

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Preliminary Geologic Map of the Wadi As Sirhan Quadrangle, sheet 30C,
Kingdom of Saudi Arabia

by

C.R. Meissner 1/, Jr., M.B. Griffin, G.P. Riddler, Marcel Van Eck,
N.C. Aspinall, A.M. Farasani, and S.M. Dini

Open-File Report 90-263

Report prepared by the U.S. Geological Survey in cooperation with the
Deputy Ministry for Mineral Resources, Saudi Arabia

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

1/ U.S. Geological Survey

CONTENTS

	Page
ABSTRACT.....	1
INTRODUCTION.....	2
Location.....	2
Previous investigations.....	2
Present work.....	4
Acknowledgments.....	4
GEOLOGIC SETTING.....	5
PHANEROZOIC SEDIMENTARY ROCKS.....	5
Tayyarat formation.....	5
Tawil Formation.....	7
Sudair Shale.....	8
Cretaceous rocks, undivided.....	8
Aruma Formation.....	9
Turayf group.....	10
Jalamid formation.....	10
Thaniyat Phosphorite member.....	10
Kuwaykabah member.....	11
Mira formation.....	11
Ghinah Phosphorite member.....	11
Hawsa member.....	12
Sib member.....	12
Umm Wu'al formation.....	13
Hidrij member.....	13
Arqah Phosphorite member.....	13
Al Amud member.....	14
Hamad member.....	14
Tarbah member.....	14
Shihiyah member.....	14
Turayf group, undivided.....	15
Sirhan formation.....	16
VOLCANIC ROCKS.....	17
QUATERNARY DEPOSITS.....	19
Duricrust.....	19
Unconsolidated surficial deposits.....	20
Gravel (Al Busayta).....	20
Terrace deposits.....	22
Sabkhas.....	22
Alluvial and eolian deposits.....	22

	Page
STRUCTURE.....	23
ECONOMIC GEOLOGY.....	24
Phosphorite.....	24
Thaniyat Phosphorite member.....	24
Ghinah Phosphorite member.....	25
Sib member.....	25
Arqah Phosphorite member.....	25
Oil and gas.....	25
Opal claystone.....	26
DATA STORAGE.....	29
Data file.....	29
Mineral Occurrence Documentation System.....	29
REFERENCES CITED.....	30

ILLUSTRATIONS

[Plates in pocket]

Plates

1. Geologic map of the Wadi as Sirhan quadrangle, Sheet 30 C, Kingdom of Saudi Arabia.
2. Detailed geologic maps of parts of the Wadi as Sirhan quadrangle.

Figures

1. Location map of the Wadi as Sirhan quadrangle and surrounding area..... 3
2. Schematic lithostratigraphic column of rocks in the Wadi as Sirhan quadrangle..... 6

TABLES

Table

1. Chemical composition of phosphorites..... 27

PRELIMINARY GEOLOGIC MAP OF THE WADI AS SIRHAN QUADRANGLE, SHEET 30 C, KINGDOM OF SAUDI ARABIA

By

C. R. MEISSNER, Jr., M. B. GRIFFIN, G. P. RIDDLER,
MARCEL VAN ECK, N. C. ASPINALL, A. M. FARASANI,
AND S. M. DINI

ABSTRACT

The Wadi as Sirhan quadrangle lies in the northwestern part of Saudi Arabia on the border with Jordan. It is located in the west-central part of the Sirhan-Turayf basin and is underlain by Silurian to Miocene-Pliocene sedimentary rocks that are partly covered by volcanic flows. The map area also contains large areas of surficial sand and gravel.

The study area is mainly a structural depression formed by the Wadi as Sirhan graben complex, and it is flanked by highlands of moderate altitude. The Wadi as Sirhan graben is believed to have been formed by tensional forces associated with rifting in the Red Sea.

The map area contains the Thaniyat, Ghinah, and Arqah phosphorite members, and the phosphate-bearing Sib member. Hypothetical estimates of mineral resource potential of the phosphate rock in the quadrangle are high, but most prospects are either covered with too much overburden or are too thin and of too low a grade to be considered for economic exploitation at this time.

Several deep drill holes in the Wadi as Sirhan depression have penetrated thick sequences of marine rocks that are potential sources of oil and gas. Geological and geophysical conditions are favorable for the accumulation of hydrocarbons, and additional exploration is recommended.

INTRODUCTION

LOCATION

The Wadi as Sirhan 1:250,000-scale quadrangle, sheet 30 C, is located in northwestern part of the Kingdom of Saudi Arabia, about 1,000 km north of Jeddah, and lies between lat 30° 00'-31° 00' N. and long 37° 30'-39° 00' E. It includes Saudi Arabia's western border with the Hashemite Kingdom of Jordan (fig. 1).

Much of the area is occupied by Wadi as Sirhan, a broad, elongate trough that trends southeastward across the quadrangle and contains scattered, irregular-shaped, mostly low-lying (3 to 6 m high) outcrops surrounded by sand and gravel. Hazawza is a prominent sabkha at the north end of Wadi as Sirhan. Al Busayta, a large featureless gravel plain, lies in the south-central part of the quadrangle. Cenozoic lava flows and volcanic cones of Al Harrah cover the northeastern part of the map area, part of which contains windows that expose the underlying sedimentary rocks. These windows of sedimentary rock are located in the Al Amud phosphate-bearing area. The southwestern corner of the quadrangle contains a deeply dissected plateau comprising hills of moderate altitude bisected by several large wadis; these hills are located in the northern part of the phosphate-bearing Southwestern Area, also known as the Thaniyat area. [Note: Griffin and others (1984) refer to the Thaniyat phosphate-bearing area as the "Southwestern Area" probably because it has a broader connotation than the more restrictive name of Thaniyat.]

In recent years, agriculture has become important in the map area, especially in the vicinity of Tabarjal in Wadi as Sirhan. Deep water wells supply irrigation water to farms that produce wheat and mixed crops of fruits and vegetables. Other smaller communities near shallow water wells support groves of date palms. Since early times, oases along Wadi as Sirhan attracted inhabitants who lived in adobe houses; now abandoned, these structures are picturesque reminders of a former way of life.

A modern paved highway that traverses the quadrangle from the southeast to the northwest connects with Al Jawf and Sakakah to the southeast and Tabuk to the southwest; it leads northward to the border with Jordan.

PREVIOUS INVESTIGATIONS

Bramkamp and others (1963) mapped the geology of the quadrangle at a scale of 1:500,000. The sedimentary geology of the region was described by Powers and others (1966) in a report that encompasses the sedimentary geology of Saudi Arabia. Reconnaissance mapping of the phosphate-bearing rocks and the general geology of the Wadi as Sirhan area was done by Mytton (1966) and Meissner and Ankary (1972). Several reports on the geology of Jordan pertain to adjacent areas in Saudi Arabia, especially in the vicinity of Wadi as Sirhan. These reports include Quennell

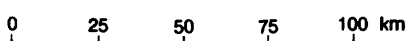
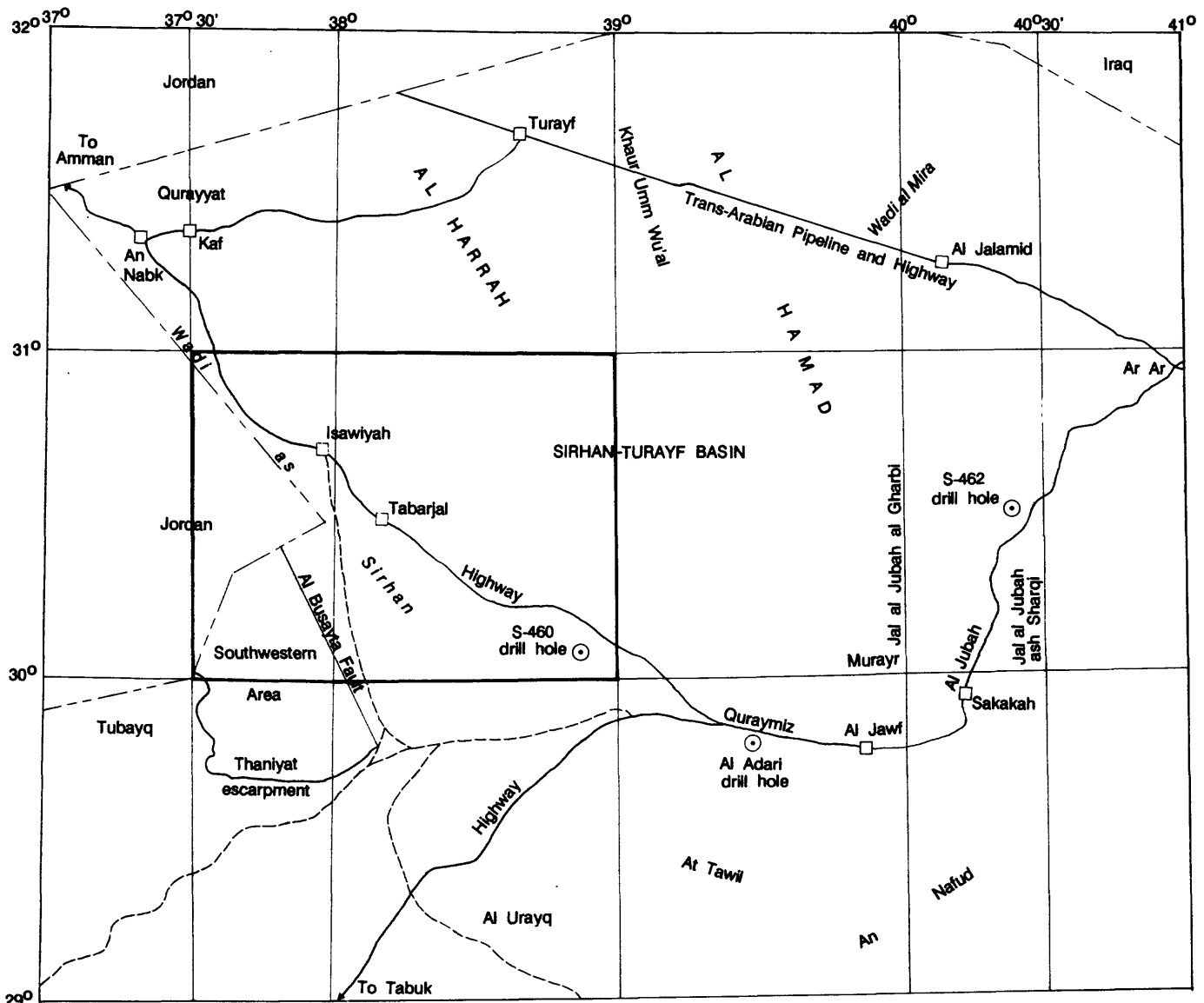
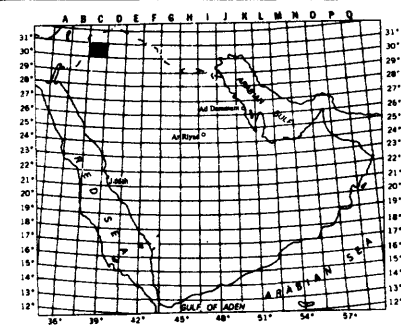


FIGURE 1.—Location map of the Wadi as Sirhan quadrangle and surrounding area.



(1951, 1958), Gardner (1955), McKelvey (1959), Burdon and Quennell (1959), and Bender (1974, 1975).

In 1976, Riofinex Limited was requested by the Directorate General for Mineral Resources (DGMR) to undertake a phosphate resource assessment of the Sirhan-Turayf region, including parts of the Wadi as Sirhan quadrangle. Several Riofinex reports were published describing the phosphate-bearing rocks of Cretaceous and Tertiary age; these include Futyan and Nicholson (1979), Bayliss (1981, 1983), Kluyver and others (1981), Riddler and others (1983), Riddler and van Eck (1984), and Riddler and others (1984). Riofinex reports that include the geology and phosphorite resources of parts of the map area are Smith (1983), Griffin and others (1984), Aspinall and others (1985), and Riddler and others (1986).

PRESENT WORK

The geologic map of the Wadi as Sirhan quadrangle (pl. 1) was compiled from unpublished data that included twelve 1:50,000-scale maps produced by Riofinex as part of its phosphate resource assessment; these maps are stored in Riofinex Data File RF-DF-00-05. Additional data for the Wadi as Sirhan depression, the Busayta plains, and part of the Al Harrah basalt flows was provided from mapping by the U. S. Geological Survey conducted during October, November, and December of 1986.

The lithostratigraphic framework of the Late Cretaceous-Tertiary rocks (the Turayf group) was established by Riofinex (Riddler and others, 1984); the description of the pre-Tertiary rocks and post-Turayf group Tertiary rocks was done by the U. S. Geological Survey. The lithostratigraphic nomenclature used in this report is in accordance with the DGMR Stratigraphic Code, but many names are new and not yet formalized.

ACKNOWLEDGMENTS

The authors wish to express appreciation for the sample preparation and analyses of basalt samples performed by the U. S. Geological Survey laboratories, Jeddah, and thank J. E. Quick and C. R. Thornber for helpful discussions on the petrology of the Al Harrah basalt.

The authors also wish to express appreciation and thanks for the outstanding field support provided by the U.S. Geological Survey Field Services office, the former Riofinex Geological Mission, and Special Flights Services of the DGMR.

The work leading to this report was performed in accordance with a work agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U. S. Geological Survey, designated as Subproject 2.11.01 under the DGMR Work Program.

GEOLOGIC SETTING

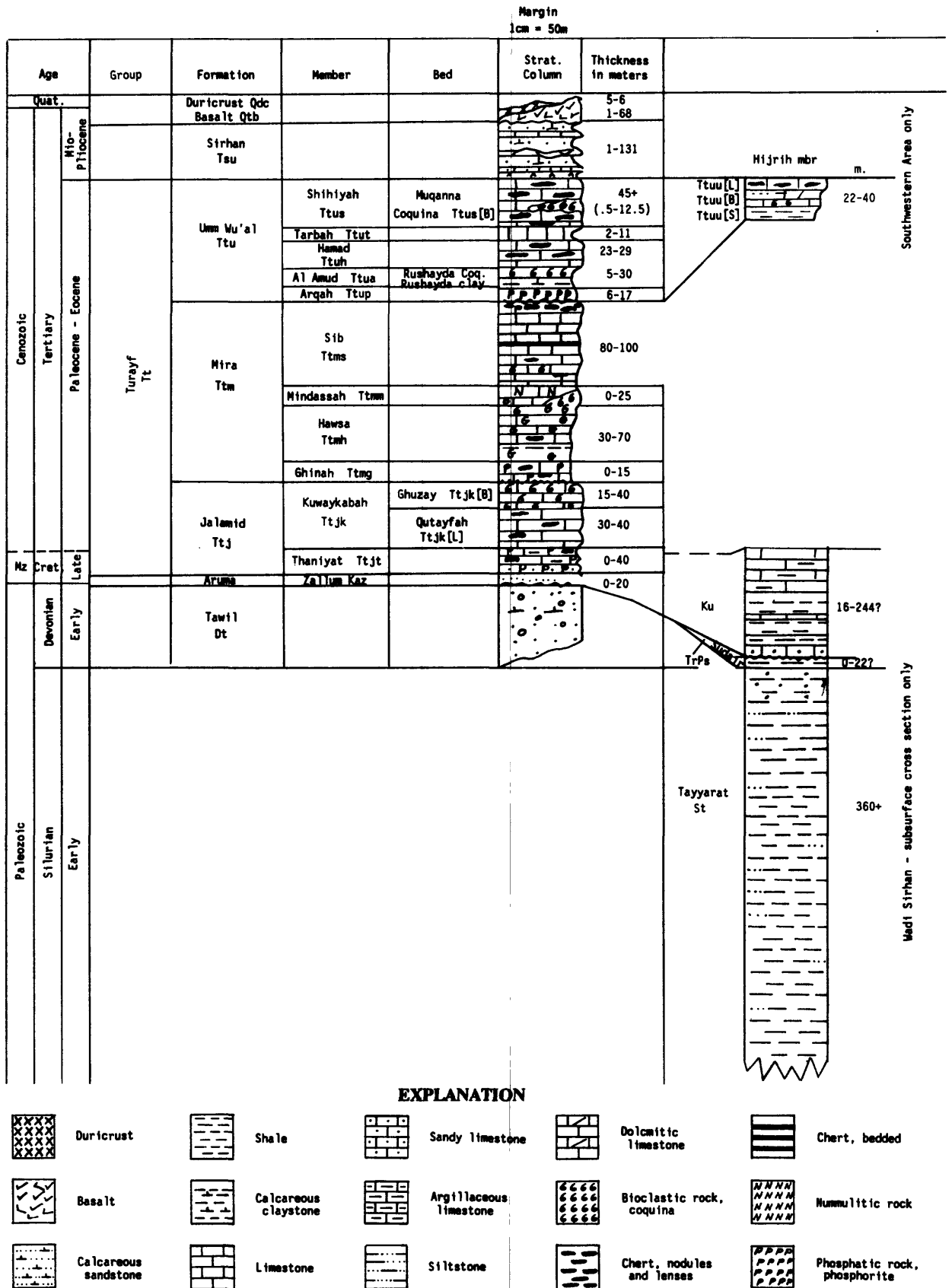
The Wadi as Sirhan quadrangle is located in the west-central part of the Sirhan-Turayf basin of northwestern Saudi Arabia (fig.1; Regional Geologic Setting, pl. 1). The Sirhan-Turayf basin is a shallow sedimentary basin that extends north and west into Iraq and Jordan. Sedimentary rocks and surficial deposits range in age from Cambrian to Recent with a maximum thickness of at least 2,300 m (Powers and others, 1966). The east side of the basin is flanked by the Hail Arch, a broad anticlinal feature that is thought to separate sedimentary facies of the Arabian Gulf from those of the Mediterranean basin (Powers and others, 1966, p.D103-104). The central part of the map area is located in the Wadi as Sirhan graben complex: it is bounded by the Al Busayta fault to the west and the Wadi as Sirhan and Al Khalad-Al Misma faults to the east. Prominent northwest- and northeast-trending lineaments are visible on Landsat imagery and aerial photographs. Those on the west side of the basin are probably related to movement of the Wadi as Sirhan graben, while those on the east side may be related to uplift and other structural movement along the Hail Arch. Tertiary-Quaternary volcanism produced an extensive lava field in the middle of the Sirhan-Turayf basin, a large part of which lies within the map area.

PHANEROZOIC SEDIMENTARY ROCKS

Surface exposures of Phanerozoic rocks in the map area include those of Early Devonian, Late Cretaceous, and Tertiary through Quaternary age, and are described from surface mapping, outcrop sections, and shallow-drill-hole data (fig. 2; cross section A-A', pl. 1). Rocks described from subsurface data only include those of the Early Silurian, Triassic-Permian, and Cretaceous penetrated in two widely spaced deep drill holes (fig. 2; cross section B-B', pl. 1).

TAYYARAT FORMATION

The oldest rocks described in the map area are Early Silurian (Llandoveryan) shale and siltstone. They were penetrated in the Al Isawiyah water well (lat 30° 44' N., long 37° 59' E.) from 991 m to the total depth of the hole (1,449 m), and in the Aramco S-460 drill hole (lat 30° 07' N., long 38° 49' E.) from 617 m to the total depth of the hole (978 m) (Aramco, unpub. data); they do not crop out in the map area (cross section B-B', pl. 1). These rocks, tentatively correlated with the Tayyarat formation (St) (Vaslet, 1987), were formerly assigned to the middle part of the Tabuk Formation. The type locality of the Tabuk Formation (Powers, 1968) is in the vicinity of the town of Tabuk, about 300 km southwest of the map area, where the type sequence was composited from several sections totalling 1,071.5 m. The age of the Tabuk at its type locality is Ordovician, Silurian, and Early Devonian.



EXPLANATION

FIGURE 2 -- Schematic lithostratigraphic column of the Wadi as Sirhan quadrangle

The Tayyarat formation in the Al Isawiyah water well consists of dark gray, fissile shale that breaks into hard, sharp chips. Chitinozoan and acritarch marine palynomorphs were identified in the shale, both of which are excellent indicators of a Llandoveryan age. The Chitinozoan assemblage contains *Clathrochitina carminae*, *C. sylvanica*, *Ancyrochitina ancyrea*, *Conochitina gordonensis*, and *Sphaerochitina longicollis*. The acritarch assemblage contains *Geron gracilis*, *Baltishphaeridium denticulatum*, *Neoveryhachium carminae*, *Baltisphaeridium cymula*, and many others (Aramco, unpub. data).

No drill samples were available of the Tayyarat in the Aramco S-460 drill hole, but equivalent rocks in the Al Adari water well (lat 29° 50' N., long 39° 30' E.), about 70 km southeastward in Wadi as Sirhan, contained essentially the same assemblages of Early Silurian palynomorphs as identified in the Al Isawiyah well. According to the lithologic log from Aramco S-460, the Tayyarat formation consists of partly silty shale, subordinate interbedded silty shale and siltstone, and a minor amount of sandstone at the top of the stratigraphic sequence that possibly is a facies of the Tawil formation.

The Tayyarat Formation was deposited in a transgressive marine environment, partly in an outer-shelf domain (Vaslet, 1987). It is in unconformable contact with the overlying Sudair Shale, or where the Sudair is absent, with overlying undivided Cretaceous rocks (cross section B-B', pl. 1).

TAWIL FORMATION

The Early Devonian Tawil Formation (Dt) is absent in the Al Isawiyah drill hole, but a minor amount of sandstone at the top of the Tayyarat formation in the Aramco S-460 drill hole may be equivalent to the Tawil. It is thought to occur in the subsurface along much of the southern border of the map area (cross section A-A', pl. 1) and is exposed in a small area in the extreme southwestern corner of the quadrangle, at the Jordan border, where it is directly overlain by Late Cretaceous and Tertiary rocks.

The Tawil Formation is equivalent to the original "Tawil Member" of Powers and others (1966) and Powers (1968). At the 23rd meeting of the DMMR Stratigraphic Committee, a proposal was made by D. Vaslet (BRGM) to revise the nomenclature for the Tabuk Formation of Powers (1968). This led to the abandonment of the term "Tabuk Formation" and a change in rank of the "Tawil Member" to "Tawil Formation". For the purposes of this report, however, the type section of the "Tawil Member" in the north-facing escarpment of At Tawil (lat 29° 29' N., long 39° 30' E.) is retained for the Tawil Formation.

The Tawil consists of tan to light-gray sandstone that weathers dark reddish brown to black. The sandstone is medium to coarse grained and contains scattered quartz pebbles; in many places, the sandstone is hardened by ferruginous cement.

Iron concretions are a common feature, as well as thick, high-angle cross-beds. The Tawil is medium to thick bedded. It contains minor thin interbeds of shaly and silty sandstone that is calcareous in most places. A section of the formation only a few meters thick is exposed within the map area, but it is over 200 m thick at its type locality (located about 75 km southeast of the quadrangle). Its depositional environment is believed to have been fluvial deltaic (Lozej, 1984).

SUDAIR SHALE

The type section of the Sudair Shale (TrPs) has been pieced together from three sequences exposed along the Al Arid escarpment, at the west edge of the Rub Al Khali (lat 19° 17'-19° 36' N. and long 45° 06'-45° 08' E.) (Powers, 1968). At its type locality, the Sudair consists of 116 m of brick- to dark-red shale that is locally silty. It contains no fossils and its age designation as "Lower" Triassic- "Upper" Permian is based on stratigraphic position and well-dated subsurface equivalent rocks. However, in recent lithostratigraphic and paleoenvironmental studies, Vaslet and others (1986) have found Jurassic fossils in the designated type section of the Sudair and conclude that the facies originally assigned to the Sudair Shale falls entirely within the Jurassic Dhurma Formation. Vaslet and others (1986) have proposed a new reference outcrop section for the Early Triassic (Sythian) Sudair Shale in the Qasim area of central Saudi Arabia, but as yet this proposal has not been formalized.

In the Al Isawiyah well, the interval between 969 and 991 m contains reddish-gray to reddish-brown shale believed to be the Sudair. The shale is semi-fissile to semiacicular and is slightly calcareous. The Sudair Shale is absent in the Aramco S-460 drill hole.

The Sudair was deposited in a restricted sea/closed basin environment (Powers, 1968; Vaslet and others, 1986). The stratigraphic relationship infers that the Sudair contact with the overlying Cretaceous rocks in the Al Isawiyah well is unconformable.

CRETACEOUS ROCKS, UNDIVIDED

The interval between 725 and 969 m in the Al Isawiyah well contains limestone and shale interpreted to be part of the Cretaceous rocks sequence (Ku). The limestone is pale to dark gray, micritic, partly argillaceous, hard and brittle; the shale is gray to dark gray and nonfissile. Although no paleontological examination was made of samples from this well, equivalent rocks in the Qurayyat water well (lat 31° 20'08" N., long 37° 20'16" E.), located about 90 km to the northwest in Wadi as Sirhan, contained Cretaceous foraminifera, including *Globotruncana* sp., which identified those rocks as Late Cretaceous.

Only 16 m of Cretaceous rock (between 601 and 617) was identified in the Aramco S-460 drill hole. According to the lithologic log, this interval contains sandy limestone.

The Cretaceous sequence is marine in origin and contact with overlying Paleocene rocks is apparently conformable.

ARUMA FORMATION

The type section of the Aruma Formation is located at the Al'Aramah plateau, more than 1,000 km southeast of the map area, where a composite sequence was reconstructed from several sections located along a traverse from Khashm Khanasir (lat 25° 38'12" N., long 46° 22'29" E.) northeast to a point on the back slope of Al'Aramah escarpment (lat 25° 39'18" N., long 46° 30'41" E.), in which the Aruma Formation is exposed (Powers and others, 1966; Powers, 1968). At the type section, the Aruma is 141.5 m thick and consists of dolomite, limestone, and calcareous shale with a few sandy layers near the bottom of the sequence. The age of the Aruma is Late Cretaceous; diagnostic foraminifera, ostracods, and megafossils are listed in Powers (1968).

Powers (1968, p. 46) described the marked changes of the Aruma in the northern part of its outcrop where at Khashm Zallum (lat 30° 18' N., long 40° 21' E.), in the southeastern part of the Sirhan-Turayf basin, 61 m of sandstone overlies an 11-m-thick basal Aruma limestone bed. The sandstone has been informally called the Zallum sandstone by Powers (1986). To facilitate the production of the base maps for the phosphate resource assessment, the Aruma Formation has been informally redefined in this area by Riofinex (van Eck, 1985). It has three subdivisions, in ascending stratigraphic order: the Hudayb, Zallum, and Badanah members. Of these three members, only the Zallum is thought to occur within the Wadi as Sirhan quadrangle.

The Zallum member (Kaz) is not exposed in the map area, but shallow drilling in the Southwestern (Thaniyat) Area, just north of the southern border of the quadrangle, suggests that it exists in the subsurface (Riddler and others, 1984, fig. 11; also cross section A-A', pl. 1 of this report). The nearest outcrops of the Zallum are in the Thaniyat escarpment (about 35 km to the south), where it consists of buff to yellowish-brown, locally brownish-red and purple very loose, friable, unconsolidated sandstone. Northwest of the Thaniyat escarpment, the Zallum grades from loose sand to limestone, marl, and shale with interbeds of sandstone. Contact with the overlying Thaniyat Phosphorite member of the Turayf group is transitional.

TURAYF GROUP

The Turayf group (Tt) is an informal designation used for the sedimentary phosphatic-carbonate succession of the Sirhan-Turayf basin. The group ranges in age from Late Cretaceous (Maastrichtian) to Middle Eocene (Lutetian) (Riddler and others, 1984) and is subdivided into three formations: the Jalamid, the Mira, and the Umm Wu'al, in ascending stratigraphic order (fig. 2). These formations represent three periods of cyclic carbonate sedimentation comprising repetitive, short, onlapping transgressive-regressive events over a shallow marine shelf, with phosphorite members occurring at the base of each sedimentary formation. An inner shelf subtidal-to-restricted-shelf depositional environment is generally indicated (Riddler and others, 1986). Turayf group rocks have been mapped in the Al Amud area and in the Southwestern Area (Thaniyat) (pl.1). Undifferentiated Turayf group rocks (Paleocene-Eocene) were found in the Al Isawiyah water well and the Aramco S-460 drill hole (cross section B-B', pl. 1).

Descriptions of formations, members, and beds of the Turayf group given in this report are summaries of very detailed descriptions reported by Aspinall and others (1985), Griffin and others (1984), and Smith (1983). Formations and phosphate members of the Turayf group are shown on plate 1. Detailed mapping, done by the Riofinex Geological Mission, showing the formation members and beds of the Turayf group, appears on plate 2. (Note that although the Turayf group, the Jalamid formation, and the Thaniyat Phosphorite member have been assigned the map unit designations Tt, Ttj, and Ttjt, respectively, which indicate wholly Tertiary ages for the units, they do, in fact, extend partly into the Late Cretaceous.

Jalamid Formation

The Jalamid formation (Ttj) takes its name from outcrops around the Al Jalamid pump station located about 125 km northeast of the map area. The Jalamid is exposed in the southwestern corner of the map area and is subdivided into two members, the Thaniyat Phosphorite and Kuwaykabah. In turn, the Kuwaykabah member is subdivided into two beds, the Qutayfah and Ghuzay.

Thaniyat Phosphorite member: The Thaniyat Phosphorite member (Ttjt) takes its name from exposures in the Thaniyat-Turayf escarpment to the south of the map area and consists of a repeated sequence of phosphorite units (each averages 10-30 cm in thickness; locally as thick as 1 m) interbedded with shaly and silty micritic limestone, fissle shale, and some chert beds and nodules. Sandy phosphorite and phosphatic sandstone are common at the base of the member and are probably transitional with the underlying Zallum member. The Phosphorite member is as much as 40 m thick.

The Late Cretaceous (Maastrichtian) to Early Paleocene age of the Thaniyat Phosphorite member was based on microfossils and fish teeth found in the member in the Thaniyat area (Bayliss, 1983; Capetta and Riddler, 1985). Contact with the overlying Kuwaykabah member is conformable.

Kuwaykabah member: This member (Ttjk) and its subdivisions take their names from those of prominent wadis in the Southwestern Area (to the south of the quadrangle) in which the type sections are located. The lower bed of the Kuwaykabah, the Qutayfah bed (Ttjk[L]), ranges in thickness from 30 to 40 m. It consists of generally well-bedded, white or buff- to pink-stained partially recrystallized micritic limestone, and partly shaly leached micritic limestone, with grayish-brown chert nodules and lenses. Some thin bioclastic limestone interbeds are present that contain fossilized bivalve and gastropod shell fragments. The limestone at the base of the bed is slightly porous and silty, whereas secondary calcite is common toward the top. Its age is presumed to be Early Paleocene. The upper bed of the Kuwaykabah, the Ghuzay bed (Ttjk[B]), ranges in thickness from 15 to 40 m. It consists of buff to brown bioclastic limestone containing bivalve and gastropod fragments. Some shells are replaced by coarse calcite, and calcite is also present in vugs and veins. The top of the Ghuzay (and, therefore, the top of the Kuwaykabah member), is disconformable with the overlying Ghinah Phosphorite member of the Mira formation.

Mira Formation

The Mira formation (Ttm) takes its name from Wadi al Mira in the north-eastern part of the Sirhan-Turayf basin. It is exposed in the southwestern part of the map area where it is divided into four members: the Ghinah Phosphorite, the Hawsa, the Mindassah, and the Sib, in ascending stratigraphic order. The Mindassah member is not a mappable unit in the Wadi as Sirhan quadrangle; it is represented either as bioclastic limestone within the Hawsa or it is absent.

Ghinah Phosphorite member: The Ghinah Phosphorite member (Ttmg) ranges in thickness from 0 to 15 m and is found on slopes and ridges of the sharply dissected carbonate hills characteristic of the southwestern corner of the map area. Bedded exposures of the member occur in the central and western parts of Wadi al Ghinah, from which it takes its name. However, the type sections described for the Ghinah Phosphorite are located in the Thaniyat Turayf quadrangle to the south of the map area at Wadi al Kuwaykabah (lat 29° 54' N., long 37° 36' E.) and Jibal al Hawsa (lat 29° 43' N., long 37° 50' E.). The member consists of an interbedded sequence of as many as four thin (10-30 cm) phosphorite beds and slightly phosphatic micritic limestone, claystone, fissile shale, and chert. The phosphorite is semifriable to hard and carbonate cemented with fecal pellets, bioclastic debris, and fossil sharks' teeth. The uppermost phosphorite bed is commonly conglomeratic and contains poorly sorted phosphate pellets, quartz grains, and chert pebbles; its matrix is stained green (glauconitic?). The top of the member consists of highly fissile buff to yellow shale that grades upward into greenish-gray claystone. The shale and claystone are slightly phosphatic and contain small geodes.

Age determinations on diagnostic dinoflyte cysts collected from shale in the Ghinah Phosphorite indicate a Late Paleocene to Early Eocene age for the member. Contact with the overlying Hawsa member is conformable.

Hawsa member: The Hawsa member (Ttmh) crops out on hilltops above the Ghinah Phosphorite in scattered areas in the southwest corner of the quadrangle. The type locality of the Hawsa member is in the Thaniyat Turayf quadrangle to the south of the map area at Jibal al Hawsa. It ranges in thickness from 30 to 70 m and consists of generally well-bedded limestone and claystone interbedded with chert, shale, and bioclastic limestone. Its base is composed of slightly phosphatic geode-bearing claystone that is overlain by a thin interval of siliceous and carbonate-cemented phosphorite and gray chert. Above the base is highly fissile buff to yellow shale and leached, powdery micritic limestone. The upper part of the member consists of geode-bearing micritic limestone and bedded and nodular gray chert. The top of the member is made up of limestone that contains nummulite, gastropod, and bivalve fossils. This unit in the map area replaces the Mindassah member so that the Hawsa is directly overlain by the Sib member.

Early Eocene *Nummulites planulatus* have been identified in the Hawsa in the Southwestern Area (pl.1) near the Thaniyat escarpment (Bayliss, 1983).

Sib member: The Sib member (Tms) takes its name from the Khabra as Sib, in the Ash Shuwaytayah quadrangle to the east of the map area, around which are the type localities comprising three sections (lat 30° 31' N., long 39° 10' E.; lat 30° 22' N., long 39° 10' E. and lat 30° 12' N., long 39° 39' E.). In the Southwestern Area, the Sib is chiefly represented by siliceous float capping gently undulating hills. Some bedded outcrops are found in wadi banks where the member consists of 20-50-cm-thick beds of pale-gray silicified limestone comprised of coarse calcite, chert breccia, and sparry, recrystallized nonsilicified micrite interbedded with chert. The Sib also contains intervals of calcareous nummulitic limestone and several thin phosphatic beds that may cover large surface areas because of the gently undulating nature of the terrain. Phosphatic chert is relatively common and some calcareous phosphorite is present. Combined outcrop and drill-hole data indicate that the maximum thickness of the member in the Southwestern Area is 80 m.

The dominance of silicification and calcification within the Sib member suggests that this unit represents a major period of erosion that occurred during a marine regression. Minor transgressional events that occurred during deposition of the Sib are represented by the thin phosphatic intervals. Specimens of Early Eocene *Nummulites planulatus* have been identified in the Sib by Bayliss (1983). The Sib member is in disconformable contact with the overlying Hidrij member of the Umm Wu'al formation in the Southwestern Area (pl. 1). The Sib is also described, mainly from drill-hole data, in the Al Amud area of the northeastern part of the quadrangle, where windows in the Al Harrah basalt flows expose sedimentary rocks of the Turayf group. There is one small outcrop of the Sib near the head of Wadi al Rushayda, on the east-central border of the quadrangle. In the Al Amud area, the Sib member is as much as 100 m thick and the upper part consists of massive, laminated chert and silicified limestone with bands of phosphorite interbedded with gray limestone. In places, there are thick sequences of hard gray limestone that contain layers of brown ovoid chert nodules. Bioclastic limestone containing bivalve and gastropod molds and casts is also present. Brown phosphatic

chert-breccia beds at the top of the Sib are believed to mark the disconformable contact with the overlying Arqah Phosphorite member of the Umm Wu'al formation in the Al Amud area.

The Umm Wu'al Formation

The Umm Wu'al formation (Ttu) crops out in windows of the Al Harrah in the Al Amud area (pl. 1), and in the northern part of the Southwestern Area between the Al Busayta plains and the border with Jordan. It is named from the Khawr umm Wu'al graben, along which it is exposed in the north-central part of the Sirhan-Turayf basin. The Umm Wu'al formation is divided into five members in the Al Amud area: the Arqah Phosphorite, Al Amud, Hamad, Tarbah, and Shihiyah members, in ascending stratigraphic order. However, in the Southwestern Area, the Umm Wu'al is only represented by the Hidrij member, unique to that area and believed to be a deep-water facies of the Umm Wu'al formation.

Benthic foraminifera *Nummulites* sp. (both *N. gizensis* and *N. discorbinus*) and *Operculina* sp., as well as planktonic species, have been identified locally, indicating a Middle Eocene age for the Umm Wu'al formation (Riddler and others, 1985). The Umm Wu'al was deposited in an inner shelf subtidal to restricted-shelf environment. The presence of planktonic foraminifera suggests access to open water.

Hidrij member: The Hidrij member (Ttuu), found only in the Southwestern Area of the quadrangle, is named after the major wadi around which it crops out; it is the deep-water facies of the Umm Wu'al formation. It crops out in elongate ridges and isolated hills above a plain underlain by dark chert, and ranges in thickness from 22 m to more than 40 m. The basal part of the member (Ttuu[S]) consists of yellowish-brown to green highly fissile shale with interbedded shaly to silty dolomitic limestone. The shale is slightly phosphatic, contains secondary gypsum, and is locally bituminous. The middle part of the member (Ttuu[B]) consists of massive, partly dolomitic silty limestone, and claystone containing pale-gray chert fragments. The middle part locally contains a bioclastic limestone containing *Nummulites* sp. of Middle Eocene age, fossilized sharks' teeth and bivalve debris, and scattered phosphate pellets. The top of the member (Ttuu[L]) consists of massive limestone beds that contain ribbon-like bands of light-brown hill-capping chert.

Arqah Phosphorite member: The Arqah Phosphorite member (Ttup) takes its name from the type sections described from drill holes located northeast of the Umm Wu'al graben (MODS 03937). It is exposed near Wadi al Rushayda (pl. 1, Al Amud Area), where it is in contact with the underlying Sib member of the Mira formation. An outcrop of the Arqah Phosphorite located on the north bank of Wadi al Rushayda is referred to as the "shark's tooth locality" and is a popular site for collecting sharks' teeth in the phosphorite beds. The Arqah ranges from 6 to 17 m thick and consists of massive, carbonate-cemented to semifriable, pelletal and finely bioclastic phosphorite interbedded with finely crystalline limestone in the southern

part of the Al Amud Area. Farther south, it consists of interbedded, finely crystalline limestone, brown phosphatic chert, and carbonate-cemented pelletal phosphorites. Silicified phosphorite caps the member. The contact of the Arqah with the overlying Al Amud member is conformable.

Al Amud member: The Al Amud member (Ttua) is 5 to 30 m thick and contains two beds (described separately but mapped as a single unit) in the Al Amud Area (pl. 1), from which it takes its name. The lower bed is the Rushayda Claystone and the upper bed is the Rushayda Coquina. The type section originally described for these beds is located at lat 30° 36' N., long 38° 59' E. in this quadrangle. The Rushayda Claystone, which makes up most of the Al Amud member, forms a distinctive white weathered bed that is an easily recognized stratigraphic marker directly overlying the Arqah Phosphorite. The claystone bed is porous, very thin bedded white to pale yellow and greenish-gray argillaceous limestone and claystone that contain intermittent beds of opal claystone composed mostly of cristobalite and attapulgite (Outerbridge and Meissner, 1985). The opal claystone is very lightweight, has a very fine porosity (adheres to tongue when licked), exhibits a conchoidal fracture, and has a metallic ring when two fragments are struck together. Thin lenses of grayish-brown chert occur locally in the Rushayda Claystone bed.

The Rushayda Coquina bed occurs only in the Wadi al Rushayda area and is composed of bivalve and *Nummulites* sp. coquina. It forms an escarpment and caps the Al Amud member.

Hamad member: The Hamad member (Ttuh), which takes its name from the featureless flat-lying plain of Al Hamad, located to the east of Khawr Umm Wu'al and northeast of this quadrangle, occurs in wadi sections within the Al Harrah openings of the Al Amud Area (pl. 1). It is about 25 m thick and consists of well-bedded, gray to buff micritic limestone containing interbedded brown chert and chert nodules. The Hamad is in conformable contact with the overlying Tarbah member.

Tarbah member: The type locality of the Tarbah member (Ttut) is located at Wadi Tarbah, in the northeastern part of the Al Amud Area (pl. 1). It is composed of chemically pure recrystallized bioclastic limestone that contains clasts of fossilized pelecypods, gastropods, and some bryozoans near the base, while the upper part of the member contains a distinctive nummulitic horizon. The Tarbah effectively separates the Hamad member from the overlying and lithologically similar Shihiyah member, thus providing one of the few marker beds in the upper part of the Umm Wu'al formation. The Tarbah ranges in thickness from 2 to 11 m and the *Nummulites* sp. in the bioclastic limestone are 0.5 to 2.0 cm in diameter.

Shihiyah member: The Shihiyah member (Ttus) is widespread in wadi sections and windows in the basalt of the Al Amud Area. It takes its name from the type locality, Wadi Shihiyah (lat 31° 03' N., long 38° 59' E.), north of this quadrangle. It is 45 m or more thick and consists of rhythmically bedded limestone and chert lenses. The buff to off-white, finely crystalline limestone beds are generally less than 1 m

thick and the chert lenses are 5 to 10 cm thick. A high proportion of the chert is caramel colored, which distinguishes this member from the Hamad. The member also contains chert nodules that are locally phosphatic; gypsum is present along bedding planes. Another distinguishing feature of the Shihiyah is the presence of lenses of "oyster banks" (as much as 12.5 m thick) referred to as the Muqanna Coquina bed (Ttus[B]), in which large oyster-like bivalves are preserved whole. The Muqanna Coquina is believed to have formed several discontinuous banks at different stratigraphic levels within the member. The top of the Shihiyah member, which is also the top of the Turayf group (fig. 2), are in unconformable contact with the overlying Sirhan formation.

Turayf Group, Undivided

The Turayf group undivided (Tt) has been mapped in several isolated localities along the eastern side of the map area where the degree of exposure is insufficient to distinguish individual formations. The Turayf group is also undivided in cross sections A-A' and B-B' (pl. 1) because, in most cases, subsurface data is not complete enough to plot the stratigraphic subdivisions.

Paleocene and Eocene rocks equivalent to those of the Turayf group occur in the Al Isawiyah water well and the Aramco S-460 drill hole in Wadi as Sirhan (cross section B-B', pl. 1). Interpretations of drill-hole sample rock cuttings place the Paleocene-Eocene interval (Turayf group) between 113-725 m (612 m thick) in the Isawiyah well, and between 131-601 m (470 m thick) in the Aramco drill hole. The Turayf group in the Al Isawiyah well consists of limestone, claystone, and chert. The limestone is light grayish brown to gray, dense to cryptocrystalline, partly dolomitic, and contains dark-gray chert lenses and nodules. The claystone is light grayish brown to light gray, calcareous, and partly silty. The limestone and chert contain fine pellets (phosphatic?) in the lower part of the section.

The Turayf group in the Aramco S-460 drill hole consists of limestone, chert, and very small amounts of marl, shale, and sandy limestone. Eocene rocks have been identified in the group from a depth of 131 m to 510 m, and Paleocene rocks are present from 510 m to 601 m (Aramco, unpub. data). The presence of foraminifera, including *Valvulineria* sp., *Virgulina* sp., *Hopkinsina* sp., and *Globorotalia* sp., attest to the marine origin of these rocks. No phosphatic rock was identified in this drill hole.

The Paleocene-Eocene Turayf group section thickens from the southeast to the northwest along Wadi as Sirhan (cross section B-B', pl. 1) and is thicker in the central part of the Wadi as Sirhan graben than it is on its flanks, which may have been at least partly caused by deposition contemporaneous with structural subsidence (cross section A-A', pl. 1).

Sirhan Formation

The youngest Tertiary sedimentary rocks in the Wadi as Sirhan quadrangle are believed to be mostly Miocene in age, but may be in part Pliocene. Fossils are sparse and the number of fossils identified in the formation is presently too small to make positive age designations. These rocks are informally named the "Sirhan formation" for exposures in the Wadi as Sirhan depression that extends diagonally across the quadrangle from its northwestern to southeastern corners.

The Sirhan formation (Tsu) forms discontinuous flat-topped outcrops, generally only a few meters high, scattered about the alluvial plains in the area of Wadi as Sirhan. The formation ranges in thickness from 1 to 131 m and consists of sandstone, limestone, and marl, and contains interbeds of chert and minor claystone.

Sandstone in the Sirhan formation is white, buff to light yellow, light gray, light brown, and brown; it consists of poorly sorted fine to grit-size quartz grains with scattered quartz pebbles. Lenticular beds of quartz conglomerate are included within the sandstone. The quartz grains are a mixture of clear, frosted, and opaque grains that are subangular to subrounded. The sandstone is massive, very calcareous, locally argillaceous, friable, nonresistant, and slope forming. Locally, it is vuggy and bioturbated, and contains large worm-tube casts. It appears to be mostly continental in origin and possibly originated as alluvial fans deposited along the flanks of the Wadi as Sirhan graben.

Limestone beds in the Sirhan formation commonly form the cap rock of the friable nonresistant sandstone. The formation contains two main types of limestone: one is siliceous and chert-like, and the other is sandy with a high clay (marl) content. The siliceous limestone occurs as beds usually no more than 1 m thick. It is white to light gray (in places it is almost black), dense, very hard, and its weathered surfaces have a pock-marked appearance. The limestone is so siliceous that locally it resembles chert and is often associated with white chert beds. The limestone also contains light-gray to light-brown (and rarely black) chert nodules. It is everywhere in close association with sandstone either as a cap rock to forming sandstone or as an interbed in a sandstone slope. The sandy, marly limestone occurs in beds as much as 12 m thick, especially in the northern part of the quadrangle. The limestone is white, semicompact, and contains embedded fine-to-medium-sized quartz grains that are clear to translucent and subangular to subrounded. It is partly resistant and forms irregular ledges.

At least two beds of partly siliceous limestone that cap the low-lying outcrops of the Sirhan formation in Wadi as Sirhan contain vertical burrows, many interconnected, that are very similar to the ichnofossils created by *Scolithos* sp., a bottom-dwelling suspension feeder that lived in a marine intertidal environment. However, *Planorbis* sp., a fresh-water snail, and *Chara* sp., a fresh-water algae, were also found in these limestone beds, suggesting that they represent a fresh-water lake deposit (Aramco, unpub. data).

Fossil echinoids were collected from a sandy marl in the Sirhan formation north of the quadrangle, suggesting that the sandy, marly limestone of the Wadi as Sirhan quadrangle was formed by marine incursions.

There are no exposures of the complete Sirhan formation succession: the thickest exposures are in a small area located about 15 km northwest of the Aramco S-460 drill hole, where as much as 50 m of the formation can be seen in eroded mesas and buttes. However, rocks more than twice that thickness have been penetrated in the Al Isawiyah water well and the Aramco S-460 drill hole. In the Al Isawiyah well, 113 m of Sirhan sandstone, limestone, and shale was encountered, and 131 m of Sirhan sandstone, limestone, and marl was encountered in the Aramco S-460 drillhole (Aramco, unpub. data). These two widely spaced holes contain a similar sequence of Sirhan rocks. The upper part of the sequence is calcareous sandstone, the middle part is interbedded sandstone and partly sandy to marly limestone, and the basal part is claystone or marl. Whether this is a coincidence or indicates the possibility of regional subdivision of the Sirhan formation is unknown; existing subsurface data is too sparse and surface outcrops of the formation are too incomplete and discontinuous to delineate mappable stratigraphic units.

Apparently, the Sirhan formation had a varied depositional history: it contains continental sandstone and both lacustrine and marine limestone. The area may have been emergent for long periods and subjected to occasional marine incursions.

One area in the northern part of the Wadi as Sirhan quadrangle contains basalt lava flows that are interbedded with the Sirhan formation (QTb/Tsu, pl. 1). This sequence of lava flows interbedded with sedimentary rocks is more common to the north in the An Nabk and Turayf quadrangles (Meissner and others, 1987). These areas required separate map designation because basalt talus covers the underlying Sirhan formation to such an extent that, in many places, the rocks appear to be all basalt, although they are composed mostly of the Sirhan formation.

VOLCANIC ROCKS

The Al Harrah basalt lava flows and flood basalts (QTb) overlie sedimentary rocks in much of the northern and northeastern part of the map area. The volcanic field is 80 to 100 km wide and trends northwestward from the map area across the northwestern corner of Saudi Arabia into Jordan (Regional Geologic Setting, pl. 1). In places, the basalt is scoriaceous and vesicular, and includes bedded pyroclastic rocks, sills, dikes, plugs, and cones. Coleman and others (1983) state that the predominant mode of emplacement was fissure eruption followed by pyroclastic cone building. Pahoehoe and aa flows are present, but mechanical weathering has destroyed the primary features of most flows. Explosive eruptions associated with broad, low-relief craters (known as maars) brought up fragments of underlying sedimentary rocks (Aspinall and others, 1985).

The highest volcanic cone is Jabal Layla; located in the northeastern part of the map area, it is about 890 m above sea level. Jabal Layla is a classically shaped cone and contains scoria and layered volcanic debris. Many of the other cones in the area are smaller and breached. Craters as much as 50 m deep have rims and walls of very hard vesicular basalt that show flow layering and jointing; in some, the jointing is characteristically columnar. Olivine xenoliths that contain peridot-like crystals are found eroded out of the lava on the rim of the Makman Hazawza crater, located in the north-central part of the map area.

The thickness of the Al Harrah basalt ranges from about 1 m in many places to as much as 68 m in a drill hole on the east edge of Hazawza sabkha. Three holes (HZ 22, 23, and 25) were drilled at the edge of Hazawza (pl. 1) to test for the presence of brine and evaporite minerals; as many as 8 basalt flows interbedded with sabkha sediments in the upper part of the holes and sediments of the Sirhan formation in the lower part were encountered. One basalt flow was encountered at a depth of 150 m (Smith, 1980). Two flows are visible in the deeper wadis that cut the Al Harrah volcanic field. The lower flow appears to be much older than the upper. It contains numerous vugs filled with calcite and other minerals, is gray and weathered looking, coarse grained, and crumbly. By contrast, the upper flow is black, very dense, compact, and fine grained; it has only a few minute calcite-filled vugs, and is partly columnar jointed.

Two samples of the upper fresh-looking basalt were collected along the west edge of the Al Harrah volcanic field (pl. 1). Examination of thin sections of the two samples by Carl Thornber (written commun., 1986) indicated that they are alkali-olivine basalt of similar mineralogical character. The basalt is porphyro-aphanitic and is sparsely vesicular with some calcified vesicles. It contains subrounded, anhedral olivine phenocrysts ranging in size from less than 0.2 mm to 0.5 mm with iddingsitized rims of about 7 volume percent; minor zonation of phenocrystic olivine is indicated by strained extinction and slight iron enrichment during growth. The basalt also contains a few partially melted aluminum-rich clinopyroxene xenocrysts as much as 0.5 mm in diameter. The aphanitic matrix of the basalt is comprised of elongate plagioclase grains (0.1 by 0.5 mm) optically intergrown with aluminum/titanium-rich (?) clinopyroxene. Later-stage opaque minerals are interstitial to matrix silicates. In conclusion, the Al Harrah volcanic field appears to be the result of continental-rift volcanism in typical silicic alkali (olivine) basalt (Basaltic Volcanism Study Project, 1981, pp. 108-131).

The age of the Al Harrah basalt flows is generally reported as Tertiary to Quaternary. Powers and others (1966, p. D98) tentatively assigned the younger flows to the Quaternary; older flows are considered to be Miocene and Pliocene. Bender (1975, pp. 122-123) believes that the same basalt field in Jordan contains flows that are Miocene to Middle Pleistocene. The tectonic map of the Arabian Peninsula (Brown, 1971) shows the lava field of northwestern Saudi Arabia (Al Harrah) as being Middle Miocene (10-14 Ma); this age is based on K-Ar determinations and field relations. Potassium-argon ages obtained from 5 samples collected from the southwest edge of the Al Harrah volcanic field, located about 20 km northeast of

Isawiyah (same area as the HZ drill holes) range from 11.4 to 13.4 Ma (Coleman and others, 1983, table 2).

Stratigraphic relationships in the map area indicate that the basalt flows are at least younger than the Paleocene-Eocene rocks of the Turayf group: nowhere are the flows interbedded with the Turayf rocks, but rather they lie on them. A Miocene (and possibly Pliocene) age is indicated where lava flows are interbedded with rocks of the Sirhan formation along Wadi as Sirhan. In the same area, a Quaternary age for some of the basalt is suggested where flows are interbedded with Hazawza sabkha sediments.

A thin basalt flow with a veneer of basaltic gravel mixed with sand (QTb/Qg) has been mapped adjacent to basalt in the east-central part of the quadrangle. This area is mapped separately because it forms a unique topographic pattern that appears on aerial photographs and Landsat imagery as a light-colored area with dark spots.

QUATERNARY DEPOSITS

DURICRUST

Calcareous and gypsiferous duricrust (Qdc) discontinuously mantles bedrock in the Wadi as Sirhan area and is associated with the basalt lava flows. In most places, it is not practical to map because of its discontinuous nature. Therefore, the underlying rock formations have been mapped as if continuously exposed.

The calcareous duricrust is massive, consolidated, hard, and has a rough surface. It is usually sandy and resembles unevenly weathered massive limestone. The gypsiferous duricrust is also massive, sandy, and partly calcareous, but in many places it is very porous and crumbly. Thin limestone beds that cap outcrops of the Sirhan formation in Wadi as Sirhan have a partly eroded mantle of duricrust, and duricrust is found between joint and bedding planes of the limestone. The duricrust ranges in thickness from 0.5 m to 6 m.

A low, sinuous ridge completely covered by duricrust was mapped in the southeastern corner of the quadrangle (pl. 1). The ridge is about 8.5 km long and rises as much as 6 m above the surrounding plains. The duricrust that caps this feature is gypsiferous, very sandy, and hard. The underlying rock may actually be the course of an old wadi that is preserved by the durable crust, leaving it elevated above the more rapidly eroded adjacent sediments. A similarly preserved wadi, that is now a low ridge, was mapped in the Ash Shuwayatiyah quadrangle to the east of the Thaniyat Turayf quadrangle (Meissner and others, 1985).

In most parts of the map area, the basalt flows appear to have been encased in duricrust that has partly eroded away, leaving blocks of basalt scattered about on the surface. Where the duricrust is not eroded, much of it is extensively weathered and

mixed with weathered basalt. The top few inches of the soft crust are easily penetrated by driving and walking on it.

The duricrust is assigned a Quarternary age because it mantles the youngest lava flow, believed to be of Quaternary age.

UNCONSOLIDATED SURFICIAL DEPOSITS

Unconsolidated surficial deposits cover nearly half of the map area and constitute a major part of the geology of the quadrangle. The plain of Al Busayta is completely covered with various gravels that make up more than half of the surficial deposits. Wadi as Sirhan contains large areas covered with alluvial deposits of silt, sand, and gravel, as well as large, silty, salt-encrusted sabkhas. Hazawza, the largest sabkha in Wadi as Sirhan, was test drilled for the presence of brines and evaporite minerals. Terraces and eolian deposits are also important features in the quadrangle.

Gravel (Al Busayta)

The entire south-central part of the map area is covered with gravel (Qg) that forms a flat, featureless plain known as Al Busayta (pl. 1). The gravel content of the plain at Al Busayta is variable. Along the north edge, gravel pits expose 3 m of poorly bedded gravel composed of flat, elongate, and irregularly shaped pieces of chert in a sand matrix; most of the pieces of chert are 1-5 cm long (a few are as much as 15 cm long). The surface of the northern part of the plain is covered with fine gravel composed of dark chert and gray limestone probably derived from the chert-bearing carbonates of the Turayf group in the heavily drained highlands to the west and southwest.

The east-central part of Al Busayta contains abundant light-colored, partly translucent, egg-shaped quartz pebbles as much as 3 cm long; the pebbles are well rounded and smooth. Dark, irregularly shaped pieces of chert as much as 3 cm long are also in the area, and the quartz pebbles and chert are mixed with sand. Deposits of quartz pebbles of various sizes and dark chert fragments continue southward along the eastern edge of the plains where there also is much black limestone gravel. The dark chert fragments and limestone pieces could have come from erosion of the rocks of the Turayf group to the east and west, but the source of the light-colored, partly translucent pebbles is unknown. No presently exposed rocks contain light quartz veins that could have been reduced to pebbles by wave action, and there are no quartz-pebble conglomerates that could have contributed the pebbles. One theory is that a quartz-bearing formation younger than the Sirhan formation was deposited then completely eroded away, leaving only loose pebbles.

The central part of Al Busayta contains fewer quartz pebbles and more irregularly shaped dark-chert gravel. The chert clasts are subrounded to subangular and as much as 13 cm long. Coarse surface material is underlain by silt and clay. The shallow, sandy wadi traces support small plants.

The western part of Al Busayta contains an elaborate wadi drainage system flowing northeastward down a long, gentle slope into Wadi as Sirhan. The wadis head up in hills formed in the Turayf group of the Southwestern Area. The gravel (clast size as much as 13 cm; average is 2-5 cm) is a mixture of limestone and chert mixed with sand and silt. The clasts are subangular, reflecting the close proximity of the carbonate and chert source rocks of the Turayf group. Included with the gravel are bioclastic and phosphatic chert cobbles, wood-grained chert, and pieces of phosphatic limestone.

Gravel in the south-central part of Al Busayta contains mostly yellowish-brown chert pebbles 1 to 2 cm in diameter; a few anomalous clasts are as much as 15 cm long. Some bioclastic chert is also present. In parts of south-central Al Busayta, the plain is randomly pock-marked with many shallow, circular depressions 4 to 6 m in diameter and 15 to 30 cm deep. The rims of the circular depressions contain a ring of coarser material that appears to have been "swept out" from the depression. One explanation for these is given in the "Seven Pillars of Wisdom" by T. E. Lawrence: large camel trains used Wadi as Sirhan for a passage way and it is thought that drovers carrying wild cereals for food made these cleared depressions for threshing floors to prepare the cereal for eating. It is believed that vegetation and the human population were greater at the time these circular depressions were made. Another explanation is that yurts (tents) used by nomads in northwest China leave circular areas of "prepared" ground when they are moved. Similar tents may have been used by the Nomads of the Al Busayta plain. Whether these depressions in the plain are man-made or produced by natural causes remains a mystery and deserves attention because they may have important archaeological or other scientific implications.

A few shallow holes were drilled in the gravel plain of Al Busayta, none of which penetrated the gravel to underlying bedrock. Drill hole TP 261 penetrated 55 m of gravel and other unconsolidated sediments before it was abandoned (cross section A-A', pl. 1).

Smaller patches of gravel are found in Wadi as Sirhan east of Al Busayta. Just east of Al Busayta, in the Al Qasa'im area, a relatively thin patch of gravel covers Sirhan bedrock. The gravel is, for the most part, residuum composed of dense, dark-gray to black siliceous and sandy limestone apparently derived from the Sirhan formation; it also contains a few scattered quartz pebbles. Near the east side of the quadrangle, adjacent to a basalt flow, is a patch of gravel consisting of flat, light- and dark-colored chert fragments and some basalt debris. The northern part of this patch is composed mostly of the basalt that forms the coarse basalt gravel (QTb/Qg) mentioned earlier in this report (p. 17, Volcanic Rocks).

Terrace Deposits

The southeastern corner of the map area contains several terraces (Qt) that reflect former stream activity. The terraces are elevated a few meters above the surrounding plains and comprise a cap of unbedded sand and gravel, about a meter thick, underlain by at least 3 m of cross-bedded sand and gravel. Much of the gravel consists of flat to rounded white chert pebbles oriented parallel to bedding planes, indicating deposition by the high-energy flow of water.

Sabkhas

Hazawza is a large sabkha (playa) (Qsb) in Wadi as Sirhan in the north-western part of the quadrangle. It is a very flat depression, as much as 39 km long and 17 km wide, that is filled with salt-encrusted clay and silt. During the winter rainy season, Hazawza becomes a shallow lake a few centimeters deep that quickly dries up during the dry season, leaving brines just below the surface. Preliminary investigations showed that the Hazawza sabkha was an attractive target for potassium brines and evaporite minerals (Smith, 1980). Three holes were drilled (HZ 23, 24, and 25, pl. 1) along the east edge of the sabkha. The holes were located on the edge of the enclosing basalt along the east side of the sabkha in order to provide adequate support for the drill rigs. The results of drilling showed that playa sediments (composed mostly of silt containing gypsum, quartz, and calcite) are interbedded with basalt flows as deep as 30 m, below which basalt is interbedded with limestone and sandstone of the Sirhan formation. The deepest hole (HZ 25) was drilled to 319 m and did not encounter any significant bedded-evaporite deposits. Brine samples obtained from drill holes and various parts of the sabkha contained no mineral concentrations of economic interest. Of special note, however, is that drilling at Hazawza discovered relatively fresh artesian water at a depth of about 50 m.

Two smaller sabkhas southeast of Hazawza apparently are not as wet and contain salt-tolerant bushes and shrubs. A small sabkha on the border of the quadrangle north of Hazawza is filled with rain water during most of the winter and is a temporary refuge for many migratory water fowl.

Alluvial and Eolian Deposits

The map area contains large deposits of unconsolidated alluvial silt, sand, and gravel (Qu). These deposits are found in large depressions, notably Wadi as Sirhan, and smaller depressions and basins, as well as along wadi courses. The deposits are mostly alluvium mixed with eolian sediments. Finer-grained deposits consisting of silt and clay (Qs) are found in undrained depressions (khabras), especially in the Al Harrah basalt fields, and form firm, flat surfaces commonly devoid of vegetation. The southeastern corner of the map area has many scattered longitudinal sand dunes (Qes) that are generally parallel to the north-northwesterly prevailing winds. These dunes are effectively stable because their present configuration is the same as that seen on aerial photographs of that area taken seven years ago.

STRUCTURE

The Phanerozoic sedimentary rocks in the Wadi as Sirhan quadrangle lie within or adjacent to the Wadi as Sirhan graben complex (Regional Geologic Setting, pl. 1). Faults and lineaments in the quadrangle may have been caused by, or are related to, major tensional forces and subsidence produced by continental rifting associated with the spreading of the floor of the Red Sea. The map area is mainly a structurally depressed area flanked by moderate highlands and partly covered by continental rift volcanic flows.

Powers and others (1966) described Wadi as Sirhan as a half graben faulted only on the northeast side. However, recent work by Riofinex in the southwestern part of the quadrangle revealed normal faults (Al Busayta fault, Al Qasimah fault, and other unnamed faults, pl. 1, crosssection A-A') thrown down to the northeast along the southwest side of Wadi as Sirhan (Griffin and others, 1984). Gravity mapping in Jordan adjacent to Wadi as Sirhan, west of the map area, revealed several major faults whose trends are approximately parallel to the Saudi Arabian border; these faults could be continuations of those mapped by Riofinex (Bender, 1975). Evidence of possibly continuous faulting along the southwest side of Wadi as Sirhan strongly suggests that the Wadi as Sirhan graben is a full graben.

A gravity map of the Sirhan-Turayf basin shows a broadly sinuous axial low that crosses the Wadi as Sirhan quadrangle from the northwest to the southeast in the approximate position of the surface axis of the Wadi as Sirhan depression (Aramco, unpub. data; pl. 1, this report). Toward the southern part of the quadrangle, the axial gravity low bifurcates into south- and southeast-trending axes. The south-trending axis has no expression at the surface. Relief on the gravity surface from the axial low to the flanking highs is about 150 gravimetric units, which converts to 914 m; however, surface relief is a maximum of 300 m, excluding volcanic cones.

The major northeastern bounding fault of the Wadi as Sirhan graben, the Wadi as Sirhan fault (pl. 1), has been mapped or projected at the surface along discontinuous lineaments and fault traces in aerial photographs and Landsat imagery. Its surface expression is not distinct, and gravity data do not indicate faulting, so the exact position of the fault may vary from the way it is currently shown. The trend of the fault is northwestward and it extends nearly to the northern border of the quadrangle, where it apparently dies out. However, the Al Misma fault has been interpreted to be the main northeastern border fault of the Wadi as Sirhan graben offset to the west, and is mapped as such in the Turayf quadrangle to the north (Meissner and others, 1987). These two major fault traces, offset by more than 10 km, indicate the complexity of faulting in the graben area.

Step faulting (downthrown to the northeast) in the Southwestern Area is believed to continue into the graben toward its axis near Aramco drill hole S-460. Many other lineaments, some of which are faults, are visible on aerial photographs and Landsat imagery in the Tertiary sedimentary rocks, unconsolidated surficial

deposits, and basalt fields. Most of these lineaments trend to the north-northwest, but the Al Amud area contains many lineaments that trend northeastward or even eastward, which is against the regional grain.

The anomalous trend of lineaments in the Al Amud area may be caused partly by faulting and macrojointing related to an anticlinal structure across Wadi al Rushayda near the east-central part of the Wadi as Sirhan quadrangle. The double plunging anticline is about 10 km long and trends northwestward. This fold causes the Arqah Phosphorite (Ttup) to be exposed in the Al Amud area where it otherwise is encountered only by drilling. Although geophysical mapping is incomplete, it is significant that part of an anomalous gravity high is shown in the Al Amud area (Aramco, unpub. data); the surface expression of the anticline may be a reflection of that high. Furthermore, regional structural doming in the Al Amud area could account for the considerable exposures of Tertiary sedimentary rocks in the Al Harrah basalt field.

Mapping in the Al Amud area revealed that the Arqah Phosphorite is thicker and of a higher grade where it is deposited on the sides of the Al Rushayda anticline than that deposited on more flat-lying rocks. This phenomenon of thicker and higher grade phosphorite associated with paleoslopes has been noted in other areas outside the quadrangle (Aspinall and others, 1985).

ECONOMIC GEOLOGY

PHOSPHORITE

Thaniyat Phosphorite Member

The Thaniyat Phosphorite member is exposed only at the west end of Wadi al Ghinah in the southwestern corner of the quadrangle (part of the Southwestern Area, pl. 1). The thickest exposure of phosphorite in the member, seen in a twice-repeated sequence near the floor of Wadi al Ghinah (Griffin and others, 1984), is about 1 m. Here the phosphorite is semifriable, calcareous, and has a siliceous cap. The member was intersected in two drill holes, TP 173 and TP 174 (pl. 1), also located in the southwest corner of the quadrangle, just north of Wadi al Ghinah, that contained three 1-m-thick phosphorite beds with a maximum grade of about 27 percent P_2O_5 . Hypothetical resources for the area at the west end of Wadi al Ghinah, including an extension south of the quadrangle, are estimated at 694 t (Riddler and others, 1986).

A few wide-spread drill holes in the Southwestern Area indicate that the Thaniyat Phosphorite member continues in the subsurface to the east and northeast of the head of Wadi al Ghinah, as far as the Al Busayta fault. Eastward from the Wadi al Ghinah area, the member is intersected by a number of normal faults, downthrown to the northeast, forming step faults toward the plains of Al Busayta (Riddler and others, 1984, figure 11). In drill hole P 58, near the southern border of

the quadrangle, immediately west of the Al Busayta fault, the member is estimated to be located just above the Cretaceous Zallum (Kaz) sandstone at a depth of 230 m (cross section A-A', pl. 1). In drill hole TP 267 (located on the north bank of Wadi al Ghinah, to the northeast of holes TP 173 and 174), the Thaniyat Phosphorite member is about 100 m deep. Phosphorite resources of the member in the quadrangle, other than in the southwest corner, have not been estimated.

Ghinah Phosphorite Member

The Ghinah Phosphorite member crops out in many parts of the southwestern corner of the quadrangle and is believed to continue into the subsurface of the remainder of the Southwestern Area. However; the phosphorite beds are too thin (less than 0.3 m) and too low grade (less than 15 percent P_2O_5) to have economic value; although the Ghinah represents a significant episode of phosphate deposition, it contains no phosphorite resources (Riddler and others, 1986).

Sib Member

Riddler and others (1986) state that two drill holes in the Al Amud area, approximately 9 km apart, intersected phosphorite in the Sib member at 18-23 m. The thickness of the phosphorite in each drill hole was about 3 m; the average P_2O_5 concentration was 19 percent. On the basis of data obtained from these two holes, a hypothetical phosphorite resource of 1,550 t was estimated in an elongate area that includes Wadi al Rushayda and extends eastward into the adjacent quadrangle (Riddler and others, 1986, fig. 14).

Arqah Phosphorite Member

The Arqah Phosphorite member crops out in Wadi al Rushayda in the Al Amud area near the eastern border of the quadrangle; elsewhere, it is covered by younger Tertiary sedimentary rocks and, in many places, by basalt. Surface and drill-hole data have shown that the Arqah contains phosphorite beds ranging in thickness from 2-2.5 m, with maximum grades averaging 25 percent P_2O_5 . At least 20 percent of the phosphorite is semifriable to friable. Hypothetical resources of the phosphorite in the Al Amud area are estimated to be 3,250 t at an average grade of about 20 percent P_2O_5 . However, overburden thicknesses, including surface basalts, range from 20 to 90 m, and stripping ratios are generally economically unattractive, ranging from 6:1 to 47:1. The high stripping ratios and poor access (due to rugged basalt terrain) give the Arqah Phosphorite in the study area a low priority for further evaluation (Riddler and others, 1986).

OIL AND GAS

Gardner (1955) wrote about the potential for petroleum resources of eastern Jordan, a study that included Wadi as Sirhan along the east border of Jordan, where Upper Cretaceous and Paleocene-Eocene marine rocks are present. In 1985, the

Jordanian National Oil Company made Jordan's first oil discovery in the Azraq depression, a northwest extension of Wadi as Sirhan depression. Three wells that were drilled each flowed at 600 to 1,000 barrels per day (low-sulfur crude) from 10,000 feet (3,200 m). Jordan named this discovery the Hamza field. Current production of this field is unknown, but it has proved the existence of hydrocarbons in the Azraq depression and improves chances for the existence of oil in the Wadi as Sirhan depression to the south.

The Isawiyah deep water well, located at the town of Isawiyah in Wadi as Sirhan, penetrates about 1,300 m of Tertiary, Cretaceous, and Silurian marine rocks. The Aramco S-460 drill hole, located in Wadi as Sirhan near the southeastern corner of the quadrangle, penetrates about 850 m of marine rocks. All these marine rocks are potential petroleum source rocks, especially the Silurian section of dark organic shales. No oil shows were reported in these rocks, but hydrocarbons could have migrated up dip to structural traps along faults or into anticlinal folds and domes of adjacent rocks. Faults and associated structural highs on both sides of the Wadi as Sirhan graben contain potential traps. Although there are favorable signs for the accumulation of hydrocarbons in Wadi as Sirhan, more work is needed to locate potential drilling targets.

OPAL CLAYSTONE

The Rushayda Claystone bed of the Al Amud member overlies the Arqah Phosphorite member in Wadi al Rushayda near the east-central border of the quadrangle and contains opal claystone of possible economic value (Outerbridge and Meissner, 1985). It is composed mostly of cristobalite and attapulgite, and occurs intermittently in the Rushayda Claystone in beds 1-20 cm thick. The Rushayda Claystone ranges in thickness from 5-20 m. The opal claystone in Wadi al Rushayda may be used as a lightweight building material, a furnace liner, an absorbant for spilled oil, a moisture-retaining agent in soil, and an abrasive/polishing material.

TABLE 1

[Adapted from Riddler and others, 1986, Table 6]

CHEMICAL COMPOSITION OF PHOSPHORITES

Phosphorite Member		Arqah Phosphorite Member						Thaniyat Phosphorite Member			
Work Area		A L A M U D						SOUTHWESTERN			
RASS		975342	975343	975344	975345	975346	975350	Blk	#173	#161	Bed 2
Phosphorite Type		S-F,C	S-F,C	S-F,C	S-F,C	S-F,C	S-F,C	Flotation F	Flotation Conc.	Flotation Conc.	Flotation F
Constituent or Ratio	Unit										
P ₂ O	%	18.2	12.3	18.9	18.9	5.9	24.5	22.2	31.6	30.9	27.3
CaO	%	30.9	55.1	55.1	53.9	56.0	51.3	28.6	-	-	39.9
CaO:P ₂ O ₅	-	1.70	4.48	2.92	2.85	9.50	2.09	1.30	-	-	1.46
SiO ₂	%	40.0	1.60	0.70	2.10	1.90	5.80	37.80	12.10	14.10	-
SiO ₂ :F	-	33.0	1.80	0.50	1.90	3.80	4.10	-	-	-	-
F	%	1.20	0.90	1.30	1.10	0.50	1.40	-	-	-	3.00
P ₂ O ₅ :F	-	15.0	14.0	15.0	17.0	12.0	18.0	-	-	-	9.0
Al ₂ O ₃	%	0.22	0.21	0.14	0.33	0.10	0.32	0.80	0.94	0.94	1.00
P ₂ O ₅ :Al ₂ O ₃	-	83	59	135	57	59	77	28	33	33	27
Fe ₂ O ₃	%	0.28	0.13	0.16	0.27	0.12	0.32	1.4	1.5	1.6	0.9
P ₂ O ₅ :Fe ₂ O ₃	-	65	.95	118	70	49	77	16	21	19	30
MgO	%	0.19	0.29	0.28	0.29	0.19	0.67	0.28	0.28	0.31	-
P ₂ O ₅ :MgO	-	96	42	68	65	31	37	79	112	100	-
Al+Fe+Mg: P ₂ O ₅	-	0.04	0.05	0.03	0.05	0.07	0.05	0.11	0.08	0.09	-
MnO ₂	%	-	-	-	-	-	-	-	-	-	-
CO ₂	%	3.5	28.2	21.0	20.0	35.4	11.3	1.9	-	-	-
Na ₂ O	%	<0.05	<0.5	<0.05	<0.05	<0.05	<0.05	-	-	-	-
K ₂ O	%	0.14	0.06	0.06	0.07	0.05	0.05	-	-	-	-
TiO ₂	%	0.007	0.0055	0.0055	0.0055	0.002	0.0205	0.017	-	-	-
Cl	%	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.11	-	-	-
C	%	-	-	-	-	-	-	-	-	-	-
S as SO ₃	%	1.10	0.76	1.24	1.33	0.41	1.35	-	-	-	-
LOI(1000)	%	6.0	29.8	23.1	22.1	36.6	14.2	2.6	5.1	5.8	4.9
LOI(550)	%	-	-	-	-	-	-	-	-	-	-

TABLE 1 (Continued)

(Adapted from Riddler and others, 1986, Table 6)

CHEMICAL COMPOSITION OF PHOSPHORITES

Phosphorite Member		Arqah Phosphorite Member						Thaniyat Phosphorite Member			
Work Area		A L A M U D						SOUTHWESTERN			
RASS		975342	975343	975344	975345	975346	975350	Blk	#173	#161	Bed 2
Phosphorite Type		S-F,C	S-F,C	S-F,C	S-F,C	S-F,C		Flotation F	Flotation Conc.	Flotation Conc.	F
Constituent or Ratio											
Unit											
AIR	%	-	-	-	-	-	-	-	-	-	21.3
Pb	%	-	-	-	-	-	-	-	-	-	-
Cr	%	0.0122	0.0064	0.009	0.0105	0.004	0.0136	-	-	-	-
V	%	0.0114	0.0072	0.0064	0.0053	0.0027	0.0179	-	-	-	-
As	%	0.0044	0.0011	0.0007	0.0006	0.0001	0.0043	-	-	-	-
U	ppm	55	35	50	50	20	70	-	-	-	-
Th	ppm	<10	<10	<10	<10	<10	<10	-	-	-	-
Y	ppm	190	70	80	40	<20	200	-	-	-	-
Se	ppm	-	-	-	-	-	-	-	-	-	-
Cd	ppm	9	29	32	20	4	14	-	-	-	-
Rg	ppm	-	-	-	-	-	-	-	-	-	-
Sr	%	0.087	0.056	0.092	0.101	0.035	0.096	-	-	-	-
Cu	%	0.0022	0.0026	0.003	0.0025	0.001	0.0045	-	-	-	-
Zn	ppm	129	141	203	173	56	192	-	-	-	-
Mb	ppm	7	8	8	8	7	12	-	-	-	-
Ni	ppm	22	29	17	15	10	25	-	-	-	-

NOTE: Phosphorite Types:

- F = soft, friable
- S-F = semifriable
- C = medium hard, calcareous, carbonate cemented
- LOI = loss in ignition
- AIR = air insoluble residue

DATA STORAGE

DATA FILE

All field and laboratory data for this report, including petrographic descriptions, sample-site locations, thin-section descriptions, field notes, and results of geochemical analyses, are stored in Data File USGS-DF-07-7 in the Jeddah office of the USGS Saudi Arabian Mission, or in Riofinix Data File RF-DF-00-05.

MINERAL OCCURRENCE DOCUMENTATION SYSTEM (MODS)

Updated information was added to the Mineral Occurrence Documentation System (MODS) for the following new occurrences:

<u>Occurrence</u>	<u>File Number</u>
Al Amud, General (line 145N, 198E)	02256
Wadi al Ghinah	03932
Wadi al Rushayda	03933

REFERENCES CITED

- Aspinall, N. C., Farasani, A. M., Dini, S. M., 1985, Sirhan-Turayf Phosphate Project; The geology and phosphorite distribution in work areas east of Wadi as Sirhan: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-05-24, 62 p.
- Basaltic Volcanism Study Project, 1981, Basaltic volcanism on the terrestrial planets: Pergamon Press, Inc., New York, 1286 p.
- Bayliss, D. D., 1981, Lithostratigraphy and biostratigraphy of the Sirhan-Turayf phosphate area: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-01-25, 131 p.
- _____, 1983, A review of the lithostratigraphy and biostratigraphy of the Sirhan-Turayf phosphate area: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-03-6, 33 p.
- Bender, Friedrich, 1974, Geology of Jordan; Contributions to the regional geology of the earth: Supplementary edition of volume 7, Gebruder Borntraeger, Berlin, Stuttgart, 196 p.
- _____, 1975, Geology of the Arabian Peninsula, Jordan: U. S. Geological Survey Professional Paper 560-I, 36 p.
- Bramkamp, R. A., Ramirez, L. F., Steineke, Max, Reiss, W. H., 1963, Geology of the Jawf-Sakakah quadrangle, Kingdom of Saudi Arabia: U. S. Geological Survey Miscellaneous Geologic Investigations Map I-201A, scale 1:500,000. [Reprinted, 1982, as Geology of the Jawf-Sakakah quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Map, GM-201A, scale 1:500,000.]
- Brown, G. F., 1971, Tectonic map of the Arabian Peninsula: U. S. Geological Survey Saudi Arabian Project Report SA-134, scale 1:4,000,000. Directorate General Mineral Resources, Arabian Peninsula Map AP-2, scale 1:4,000,000.
- Burdon, D. J., and Quennell, A. M., 1959, Handbook of geology of Jordan; Jordan east of the rift: Government of the Hashemite Kingdom of Jordan, 133 p.
- Capetta, H., and Riddler, G. P., 1985, Age determination on a selection of fish remains from phosphorite beds in the Sirhan-Turayf region: Riofinex Internal Report. in Data-File RF-DF-00-05.
- Coleman, R. G., Gregory, R. T., and Brown, G. F., 1983, Cenozoic volcanic rocks of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-93, 82 p. U.S. Geological Survey Open-File Report 83-788.

- Futyán, A., and Nicholson, C. A., 1979, Saudi Arabia phosphate stratigraphic study, stratigraphical, petrographical, and micropaleontological studies of 195 field samples from the Wadi Sirhan basin, northern Saudi Arabia: Directorate General of Mineral Resources, Kingdom of Saudi Arabia, Riofinex Geological Mission, RFO-1979-41, v. I and II.
- Gardner, L. S., 1955, Oil and gas possibilities in the Hashemite Kingdom of Jordan: Prepared by the U. S. Geological Survey on behalf of the International Cooperation Administration for the Government of the Hashemite Kingdom of Jordan, 116 p.
- Griffin, M. B., Farasani, A. M., Watson, A. D., Dini, S. M., and Riddler, G. P., 1984, Sirhan-Turayf phosphate project; the geology and phosphorite resources of the southwestern area: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-21, 70 p.
- Kluyver, H. M., Bege, V. B., Smith, G. H., Ryder, J. M., and van Eck, Marcel, 1981, Sirhan-Turayf phosphate project; results of work carried out under the phosphate agreement, 29th Dhual Hijjah 1398-30th Jumad Thani 1401 (29th November 1978-4th May 1981): Saudi Arabian Deputy Ministry for Mineral Resources Technical Record RF-TR-01-5, 77 p.
- Lozej, G. P., 1984, Sirhan-Turayf phosphate project, a contribution to the regional stratigraphy: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-15, 82 p.
- McKelvey, V. E., 1959, Investigations needed to stimulate the development of Jordan's mineral resources: Prepared by the U.S. Geological Survey for the Government of the Hashemite Kingdom of Jordan and the U.S. International Cooperation Administration, 164 p.
- Meissner, C. R., Jr., and Ankary, Abdullah, 1972, Phosphorite deposits in the Sirhan-Turayf basin, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources, Mineral Resources Report of Investigations 2, 27 p.
- Meissner, C. R., Jr., Mytton, J. W., Riddler, G. P., van Eck, Marcel, Aspinall, N. C., Farasani, A. M., and Dini, S. M., 1985, Geologic map of the Ash Shuwayhitiyah quadrangle, Sheet 30 D, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-06-1, 26 p. U.S. Geological Survey Open-File Report (in press)
- Meissner, C. R., Jr., Riddler, G. P., van Eck, Marcel, Aspinall, N. C., Farasani, A. M., and Dini, S. M., 1987, Preliminary geologic map of the Turayf quadrangle, Sheet 31 C, and part of the An Nabk quadrangle, Sheet 31 B, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-07-3 (IR 773), 28 p. U.S. Geological Survey Open-File Report 89-336.

- Mytton, J. W., 1966, Geologic map of the Turayf phosphate area (with text): Saudi Arabian Directorate General of Mineral Resources, Mineral Investigations Map MI-3, scale 1:250,000.
- Outerbridge, W. F., and Meissner, C. R., Jr., 1985, Opal claystone associated with phosphate rock in northern Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-05-20, 16 p. U.S. Geological Survey Open-File Report 86-103.
- Powers, R. W., 1968, Saudi Arabia-Lexique stratigraphique internationale v. 3, f. 10 b 1, Paris, 177 p.
- Powers, R. W., Ramirez, L. F., Redmond, C. D., and Elberg, E. L., Jr., 1966, Geology of the Arabian Peninsula; sedimentary geology of Saudi Arabia: U.S. Geological Survey Professional Paper 560-D, 147 p.
- Quennell, A. M., 1951, The geology and mineral resources of (former) Trans-Jordan: Colonial geology and mineral resources v. 2, no. 2, p. 85-115.
- _____, 1958, The structural and geomorphic evolution of the Dead Sea rift: Quarterly Journal of the Geological Society of London v. 114, p. 1-23.
- Riddler, G. P., Khallaf, H. M., and Farasani, A. M., 1983, Exploration for phosphate in the Sirhan-Turayf region, northwest Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File RF-OF-03-22, 12 p.
- Riddler, G. P., and van Eck, Marcel, 1984, Sirhan-Turayf phosphate project progress report for 1402-1403 program (August 1982-August 1983): Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-6, 38 p.
- Riddler, G. P., van Eck, Marcel, Aspinall, N. C., McHugh, J. J., Griffin, M. B., and Farasani, A. M., 1984, Sirhan-Turayf phosphate project lithostratigraphy of the Turayf group: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-2, 40 p.
- Riddler, G. P., van Eck, Marcel, Aspinall, N. C., McHugh, J. J., Parker, T. W. H., Farasani, A. M., and Dini, S. M., 1986, An assessment of the phosphate resource potential of the Sirhan-Turayf region: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record RF-TR-06-2, 152 p.
- Riddler, G. P., van Eck, Marcel, Meissner, C. R., Jr., and Mytton, J. W., 1985, Geologic map of the Al Hamad quadrangle, Sheet 31 D and part of the Jabal Unazah quadrangle, Sheet 32 D, scale 1:250,000: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-05-17, 28 p.
- Smith, C. L., 1980, Brines of Wadi as Sirhan, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission, prepared for the Directorate General of Mineral Resources, USGS-TR-1, SA(IR)-295, 26 p. U.S. Geological Survey Open-File Report 80-1261

- Smith, G. H., 1983, Reconnaissance exploration for phosphate in the Thaniyat-Quraymiz district: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-03-3, 67 p.
- van Eck, Marcel, 1985, Sirhan-Turayf phosphate project; Lithostratigraphy of the Aruma Formation: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-05-23, 26 p.
- Vaslet, Denis, 1987, Early Paleozoic glacial deposits in Saudi Arabia, a lithostratigraphic revision: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record BRGM-TR-07-1, 21 p.
- Vaslet, Denis, Manivit, Jacques, and Le Nindre, Yves-Michel, 1986, Geologic revision of the Al Arid area and proposal for a new reference section of the Early Triassic Sudair Shale, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record BRGM-TR-06-4, 29 p.