 15.7 | 2.7 | 1.53 | 90.8 | 74 | 19 | 7 |
| | | Cum. head | 100 | 25.5 | 38.8 | - | - | 23.9 | 2.5 | 1.53 | 100 | 67 | 16 | 17 |
| C5 | 43-45 | +65 | 17.7 | 27.5 | 40.3 | - | - | 25.6 | 1.8 | 1.47 | 15.7 | 72 | 4 | 24 |
| | | -65 +100 | 17.4 | 31.3 | 45.9 | - | - | 16.7 | 2.0 | 1.47 | 17.6 | 82 | 2 | 16 |
| | | -100 | 64.9 | 31.8 | 47.1 | 1.3 | 2.9 | 7.8 | 3.0 | 1.48 | 66.7 | 83 | 16 | 1 |
| | | Cum. head | 100 | 31.0 | 45.7 | - | - | 12.5 | 2.6 | 1.48 | 100 | 81 | 11 | 8 |
| C6 | 46-50 | +65 | 13.0 | 8.1 | 14.4 | - | - | 77.4 | 0.8 | 1.78 | 5.6 | 21 | 3 | 76 |
| | | -65 +100 | 15.0 | 12.9 | 20.7 | - | - | 63.4 | 1.1 | 1.60 | 10.3 | 34 | 5 | 61 |
| | | -100 | 72.0 | 21.9 | 39.9 | 1.9 | 3.6 | 24.6 | 5.0 | 1.82 | 84.1 | 58 | 32 | 10 |
| | | Cum. head | 100 | 18.8 | 37.3 | - | - | 37.7 | 3.9 | 1.78 | 100 | 49 | 24 | 27 |
| C6a | 46-48 | +65 | 4.0 | 17.6 | 24.7 | - | - | 51.6 | 1.1 | 1.40 | 3.0 | 46 | 4 | 50 |
| | | -65 +100 | 15.0 | 16.7 | 23.1 | - | - | 56.5 | 1.0 | 1.38 | 10.7 | 44 | 0 | 56 |
| | | -100 | 81.0 | 24.9 | 39.1 | 2.5 | 4.4 | 18.7 | 4.4 | 1.57 | 86.3 | 65 | 29 | 6 |
| | | Cum. head | 100 | 23.4 | 36.1 | - | - | 25.7 | 3.7 | 1.54 | 100 | 62 | 23 | 15 |

[a] $2.63 \times P_2O_5$. $2.63 = \dfrac{100}{38\text{(intercept on } P_2O_5 \text{ axis)}}$

[b] $1.82\ X$. $1.82 = \dfrac{100}{100 - 45 \text{ (intercept on acid-insoluble axis)}}$

$X = 100 - (2.63\ P_2O_5 + \text{acid insoluble})$

[c] By difference.

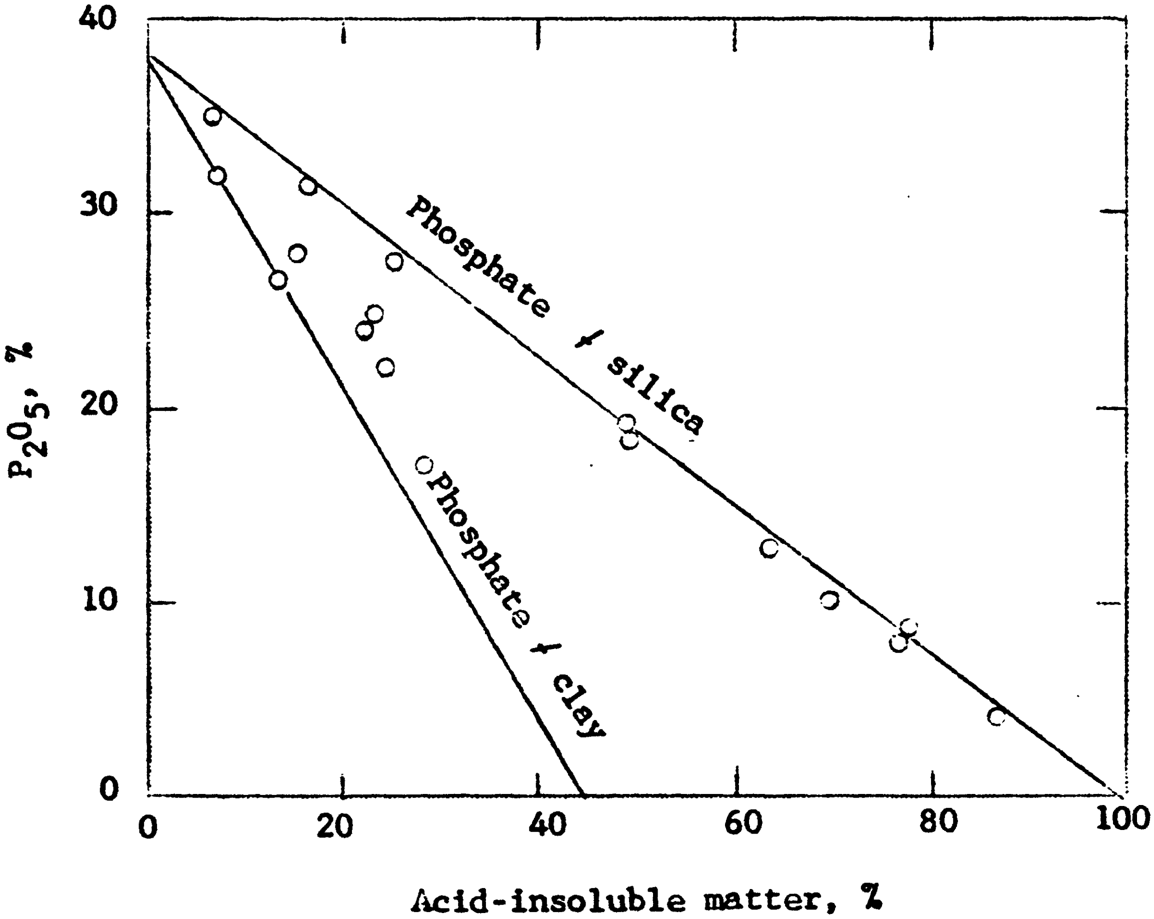



Figure 10.- Relation between $P_2O_5$ and acid-insoluble contents of size fractions of dry-ground Saudi Arabian phosphate ore

ratio in the composites ranged from 1.47 to 1.78 as compared with 1.46 in the outcrop sample. The beneficiation treatment afforded no significant separation of limestone from phosphate -- the average ratio of $CaO:P_2O_5$ in the concentrates (1.58) was about the same as that in the head composites (1.59).

Only composite C5 yielded a concentrate that contained more than 28% $P_2O_5$. The relatively high $P_2O_5$ content (31.8%) of this concentrate was due to the high initial $P_2O_5$ content (31.0%) of the ore composite, rather than to the beneficiation treatment. Enrichment due to the treatment was negligible. The concentrate of next highest $P_2O_5$ content (28.0% $P_2O_5$) was from composite C4. The beneficiation treatment of this composite raised the grade from an initial 25.5% $P_2O_5$ content, and recovery as concentrate was 90.8%. The concentrates from composites C1, C3, and C6 contained 21.9 to 24.9% $P_2O_5$ as compared with initial $P_2O_5$ concentrations of 16.7 to 21.0% in the ore (head sample). Recoveries of $P_2O_5$ were 82 to 85%. The remaining concentrate, from composite C2, contained only 17.1% $P_2O_5$. This composite did not contain as much limestone as expected, but contained a large amount of clay instead. Because of its high clay and low quartz content, the plus 100-mesh fraction of this sample was of higher grade (19.6%) than the minus 100-mesh fraction, although most of the phosphate was in the fines.

The results of these dry-beneficiation tests are unpromising. Also, because of the softness of the phosphate, wet methods of beneficiation such as flotation or washing probably would result in low recovery of phosphate. No further work with the ore is planned.

## Summary

Previously (June 1968 report) study of the beneficiation of a sample of phosphate ore from a deposit located in West Thaniyat, Saudi Arabia, had indicated promise for a beneficiation method that involved (1) screening at 10 mesh to remove clay lumps, (2) dry grinding of the minus 10-mesh material to preferentially pulverize the phosphate in the presence of quartz impurity, and (3) air classification at 100 mesh to separate the pulverized phosphate from the quartz. In an extension of this study, 49 core samples from the same deposit now have been evaluated, with the conclusion that this type of beneficiation would not be applicable to the bulk of the ore in the deposit. Most of the core samples were much higher in clay content than the sample tested previously, and this clay was not in a lump form that could be separated by coarse screening. The clay was so soft that it remained with the phosphate throughout the later grinding-sizing procedure. Of concentrates prepared by beneficiation of six composite samples that represented the more promising areas of the deposit, only one contained more than 28% $P_2O_5$, and the $P_2O_5$ concentration (31.8%) in this concentrate was not significantly greater than that (31.0%) of the sample before beneficiation. Concentrates from the other composites ranges in $P_2O_5$ content from 17 to 28% as compared with $P_2O_5$ contents of 17 to 25% in the unbeneficiated samples. Because of the softness of the phosphate, wet methods of beneficiation such as flotation or washing probably would result in low recovery of phosphate. No further work with the ore is planned.

## Appendix

The data for the composite sample C-6 representing the lower portion of bed 2, hole WT-6 (Lab. Samples 46-50, table 12) indicated significant differences from sample C-5, representing the upper part of bed 2, hole WT-6. A major factor contributing to this difference was the inclusion of fractions in the composite C-6, which were not representative of the best ore in the bed. The inclusion of the lower two fractions, Lab. Samples 49 and 50 (table 12) in composite C-6, had a distorting effect on the composition of the sample and its response to beneficiation. A new composite, C-6a, was prepared from weighted portions of samples, Lab. Nos. 46, 47, and 48 (table 12) and this composite sample was treated by the beneficiation procedure used on the other drilling sample composites. The results of the tests on sample C-6a are shown in table 13.

The data in table 13 show that exclusion of the low-grade fractions from the composite representing the lower portion of bed 2, hole WT-6, resulted in significant upgrading of the head sample. The sample C-6a contained much less silica, slightly less CaO, but significantly more $P_2O_5$. The $CaO/P_2O_5$ ratio was about normal. However, sample C-6a showed less response to beneficiation than sample C-6 because most of the clay fraction appears to have remained with the partials in the new composite and reported with the minus 100-mesh portion as might have been expected. Evaluation of hole WT-6 on the basis of composite C-6a, rather than composite C-6, raises the overall quality of the ore represented by hole WT-6. However, the ore at WT-6, already considered to contain the highest quality ore found at West Thaniyat, continued its poor response to beneficiation by the technique tested.

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