Geology and Mineral Resources of Libya—A Reconnaissance

GEOLOGICAL SURVEY PROFESSIONAL PAPER 660

Prepared in cooperation with the Ministries of Industry and National Economy of the Government of Libya, under the auspices of the Agency for International Development, U.S. Department of State

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By GUS H. GOUDARZI

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Ad Dafinīyah	32°23′	14°52′
Ad Duwaysah	27°34′	14°33′
Agar (Āqār)	27°32′	14°09′
Agedabia (Ajdābiyah)	30°45′	20°10′
Agelát (Al 'Ujaylāt)	32°45′	12°23′
Al Abyār	32°11′	20°36′
Al Barkāt	24°54′	10°11′
Al Fogha (Al Fuqahā')	27°50′	16°22′
Al Ghiran	32°21′	15°02′
Al Hufrah (*see also* Wādī Hufrah)	25°55′	14°20′
Al Jabal al Akhḍar	32°30′	21°30′
Al Jawf	24°11′	23°19′
Al Kussabat (Al Qaṣabāt, Cussabát) (*see also* Cussabát)	32°35′	14°03′
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Al Qanāfidh	31°50′	11°50′
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Antelat (Antalāt)	31°10′	20°35′
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As Sidādah	31°30′	14°45′
As Shabb (*see also* Sheb)	27°35′	14°40′
Ashkada (Eshkeda)	27°30′	14°30′
Atshan (Ḩasy 'Aṭshān)	27°10′	10°25′
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Bir el Maaruf (Bi'r al Ma'rūf)	25°05′	18°35′
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Brach (Brak)	27°33′	14°16′
Bū Ghaylān	32°16′	13°02′
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Edri (Adrī)	27°32′	13°09′
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El Giofra (Al Jufrah)	29°10′	16°10′
El Haderiat	28°00′	18°30′
El Nofilia (An Nawfalīyah)	30°47′	17°50′
Es Soda (*see also* Jabal as Sawdā')	28°30′	15°10′
Fort Sainte (in Tunisia)	30°15′	9°35′
Fredga	26°55′	13°28′

Name	Location Lat (N.)	Location Long (E.)
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Gal Moi	27°40′	14°45′
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Gargaf arch	28°00′	14°00′
Gargaresh (Qarqarish)	32°45′	12°50′
Garian (Gharian)	32°10′	13°01′
Gatrun (Al Qaṭrūn)	24°56′	14°38′
Gefara	32°30′	12°30′
Gelta	29°48′	16°00′
Gesscia	32°22′	21°35′
Ghadamēs (Ghudāmis)	30°08′	9°03′
Gharabulli (Qaṣr Al Qarahbullī)	32°44′	13°43′
Ghāt	24°54′	10°12′
Gheriat (Al Qaryah ash Sharqīyah)	30°24′	13°26′
Ghudwah	26°25′	14°12′
Giado (Jādō)	31°56′	12°00′
Gialo (Jālū)	29°02′	21°32′
Giarabub (Jaghbūb)	29°43′	24°36′
Gioac (Al Jawsh)	32°00′	11°40′
Gotah (Quṭṭah)	27°30′	13°45′
Guira (Qīrah)	27°35′	14°25′
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Hamāda al Ḥamrā' (Al Hammādah Al Hamrā')	30°00′	12°00′
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Hoggar (Ahaggar; in Algeria)	23°00′	9°00′
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Jabal Arkenu	22°20′	24°40′
Jabal as Sawdā'	28°30′	15°10′
Jabal Auknat (*see also* Jabal Awenat)	21°54′	24°58′
Jabal Awenat (Al 'Uwaynāt)	21°54′	24°58′
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Jabal Dalma	26°00′	23°45′
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Maatan Trona	26°55′	12°29′
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Majdūl	25°53′	15°06′
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Marāwah (Marawha)	32°29′	21°25′
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Nālūt	31°52′	10°59′
Nashnusha	26°57′	13°30′
Oberdan	32°39′	21°07′
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Qaminis	31°39′	20°03′
Qaṣr Al Jifarah ..... approx. location	32°42′	13°51′
Qaṣr Bū Hādī	31°05′	16°40′
Rebiana Sand Sea	24°30′	20°00′
Ras el Hamia	32°25′	13°10′
Rebiana (Rabyanah)	24°15′	22°00′
Regima (Ar Rajmah)	32°04′	20°21′
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Sabkhat Kurkūrah	30°06′	19°10′
Sabratah	32°47′	12°30′
Sahabi	30°00′	20°45′
Samnū	27°17′	14°53′
Sarīr al Gattusa (Sarīr al Qaṭṭūsah)	26°40′	15°15′
Sarīr Calanscio (Serīr di Calanscio)	28°00′	22°00′
Sarīr Tibesti (Serīr el Tibesti)	24°00′	17°00′
Sebcha Kebirah (As Sabkhah al Kabīrah)	30°15′	18°50′
Sebha (Sabhah)	27°03′	14°26′
Serdeles (Sardalas)	25°48′	10°30′
Sheb (As Shabb)	27°35′	14°40′
Shecshuk (Shakshūk)	32°02′	11°57′
Shumaykh	31°23′	13°59′
Shuwayrif (Ash Shuwayrif)	30°00′	14°15′
Sināwan	31°02′	10°36′
Sirte (Surt)	31°12′	16°35′
Slonta (Suluntah)	32°36′	21°43′
Socna (Sawknah)	29°05′	15°46′
Soluch (Sulūq)	31°38′	20°15′
Suq as Sabt	32°36′	13°10′
Surman	32°45′	12°35′
Tadrart	25°00′	10°30′
Tajarbī	24°21′	14°28′
Tajura	32°53′	13°23′
Tāknis	32°29′	21°08′
Tamanhint	27°13′	14°36′
Tamzin	31°51′	11°25′
Tarhuna (Tarhūnah)	32°26′	13°38′
Tārūt	27°31′	13°54′
Tauorga sebcha (Sabkhat Tāwurghā')	32°03′	15°10′
Tauorga (Tāwurghā)	32°02′	15°09′
Tazerbo	25°45′	21°10′
Thamad al Ksour (Tmed el Ksour)	29°45′	17°35′
Tihemboka	27°00′	9°30′
Tibesti	21°30′	17°30′
Umm Al Abyaḍ	26°45′	14°00′
Wādī al Athrūn (Atrun)	32°52′	22°17′
Wādī Bakur (Bacur)	32°31′	20°37′
Wādī Bay al Kabīr	31°00′	15°30′
Wādī Caam (Kaām)	32°30′	14°20′
Wādī Al Cuf (Kūf)	32°43′	21°40′
Wādī ash Shāṭi')	27°30′	13°15′
Wādī el Hassien (near Derna; *see also* Derna)		
Wādī Gan (Ghan)	32°20′	13°08′
Wādī Gattar (Al Qaṭṭār)	32°10′	20°05′
Wādī Gobbin	31°45′	14°30′

Name	Location	
	Lat (N.)	Long (E.)
Wādī Hufrah (*see also* Al Hufrah)	25°55′	14°20′
Wādī Kenīr	27°40′	15°00′
Wādī Lumi ... approx location	31°50′	11°25′
Wādī Maalegh	32°24′	23°04′
Wādī Maymun	31°35′	14°25′
Wādī Qubbin (*see also* Wādī Gobbin)	31°45′	14°30′
Wādī Rāshidah	27°10′	16°15′
Wādī Ruu's	30°15′	15°00′
Wādī Soffegin (Sawfajjīn)	31°30′	14°30′
Wādī Talāl	30°50′	16°40′
Wādī Tareglāt (Tāriqelāt)	32°13′	14°08′
Wādī Thāmit (Wādī Tamit)	30°30′	16°15′
Wādī Ubaraccat	25°45′	10°30′
Wādī Umm El Lebd	31°40′	14°30′
Wādī Urari	31°50′	11°50′
Wādī Zallāf	27°22′	14°22′
Wādī Zamzam	31°26′	15°15′
Wādī Zārat	32°11′	12°48′
Wādī Zmam (Wādī az Zimām)	29°30′	15°20′
Wan Kasa	34°45′	10°50′
Wanzarīk	27°31′	13°29′
Wāw al Kabīr	25°20′	16°40′
Wāw an Nāmūs	24°50′	17°45′
Yafran (Jefren)	32°00′	12°30′
Zawia (Az Zāwiyah)	32°45′	12°44′
Zawīlah	26°10′	15°07′
Zella (Zillah)	28°33′	17°35′
Zighan (Zighan)	25°30′	22°10′
Zliten (Zlitan)	32°28′	14°34′
Zuara (Zuwārah)	32°54′	12°06′

GEOLOGY AND MINERAL RESOURCES OF LIBYA—A RECONNAISSANCE

By Gus H. Goudarzi

ABSTRACT

Libya covers an area of about 1,600,000 square kilometers along the northern coast of Africa. It has a population of about 1,500,000 (1964). Although most of Libya is in the Sahara Desert, it is crossed by three climatogeographic zones—the Mediterranean, a semidesert, and a desert zone that contains several fertile oases. The Mediterranean zone has an annual rainfall of as much as 600 millimeters and has a climate comparable to some parts of southern Europe, but southward this gradually gives way to intense desert conditions.

The present report is based on investigations made by the U.S. Geological Survey during 1954–62, in cooperation with the Libyan Government, under the auspices of the Agency for International Development of the U.S. Department of State. Fieldwork was limited to investigations of any promising mineral deposits and to geological reconnaissance that would aid in the examination and evaluation of the mineral resources. Detailed sampling and geological studies were made on deposits of potential value, and general information was obtained on other mineral resources. A topographic map of Libya was prepared in 1960–61 which was used as a base for a geologic map compiled in 1960–62; both maps were prepared in cooperation with private oil companies.

Libya as a whole is a cratonic basin on the northern fringes of the African Shield. Precambrian igneous and metamorphic rocks occur in south-central, southeastern, and west-central Libya. Tertiary and Quaternary basalts and phonolites cover large areas in the central part of the country and smaller areas in south-central and northwestern Libya.

Paleozoic rocks and Mesozoic continental deposits occupy the greater part of southern Libya south of lat 28° N. Mesozoic sedimentary rocks form the Hamāda al Ḥamrā' plateau of northwest Libya and are largely covered by a thin veneer of early Tertiary sedimentary rocks. Other Tertiary rocks occupy almost all the central and northeastern part of the country and smaller areas in south-central Libya. The narrow coastal plains are generally mantled by Quaternary deposits; a third of the country is covered by sand dunes and gravel plains.

During Precambrian time, a series of clastic sedimentary rocks was folded and metamorphosed. A period of peneplanation followed that was general throughout north Africa. This peneplaned surface is unconformably overlain by widespread Cambrian and Ordovician strata which are chiefly of continental origin. These were peneplaned before the Tassilian (Silurian) transgression. An Early Silurian (Early Gothlandian) transgression in the Murzuk basin of southwestern Libya is marked by a littoral facies which is overlain by thick marine beds. Regression at the end of Silurian time was followed by renewed marine transgression in Late Devonian and Early Carboniferous times. By the end of the Visean Stage of the Lower Carboniferous, regression of the seas gave rise to continental deposition that became general during succeeding Namurian time. Thereafter, continental sediments accumulated, perhaps intermittently, in south Libya until the middle of Cretaceous time, though marine sediments were being deposited in parts of northern Libya. In Late Cretaceous time the seas extended south as far as lat 28° N.; and in Eocene time, as far south as lat 23° N.—to the Tibesti foothills. Following Eocene time, the seas receded northward, and several thousand meters of sediments were deposited in the Sirte embayment and several hundred meters were deposited in the northeastern part of the country. A marine incursion during the Tyrrhenian Stage of the Quaternary Period resulted in deposition of sediments along the Mediterranean coast. Extensive dune and gravel plains developed in the Libyan desert during the Quaternary Period.

Post-Eocene volcanism in general probably was concurrent with movements along deep-seated fractures that perhaps were associated with the cyclic pulse of the Alpine orogenies. Some of the cones are probably of Recent age.

Northwestern Libya is a flat coastal plain, the Gefara, that rises gently to the south and ends at the foot of a north-facing escarpment several hundred meters high. The Jabal area slopes gradually to the south for about 300 kilometers into a desert of rocky plains (the Hamāda al Ḥamrā'), but at the southeast is interrupted by Jabal as Sawdā' that rises more than 300 meters above the surrounding land surface. Elsewhere the southern limit of the Hamada is a line of precipitous cliffs that mark the northern edges of the great Ubari Sand Sea and a broad arch of Paleozoic rocks, the Gargaf, which also bounds the Ubari (Awbārī) Sand Sea on the north. The Ubari Sand Sea is separated from the Murzuk Sand Sea on the south by a continuous escarpment that originates east of Sebha (Sabhah), rises westward toward Ubari (Awbārī) and swings south at about 11° E. to the Algerian border. The Acacus Mountains form the high escarpments near the Algerian border in southwestern Libya.

In north-central Libya much of the region south of the Gulf of Sirte (Khalīj Surt) is a fault-controlled series of northwest-southeast ridges bordered on the south by lava flows of Al Harūj al Aswad and by the Calanscio sarir (gravel plain). Jabal Ben Ghenema (Jabal Bin Ghunaymah) and Dor el Goussa (Dur Al Gussah) form a high massif in south-central Libya. Farther east is the Jabal Eghei, a northern prong of the high Tibesti Mountains.

In northeastern Libya the Jabal al Akhḍar (Green Mountains) is bounded on the north and west by a succession of abrupt faultline escarpments and terraces. This jabal area slopes gradually downward to the east and south forming hamada-type surfaces (the Baltat) toward the Egyptian border and the Cyrenaica desert. This desert is broken by Jabal Dalma in east-central Libya and by the Jabals Arkenu and Awenat in southeastern Libya near the Sudan-Egyptian border.

Libya contains several sedimentary and structural basins; the Gefara, Hamada, and Murzuk basins, combined with the Garian uplift and the Gargaf arch, are the main structural features in western Libya. The Sirte basin is a northwest-trending embayment in central Libya, the southern part of which is largely concealed by the Calanscio desert. The Jabal al Akhdar uplift and the Cyrenaica platform are major tectonic features in northeast Libya; the Cufra basin underlies the southeastern part of the country.

Northwest-trending faults are predominant in the Jabal area and the Sirte, the most important being the Hun (El Giofra or Al Jufrah) graben faults that separate the Sirte from the Hamada basin. Northeast-trending faults in south-central Libya extend from the Republic of Niger to the Al Harūj al Aswad area. Major faults of east trend are in northwest and northeast Libya, and another is south of the Gargaf arch in west-central Libya.

Libya's largest known oil reservoirs are in the Tertiary and Upper Cretaceous rocks of the Sirte basin, but oil also occurs in rocks ranging from Cambrian to Triassic in age. Oil exports averaged about 350,000 barrels per day for the first 6 months of 1963, 760,000 barrels per day in March 1964, and 1 million barrels per day in March 1965.

Except for petroleum, potential mineral resources are limited to a large iron-ore deposit and appreciable amounts of nonmetallic commodities such as gypsum, salt, building stone, silica sand, and cement rock. Small and scattered deposits of trona, sulfur, alum, manganese, low-grade phosphate, barite-celestite, and clay are also present.

The largest iron-ore deposit in Libya is in the Shati Valley area of Fezzan where flat-lying iron-bearing sedimentary beds of Tournaisian (Early Carboniferous) Age persist with remarkable regularity for about 100 kilometers. The beds are exposed in a zone 2 to 3 kilometers wide and probably persist some distance farther south under younger strata. The thickness of the iron-bearing beds ranges from 2 to 11 meters and averages about 5 meters. The ore is oolitic to finely granular and in places is a permeation or interstitial filling of clastic rocks. Hematite, chamosite, limonite, and siderite constitute the ore minerals. Locally manganiferous veinlets cut across the iron-bearing beds. In most areas the base of the beds is highly impregnated with petroliferous material. Silica is the main impurity, and sulfur and phosphorus are present in varying quantities. The ore reserves are calculated from 42 drill holes and many outcrop samples.

A total of 1.6 billion metric tons of indicated iron ore reserves has been computed, based on four grades of ore ranging from 30 to 48 percent iron.

The most important saline deposits in Libya are near Marada (Marādah) about 125 kilometers south of El Agheila (Al 'Uquaylah) on the Gulf of Sirte. They cover an area of about 150 square kilometers, about 15 square kilometers of which were worked experimentally by Italian operators who exported 21,000 metric tons of potash salts in 1939. These surficial deposits of recent origin are accumulating by processes of capillary migration and evaporation during the hot dry summer months. The brines yield a mixture of $MgSO_4$, $MgCl_2$, NaCl, and KCl, the chief minerals being halite and carnallite. Reserves are estimated to be 1.6 million tons of potassium salts containing 40 percent K_2O equivalent and 7.5 million tons of magnesium chloride.

The Edri saline deposits in Fezzan cover an area of about 35 square kilometers. They consist of a hard crust as much as 40 cm thick containing about 70 percent NaCl, 3.4 percent K_2O equivalent, and 1.6 percent $MgCl_2$. A mixture of sand and salts beneath the crust and the brine contain small amounts of potassium and magnesium salts.

The Pisida saline deposits, along the Mediterranean coast near the Tunisian border, cover an area of about 50 square kilometers. They are ephemeral deposits of brine-impregnated salt, formed during the dry season by solar evaporation of sea water percolating through a pervious sand barrier. The crust contains 4.2 percent K_2O equivalent, and the brine contains about 11.6 percent magnesium chloride ($MgCl_2$). The concentration of magnesium and potassium chlorides, about 7 percent and 14 percent, respectively, is greatest in the northwestern part of the area.

Gypsum is present in several areas in Tripolitania and Cyrenaica (Marmarica); the most important occurrence being the gypsum-anhydrite deposits in Lower Jurassic rocks in the Bi'r al Ghanam-Yafran area about 90 kilometers southwest of Tripoli. These deposits are exposed almost continuously for about 60 kilometers along the Jabal escarpment. In the Yafran area the deposit exceeds 400 meters in thickness, but it pinches out to the east over a distance of 42 kilometers. The deposit is in general flat lying, but is disturbed locally. In outcrop, the material is chiefly gypsum interbedded with dolomitic limestone, but considerable thicknesses of anhydrite were drilled. The gypsum has formed by hydration of anhydrite, mostly within the upper 30 meters of the deposit. Computed indicated reserves of gypsum are about 185 million tons, and the inferred reserves are essentially unlimited. Only material averaging more than 65 percent $CaSO_4 \cdot 2H_2O$ was considered as gypsum.

No waterpower exists in the country, for there are no perennial streams. Except in a few oases, the ground-water supply is scant; in the desert areas, water is too scarce to support permanent habitation by man.

INTRODUCTION

Libya is in north Africa, approximately between lat 20° and 33° N. and between long 10° and 25° E. It is bounded on the north by the Mediterranean Sea, on the east by the United Arab Republic (Egypt) and Sudan, on the west by Tunisia and southern Algeria, and on the south by the Republic of Chad, Republic of Niger, and Sudan (fig. 1). Libya includes a large part of the Sahara Desert, which extends across north Africa from the Atlantic Ocean to the Red Sea.

Libya contains three climatogeographic zones: (1) the Mediterranean littoral, consisting of about 45,000 square kilometers, the most heavily populated and most suitable for agriculture; (2) a semidesert area of about 100,000 sq km which is chiefly grazing land; and (3) a desert zone containing several fertile oases.

Libya was the first country to receive full independence under U.N. auspices in 1951. It was an Italian colony from 1911 to 1948. Libya comprises the former provinces of Tripolitania (Wilayat Tarabulus), Cyrenaica (Wilayat Barqah), and Fezzan (Wilayat Fazzan), with a total area of approximately 1,600,000 sq km and a population of about 1,500,000

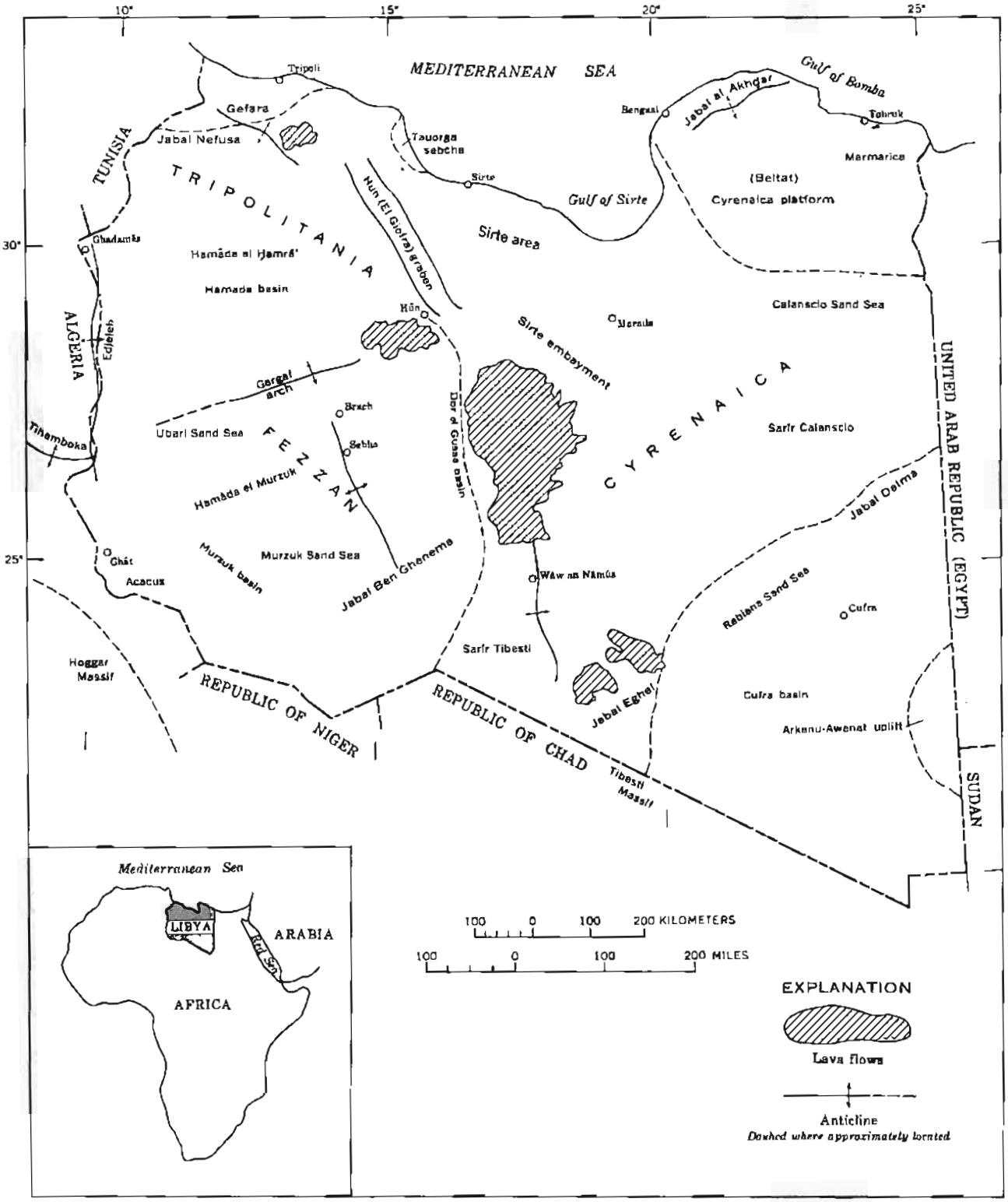


FIGURE 1.—Index map of Libya.

(1964). These provinces were recently (1963) disestablished as political divisions but are used in this report as geographic divisions.

Tripolitania in the northwest contains about 69 percent of the population, whereas Cyrenaica has 28 percent and Fezzan only about 3 percent. The two largest cities are Tripoli (Tarābulus) and Bengasi (Banghāzī) with estimated (1965) populations of about 376,000 and 279,000 respectively.

PREVIOUS GEOLOGIC INVESTIGATIONS

Geologic and other scientific studies of Libya began in the second half of the 19th century, but it was not until early in the 20th century that detailed geologic studies of the country were made by Italian, French, and English geologists.

A. Desio and his Italian colleagues made valuable reconnaissance geological studies beginning about 1915 and from 1930 to 1940 did detailed stratigraphic and paleontologic work. Their work was recorded in many publications, including a geologic map of Libya at a scale of 1:3,000,000 by Desio (1939).

French geologists did much work in Fezzan during the period 1944–52, and from the works of M. Lelubre, N. Menchikoff, and others a geologic map of north Africa was published at a scale of 1:2,000,000 (International Geological Congress, 1952). This map included the western half of Libya.

Other recent works are by Brichant (1952), Muller-Feuga (1954), and Lelubre (1952). Christie's (1955) "Geology of the Garian Area" describes recent detailed studies in Tripolitania.

The Names and Nomenclature Committee of the Petroleum Exploration Society of Libya coordinated some of the more recent unpublished works of oil-company geologists and completed a stratigraphic lexicon (started by Desio in 1956) for the International Geological Congress (Petroleum Exploration Society of Libya, 1960).

For a more complete bibliography, the reader is referred to Hill (1959), who listed most of the then-known published and some unpublished literature on Libya.

PRESENT INVESTIGATIONS

Geological investigations that led to the present report were made by the U.S. Geological Survey from 1954–62 under the auspices of the Agency for International Development (formerly Internat. Coop. Adm.), U.S. Department of State, in cooperation with the Ministries of National Economy, Industry, and Petroleum Affairs of the Government of Libya.

Although this study was undertaken primarily as an inventory of the mineral resources of Libya, considerable time was spent in geological reconnaissance and mapping and detailed sampling of potentially commercial mineral deposits. The work also included training of Libyan nationals in core drilling, collection of samples, and other field activities.

An outgrowth of the program was the preparation of the bilingual topographic map of Libya published in September 1962 as U.S. Geological Survey Miscellaneous Geologic Investigations Map I–350 B. (See pl. 1 this report.) This map was used as a base for the geologic map of Libya (pl. 2) compiled in 1960–62 in cooperation with 14 oil companies.

Owing to the large areas to be covered, inaccessibility of many areas, and the difficulty of desert travel, fieldwork was necessarily limited to systematic reconnaissance geological studies and examination of mineral occurrences. Therefore, the geology is described only in broad outline with the objective of presenting general features rather than a complete description of the geological conditions. Detailed geological studies were made only of deposits believed to have future potential.

The geologic map of Libya by Desio (1939) was used as a reference and guide to early field investigations. Use was also made of the previously published data (in Italian) that were available in Libya, principally "L'Esplorazione minerarie della Libia," by Desio (1943), "Geology of the Garian area," by Christie (1955), and "A Broad Outline of the Geology and Mineral Possibilities of Libya," by Brichant (1952). Most of the geologic names in this report conform to terminology in the stratigraphic lexicon (Petroleum Exploration Society of Libya, 1960).

To expedite analyses of samples, all analyses reported here (except a few from unidentified sources) were made at the Libyan-American Joint Services Chemical Laboratory. The laboratory was reorganized and reequipped under the writer's direction, and a training program was undertaken during the years 1955–62. The laboratory is equipped to analyze water, rocks, minerals, and all agricultural products.

MAPS AVAILABLE

Accurate base maps of sufficiently large scale for detailed geological mapping were unavailable for most areas in 1954. The bibliography of Libya by Hill (1959, p. 11–14) listed the then-existing maps of the country, but most of these maps were unavailable to us. During the period 1954–62, the writer collected most of the available maps: (1) 1:400,000-scale maps of Libya and 1:50,000-scale map of Tripolitania published by the

Italians, (2) 1:500,000-scale maps of Libya and 1:100,000-scale maps of Tripolitania and Cyrenaica published by the United Kingdom War Office, (3) 1:1,000,000-scale aeronautical charts and 1:250,000-scale maps published by the U.S. Army Map Service, and (4) several other useful miscellaneous maps of small areas. These maps, including indexes prepared for them, were deposited with the Geological Department, Ministry of Industry of the Government of Libya in Tripoli.

Since the beginning of petroleum exploration in 1954, the entire country has been mapped by aerial photographs at scales of 1:50,000 and 1:60,000 by private oil companies in Libya. Copies of these photographs as well as photomosaics of about two-thirds of the country are available from these companies.

Aerial photographs at scales 1:30,000 and 1:60,000 of areas within 180 km of the coastline, taken by the U.S. Air Force in 1953–54 for the Government of Libya, and index maps showing other photographic coverages in Libya were deposited with the Geological Department of Libya. In addition, 1:20,000-scale photographs of the Shati Valley and 1:40,000-scale aerial photographs of the inhabited areas of Fezzan, taken in 1954 by the Institute Geographique National, Paris, were deposited with the Department.

Large-scale planimetric maps were compiled by the oil companies for their own use. Some of these, and other topographic information, were made available to the present writer in 1959–60. These data were used in compiling the 1962 topographic map of Libya.

Geological maps available at the early stages of field investigation were few; however, some geologic maps were obtained, notably the 1:3,000,000-geologic map by Desio (1939). The present writer collected copies of all the available published geologic maps of Libya, including the 1:2,000,000-scale International Geological Congress map (1952) covering the western half of the country, all of which were deposited with the Geological Department of Libya.

Published data and geological information obtained from the oil companies, combined with knowledge gained during present investigations, were used to compile the geologic map of Libya (pt. 2), which was published separately as U.S. Geological Survey Miscellaneous Investigations Map I–350 A in 1964.

ACKNOWLEDGMENTS

The writer acknowledges with pleasure the many kindnesses and cooperation of the staffs of the Ministries of National Economy and Industry of the Government of Libya, particularly Ess. Munir Ba'aba, undersecretary to the Ministry of Industry, who followed the entire program with much interest. The writer is also indebted to personnel of the United States Operations Mission (USOM) of the Agency for International Development (AID), and particularly to Mr. Marcus J. Gordon, Director, USOM in Libya, 1955–59, whose interest and support made this study possible. Many thanks are due the entire Libyan-American Joint Services Minerals Investigation project personnel, and particularly to Mohammed Kalifa Jihani, Hameda Buazza, Zaid Giuma, Ahmed Drera, Mohammed Burkhais, Feraj Awad, and others for field assistance in the sampling and core-drilling operations.

The writer acknowledges, with thanks, the contribution and assistance of the oil concessionnaires and the Names and Nomenclature Committee of the Petroleum Exploration Society of Libya during compilation of the topographic and geologic maps of Libya.

The writer is grateful to Mr. Alvin F. Holzle, U.S. Geological Survey, for his review and invaluable assistance in the early stages of the preparation of this report. Fossils were identified by members of the U.S. Geological Survey.

From August 1957 until August 1959 Mr. James L. Gualtieri made a study of the gypsum-anhydrite deposits in Tripolitania and assisted in various aspects of the program. From February 1960 until June 1962 Louis C. Conant was in charge of the compilation of the geologic map of Libya (pl. 2) and gave much help during the review and editing of the topograhic map of Libya.

During the summer of 1963, Miss Jewell J. Glass made microscopic examination of many selected igneous and metamorphic rock specimens collected by the author in Libya. In addition she made a petrographic study of a large number of representative samples of the oolitic iron ores from the Shati Valley of Fezzan. The results of her work are incorporated in several places in this report.

HISTORICAL AND CULTURAL DEVELOPMENT OF LIBYA

At the beginning of the recorded history in the region, the inhabitants of Libya were probably descendants of the same people who lived there during Neolithic time. Herodotus, writing in the fifth century B.C., noted that Libya was inhabited by only two indigenous races, the Libyans in the coastal areas and the Aethiopians in the interior. The Aethiopians correspond to the negroid and distinctly African element of the population; the Libyans, from whom the present-day Berbers are descended, were people of Mediterranean stock who were also found in various parts of southern Europe.

Until the time of the Phoenicians, about 1000 B.C., the Libyans still lived in a Neolithic stage of development, but they had established small agricultural communities and lived in troglodytic dwellings (fig. 2). One of the largest tribes, the Garmantes, were sedentary and lived in Fezzan, where they raised cattle.

The Phoenicians colonized Libya between the eighth and 12th centuries B.C. They settled in western Libya in large numbers and introduced more efficient methods and improved implements for farming. At the same time, a powerful colony of Greeks was established in northeastern Libya at Cirene.

The Carthagenian empire extended into Libya about the third century B.C., and the Roman influence began in Libya after about 150 B.C.; it was not until the time of Caesar that Libya was incorporated into the Roman Empire. Under the Romans, irrigation and conservation methods brought new life to agriculture. Comfortable villas and farms spread over the countryside.

The Arab influence in Libya began about 644 A.D., and in 1551 Libya became a province of the Turks, who controlled the country until 1911. In 1911 Italy declared war on Turkey, and in 1912 Libya became an Italian colony, but fighting continued until about 1930. From 1930 to 1940 Italy launched a large-scale development program with the concession of large tracts of land to Italian settlers.

FIGURE 2.—An underground home in the Garian area, probably reflecting pre-Roman influence, possibly Phoenician culture; note the carvings on the column in the center. The depth of excavation is about 5 m. In the center of the home is a cistern for storage of water.

In the early years of World War II, Libya became a battleground, and in 1943 the Allied forces occupied Libya. After World War II Libya was under the control of the United Nations and received her independence in December 1951.

GEOGRAPHY

The geographic names in this report generally conform with the Gazetteer of Libya (1958), which lists names approved by the U.S. Board on Geographic Names; however, for several names, the more popular spelling is used, and the name according to the U.S. Board on Geographic Names system for the transliteration of Arabic is initially given in parentheses. Thereafter, only the popular spelling of the name is used—for example: Beni Ulíd (Qaṣr Banī Walīd). On plates 1, 6, and 13, however, chiefly the approved geographic names are used, and the popular spellings are given in parentheses. Further, for the convenience of the reader, a glossary gives approximate geographic coordinates.

TRIPOLITANIA

Tripolitania as used herein is that part of northwestern Libya extending from the Tunisian border at about long 10° to about 18°30′ E. and from the Mediterranean coast to an indefinite southern boundary at about lat 29° N. It covers an area of approximately 350,000 sq km and has an estimated population of about 1 million people.

Western Tripolitania may be divided into three zones: the Gefara and the coastal plain, the Jabal or the mountain area, and the Hamāda al Ḫamrā' (the stony desert) which extends south into the Sahara of the Fezzan. Eastern Tripolitania is in the great Sirte.

GEFARA AND THE COASTAL PLAIN

The Gefara in the northwest corner of Tripolitania is a triangular area of about 20,000 sq km, bounded on the north by the Mediterranean coast and on the south by the Jabal Nefusa (Nafūsah) and Jabal Garian (Gharian). Its southern edge is a high escarpment which extends eastward from the Tunisian border near Nālūt to the vicinity of Homs (Al Khums) on the coast. The elevation of the Gefara ranges from 10 to 20 meters above sea level near the coast to about 200 m at the foot of the Jabal escarpment.

Along the Mediterranean coast the Gefara is heavily populated and contains the city of Tripoli and the towns of Pisida (Bu Kammāsh), Zuara (Zuwārah), Zawia (Az Zāwiyah), Gharabulli (Qaṣr Al Qarahbullī), and Homs (Al Khums). Farther inland are the towns of Suani ben Adam (Sawānī bin Ādam), Ben Ghashīr

(Funduq bin Ghashīr, Castel Benito), Azizia (Al 'Azīzīyah), as well as the small towns of Giosc (Al Jawsh), Tījī (Tigi), and Shecshuk (Shakshūk) at the foot of the Jabal escarpment. A narrow coastal plain which contains the towns of Zliten (Zlītan) and Miṣurata (Miṣrātah) is in large part cultivated.

THE JABAL

The Jabal, an Arabic name meaning mountain, is a rocky plateau with a steep north face and a gentle south slope interrupted by some north-facing escarpments. The Jabal escarpment rises to about 400 m above the Gefara and is well populated, the principal towns being Nālūt, Giado (Jādo), Yafran (Jefren), Garian, Tarhuna (Tarhunah), Beni Ulīd, and Al Kussabat (Al Qaṣabāt). Because of its elevation, the Jabal area receives relatively more rain, and the region is partly cultivated.

HAMĀDA AL ḤAMRĀ'

The desert of Tripolitania south of about lat 31°30′ N. may be divided into eastern and western parts by a line roughly through Mizda (Mizdah), Gheriat (Al Qaryah ash Sharqīyah), and Shuwayrif (Ash Shuwayrīf). The western part is known as the Hamāda al Ḥamrā' (Al Hammādah al Hamrā'), or the Red Rocky Desert. It includes the the western part of Tripolitania south of the Jabal and a lesser area of northern Fezzan. This region of Cretaceous to Paleocene rocks covers an area of approximately 80,000 to 90,000 sq km. The well-known oasis of Ghadamēs (Ghudāmis) lies in the southwest part of the Hamada near the Algerian-Tunisian border. The eastern part of the Hamada is a dissected plateau.

The Hamada is cut by numerous wadis (dry riverbeds of intermittent streams), some of which form flood plains and wide depressions. These features are most pronounced in the north, where a cover of sand is commonly present. In the south the Hamada falls gradually to a monotonous gravel plain; its southern boundary is marked by a line of precipitous cliffs beyond which lies a vast lowland covered by dune sands of the Ubari Sand Sea. Bordering the Hamada in the southeast is the Jabal Fezzan, a massif along the 14th meridian which rises to an elevation of about 1,000 m above sea level.

THE SIRTE AREA

In this report the area north of lat 28° N., which lies approximately between long 15° and 20° E., is called the Sirte. It is separated from the eastern Hamada by a north-south trough, which is in fact a graben—the Hun (El Giofra or Al Jufrah) graben. The principal inhabited areas along the Gulf of Sirte are the towns of Sirte (Surt), Buerat (Al Bu' ayrāt), and Nofilia (An Nawfalīyah).

The only other inhabited areas between lat 30° N. and the Fezzan are the oases of El Ghadehia (Al Qaddahīyah), Bu Ngem (Bu Nujaym), Hūn, Socna (Sawknah), and Waddān (Uaddan). The group of oases, Hūn, Socna, and Waddān, are sometimes referred to as the El Giofra (Al Jufrah). The oasis of Zella (Zillah) lies about 150 km to the east-southeast of Waddān.

The Sirte area has a high relative humidity, steppe-type vegetation, and internal drainage. The internal drainage has resulted in the formation of many salt flats called sebchas and playas, the most important being the sebcha at Marada, the site of the Marada potash deposits. Flat-topped hills, several tens of meters high, are scattered throughout the area; near Bu Ngem are large areas of unstable sand dunes.

Unusual features of this desolate region are the volcanic massifs of Jabal as Sawdā' and Jabal Al Harūj al Aswad. They cover an area of approximately 45,000 sq km. The highest part of Jabal as Sawdā' is about 840 m above sea level, and an elevation of 1,200 m has been reported for the highest point of the Jabal Al Harūj al Aswad (pl. 1).

Black basalts of the Jabal Al Harūj al Aswad emerge abruptly from a plain west of the Jabal. Most of this gravel flat or plain, Sarīr al Gattusa (Sarīr al Qaṭṭūsah), is so devoid of vegetation that one can drive more than 80 km over its hard pebbly surface without seeing a single plant.

A small part of the Sirte area is included in Cyrenaica, extending from Tripolitania east to Antelat (Antalāt) at about lat 31°10′ N. and long 20°35′ E. It includes the coastal zones east of the Gulf of Sirte as far north as Regima (Ar Rajmah) east of Bengasi at lat 32°0′ N. and long 20°15′ E. and as far south as Wādī Al Fāregh (Wādī Al Farigh). Its most populated localities are El Agheila, Agedabia (Ajdābiyah), Soluch (Sulūq), Qamīnis, and the new Esso port of Marsa Brega (Qaṣr al Burayqah).

Along the coast of the Gulf of Sirte parallel to the coast is a narrow strip of semiconsolidated sand dunes that separates the sea from the coastal lagoons or marshes along the coast. Farther inland, beyond the lagoons, is a flat plain that rises gently towards Antelat, at the base of the Jabal escarpment, and extends north to near Regima. Several closed basins or depressions that have become salt flats lie within the area. With the exception of those in Wādī Al Fāregh and a few other limited exposures in small depressions, no rocks crop out in the region.

TAUORGA SEBCHA

In northwestern Tripolitania west of the Gulf of Sirte is the Tauorga sebcha (Sabkhat Tāwurghā'), an immense coastal marsh extending from Miṣurata to Buerat, separated from the sea by a belt of partly cemented coastal dunes. Within its limits are fluvial fans of Pliocene age formed by the wadis Soffegin (Sawfajjīn) and Zamzam. The water of the sebcha is largely floodwater from these wadis, supplemented by spring discharge at Tauorga and infiltration from the sea through the coastal dunes.

DRAINAGE AND CLIMATE

The most important drainage system in Tripolitania is the Wādī Soffegin which originates in numerous headwater tributaries between Giado and Yafran. It rises in the folds of the Jabal south of Yafran and flows southeastward past Mizda; then in a succession of great arcs it continues eastward for about 250 km where it enters the Tauorga sebcha at the Gulf of Sirte.

Another large drainage basin is that of the Wādī Zamzam system, which originates on the east flank of Hamāda al Ḥamrā' and parallels Wādī Soffegin. It empties into the extreme southern part of the Tauorga sebcha.

Wādī Tareglāt (Tāriqlāt) is another main drainage system of the Jabal that drains the area southeast of Tarhuna and south of Cussabat (Al Qaṣabāt, Al Kussabat). It empties into Wādī Caam (Kaām) which reaches the sea between Homs and Zliten.

Another important drainage system is Wādī Bay al Kabīr, which has several tributaries that originate in the southeastern part of the Hamada. North of Bu Ngem these tributaries join to form Wādī Bay al Kabīr, which, trending northeast, reaches the sea east of Buerat.

Wādī Megenin (Wādī al Majānīn), the largest north-south drainage system of the Gefara, has a watershed area of about 600 sq km on the Jabal. This is an area of relatively high rainfall, so that damaging floods often occur at Tripoli and elsewhere along its course.

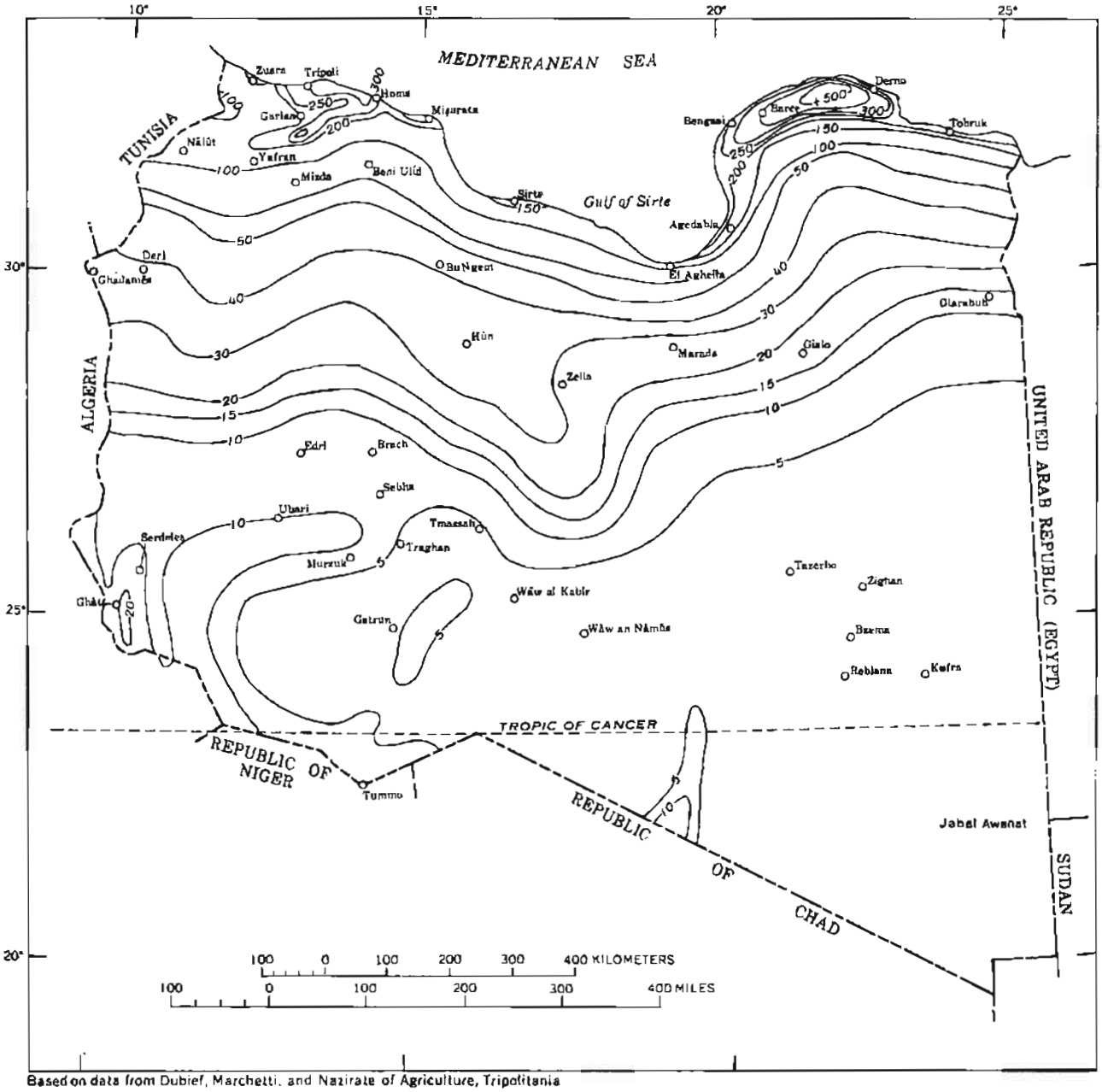
No stream in the entire country has a permanent flow, but during the rainy season any of the wadis may carry flood runoff, generally raging torrents of short duration (fig. 3*A*, *B*). Many of the wadis, especially the larger ones in areas of heavier rainfall, may contain underflow a short distance below the surface.

In Tripolitania the rain comes between October and March; December and January are the wettest months, but rain occasionally falls in April and May. Drought is normal during June, July, and August. Annual rainfall is less in the east, west, and south (fig. 4); for example, 380 millimeters fell at Garian and 150 mm at Nālūt during 1958, while only about 50 mm fell at Mizda. The irregularity of rainfall is a striking feature; south of lat 32° N., many areas receive no rainfall in some years. Snow in the Jabal area is occasional. It fell in 1949 and again in February of 1956, 1958, and 1962. The Jabal escarpment of Tripolitania which rises more than 600 m above sea level does not

A

B

FIGURE 3.—Floodwaters at Wādī Beni Ulīd. *A*, Rainwater running over the road at the village of Beni Ulīd. Photograph taken 2 days after peak of flood in April 1955. *B*, Rainwater which stood in Wādī Beni Ulīd, one of the tributaries of Wādī Soffegin, for several days after the flood in April 1955 at the village of Beni Ulīd.



Based on data from Dubief, Marchetti, and Nazirate of Agriculture, Tripolitania

FIGURE 4.—Rainfall distribution in Libya, in millimeters.

form a marked climatic barrier between the sea and the Sahara, such as do the much higher Atlas Mountains of Algeria.

Variation in temperature in Tripolitania is much the same as in southern Europe, the mean temperature being about 20°C (centigrade). Winters are cold, and summers are hot with temperatures in excess of 43°C. A record-high temperature of 57°C was recorded in 1932 near Azizia in the Gefara; the lowest temperature, recorded in 1949, was −7°C at Nālūt in the western Jabal area close to the Tunisian border; but the eastern Jabal area (Al Kussabat, Tarhuna area) is considerably warmer.

In winter the coastal area is warmest, the temperature rarely dropping below the freezing point, but inland in the Gefara, temperatures as low as −2°C are not unusual.

The prevailing winds in the Gefara are from the northeast with occasional north winds. Occasionally in the summer, hot winds blowing northward from the

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A

desert fill the air with sand and dust, raising the temperature to about 50°C. Locally this weather feature is called a "ghibli."

AGRICULTURE AND VEGETATION

Agriculture in Tripolitania is largely dry farming; less than 100,000 hectares (250,000 acres) of fully irrigated land exists in Tripolitania. Water for irrigated farms is furnished from flowing and pumped wells. Cultivation in the Gefara is mostly within 30 to 40 km of the sea, and chiefly consists of olive and citrus orchards, vineyards, small vegetable gardens, and wheat and barley plots among date palms. Other crops are potatoes, tomatoes, and lettuce. Sheep, camels, and goats also contribute to agricultural income. The cultivation on the Jabal, consisting of olive groves and grain farms, is entirely dry farming. Tobacco is also an important crop in the Jabal area.

In Tripolitania natural vegetation is sparse and generally restricted to drought-resistant plants. The only common phreatophytes are the date palms growing along the coast where the water table is close to the land surface. Reeds and other marshgrasses also exist locally. Natural vegetation also exists in most wadis, particularly in Wādī Zamzam and Wādī Soffegin areas where there are small trees and bushes.

Other plants such as eucalyptus, acacia, several varieties of saltcedar, and tamarisk have been introduced into the country and thrive without irrigation. These varieties are used extensively for windbreaks and firewood. Eucalyptus is also used for making charcoal.

B

FIGURE 5.—Sand-dune encroachment near village of Agelát (Al 'Ujaylāt). *A* (facing page), Wasteland resulting from destruction of natural vegetation and lack of cultivation. The sand is taking over in this oasis south of Agelát. *B*, Some of the wasteland recently reclaimed by dune fixation (dissing). The dissing is finished on this dune near Gharabulli, and the area is ready for tree planting.

The uncultivated parts of the Gefara are sandy and somewhat undulating steppe mostly covered with small brush. Destruction of natural vegetation and lack of cultivation has resulted in accumulation of extensive dune areas and wasteland (fig. 5*A*, *B*). Recently some of this wasteland has been reclaimed by dune fixation and other control methods.

CYRENAICA

Cyrenaica is defined here as that part of Libya extending eastward from about 18°30′ E. (west of El Agheila) to the Egyptian border at about 25° E. and from the Mediterranean coast south to the border of the Republic of Chad and the Sudan. This constitutes an area of approximately 780,000 sq km inhabited by only about 450,000 people. Cyrenaica may be divided into the coastal plains, the Jabal area including eastern Cyrenaica, and the desert.

THE COASTAL PLAIN

Behind the coastal dunes that stretch north and south of Bengasi is a gently sloping plain with an average gradient of about 1°. This plain extends to more steeply rising ground that ultimately becomes an escarpment. South of Bengasi this coastal plain is about 30 km wide, but it narrows towards the north and is only 4 to 5 km wide at Tocra (Tūkrah) and less than a kilometer wide at Tolemaide (Tulmaythah). It is extensive north of Bengasi where it is called the Bengasi Plain. The coastal plain, west of the Gulf of Bomba (Golfo di Bomba), contains the towns of Apollonia (Marsá Sūsah), Derna (Darnah), and Timimi (At Tamīmī), which are the more important populated places.

THE JABAL AREA

The Jabal area described herein is that part of Cyrenaica east of Sirte to the Egyptian border and south from the Mediterranean to about lat 31° N. It includes the eastern plateau (Marmarica).

At Barce (Al Marj) a pronounced terrace occurs at an elevation of about 230 m. The escarpment of this terrace starts at Antelat, lat 31°7′ N., long 20°35′ E., about 100 m above sea level, and rises gradually to about 300 m in the vicinity of Regima. From Regima it swings northeastward past Barce and approaches the sea near Tolemaide, continues eastward at about the same elevation to the vicinity of Cirene, then rises to a height of about 500 m at Ra's el Hilāl. It then slopes downward to a height of 250 m near Derna, beyond which it abruptly loses its prominence.

The next terrace level originates in a conspicuous feature near Al Abyār at an elevation of about 450 m and rises gradually to about 625 m near Cirene and 675 m south of Ra's el Hilāl, beyond which it descends gradually to the east. Inland for 10 to 20 km from this upper escarpment, the land rises somewhat irregularly to greater heights, reaching a maximum of about 875 m about 20 km south of Cirene. All these upland areas of Cyrenaica are known as the Jabal al Akhḍar (Green Mountains) because the greater rainfall supports a thin forest.

This high plateau descends gradually southward into a rocky semidesert area, Baltat, which extends south for about 120 km to the desert. The Jabal area is partly cultivated and remarkably populous. Major towns are Al Abyār, Beda (Al Baydā'), Barce (Al Marj), and Cirene; the area contains several smaller communities.

The eastern plateau lies between the Gulf of Bomba and the Egyptian border. The coastal zone of this plateau is about 30 km wide and is marked in many places by precipitous cliffs rising more than 100 m from the sea. It contains the cities of 'Ayn al Ghazāla, Tobruk (Tubruq), and Port Bardia (Bardīyah). Inland from this coastal zone is a second plateau, which is broken into terraces and has an elevation of about 200 m. Its surface is nearly horizontal and slopes gradually south to the village of Giarabub (Jaghbūb) on the northern edge of the Sand Seas of Calanscio.

THE DESERT OF CYRENAICA

The Cyrenaica desert extends from the slopes of the Jabal area at about lat 31° N. to the southern border of Libya. Along the slopes of the Jabal in the northern part of this desert (above the 30th meridian) is a limestone plateau (Cyrenaica platform), an undulating plain that slopes gently southward to almost below sea level. It contains several closed basins and depressions that collect the floodwaters of the Jabal and includes the oases of Marada, Augila (Awjilah), Gialo (Jālū), and Giarabub. This line of oases is the lowest part of the Cyrenaica desert. From this line the ground gradually rises to the south reaching an elevation of about 350 m above sea level at Cufra (Wahat Kufrah) and about 600 m at the foot of the Jabal Arkenu and Jabal Awenat (Al 'Uwaynāt). Jabal Eghei, in the southwestern part of the desert, rises to heights of 750 to 1,000 m. South of the Cyrenaica platform Sarīr Calanscio (Serir di Calanscio) occupies an area of about 120,000 sq km; the Great Calanscio and the Rebiana Sand Seas cover 100,000 and 70,000 sq km, respectively. South of these great sand-dune areas and gravel plains the desert consists of rocky plains and hills separated by gravel plains and minor sand areas. The isolated oases of Cufra, Tazerbo, Rebiana (Rabyanah), and Bzema (Buzaymiah) are the only populated areas of this vast desert.

DRAINAGE AND CLIMATE

Wādī Al Fāregh is the principal drainage system in the Sirte area of Cyrenaica. It flows westward, discharging into the great depression of Sabkhat Kurkūrah southeast of El Agheila. Wādī Gattar (Al Qaṭṭār), which starts at the southwestern flank of the Jabal al Akhḍar and flows toward the Bengasi Plain, is the most important drainage system of the coastal plains, even though its water is above ground only during heavy floods.

The northern face of the Jabal al Akhḍar is cut by several wadis flowing northward, but most of them terminate at the foot of the Jabal escarpment. In the Jabal area the wadis radiate from the high watershed and follow the general slope of the land. The most important drainage systems are Wādī Derna and Wādī Al Cuf (Kūf) which run parallel to the edge of the escarpment in opposite directions away from the high part of the terrace south of Ra's el Hilāl. They both turn at right angles and descend to the sea transversely to the escarpments and terraces. The drainage in the desert of Cyrenaica is entirely internal, and no system is recognizable.

The climate of Cyrenaica is comparable to that of Tripolitania, with mean temperatures of about 20° to 21°C. The high precipitation and humidity of the Jabal result in forested areas on the slopes of the northern face of the escarpment and perennial vegetation on the upper plateau. Rainfall increases with increase in elevation from the coast to the upper Jabal area, decreases towards the interior, and is rare in the desert.

The temperature increases from the coast to the interior and from west to east; however, it decreases with increase in elevation in the Jabal al Akhḍar area.

The average annual rainfall on the upper part of the Jabal is about 450 mm, whereas it is about 250 mm on the coastal plains (fig. 4). Snow is rare, but 40 centimeters was recorded in early 1934, covering the Jabal and the second terrace (Little, 1945).

The rainy season is from October to March with January and December as the wettest months; drought is normal between June and September.

The prevailing winds are from the northwest with occasional north winds from the sea. On occasion, during the dry season, south winds blow from the desert and create conditions similar to the ghibli in Tripolitania, during which time the air is filled with sand and dust and the temperatures rise substantially above normal.

AGRICULTURE AND VEGETATION

With the exception of parts of the Bengasi Plain and the areas near Apollonia and Derna, the coastal plains of Cyrenaica have insufficient rainfall, poor soil, and inadequate ground water of suitable chemical quality for extensive agriculture.

The limestone surface of the first terrace at Barce is covered with thick red earth. This terrace has several closed basins that are generally flooded during the rainy season and provide good soil and water for agriculture.

The surface of the upper plateau of Jabal al Akhḍar is grassland, and the slopes of the northern face are forested. On the higher parts of the plateau the red earth is fertile and provides good grazing ground, but about 120 km inland the plateau is a desert. Springs are relatively numerous on the northern slopes of the plateau, providing water for domestic and agricultural uses.

The main crops are wheat and barley, olives, dates, citrus fruits, grapes, and minor amounts of vegetables; grazing is an important source of agricultural income.

Natural vegetation in Cyrenaica is principally grasses on the plateau of Jabal al Akhḍar and wooded areas of wild olive trees, juniper, cypress, pine, and oak. Palm trees, reeds, and marshgrasses grow where the water table is near the surface. The uncultivated lands, particularly south of the Jabal slope, are sandy and undulating steppe sparsely covered with small brush. Vegetation exists in depressions where sufficient moisture accumulates. Perennial vegetation exists in the Cyrenaica desert only around the oases.

FEZZAN

Fezzan covers an area of approximately 470,000 sq km and has an estimated population of about 45,000 people. To a large extent, it is a great topographic basin in the northern Sahara bordered indistinctly on the north by the southern slopes of the Hamāda al Hamrā' and by Jabal as Sawdā', on the east by Jabal Al Harūj al Aswad and southern Cyrenaica, on the southeast and south by the Tibesti Mountains of the Republics of Chad and Niger, and on the west by the Tassilian Ajjer foothills of Algeria. Sebha is the principal town and the seat of the provincial government.

The average elevation of Fezzan is less than 450 m above sea level, whereas the average elevation of the encompassing Sahara is about 1,000 m, with reported elevations of 3,400 m and 3,300 m in the massifs of the Tibesti Mountains.

Most of the Fezzan is covered by the Ubari (fig. 6) and Murzuk Sand Seas with areas of about 80,000 and 70,000 sq km, respectively. These dune areas are oriented northeast to southwest, narrowing northeastward. They are separated by an escarpment of Nubian sandstone, the southern slopes of which form the Hamāda el Murzuk.

More than 90 percent of the population of Fezzan is concentrated in several chains of oases that stretch along the north and south edges of the sand-dune areas. The Shati Valley, on the north side of the Ubari Sand Sea, contains the oases of Ashkada (Eshkeda), Guira (Qīrah), Brach (Brak), Mahruga (Al Mahrūqah), Barqin, Wanzārik, and Edri (Adrī). It is the most heavily populated region in Fezzan, and Brach is the most important center of the area.

Wādī Ajal, on the southern boundary of the Ubari Sand Sea, contains several oases that extend northeastward from Ubari to Umm Al Abyaḍ. It may be extended northeastward to include Sebha and the oases of Timmenhent, Zighan (Zīghan) and Samnū and Umm al Abid northeast of Sebha which constitute the Bouanis. North of the Murzuk Sand Sea are a number of oases, the most important ones being Murzuk (Marzūq), Trāghan (Trāghan), Zawilah, Umm al Arānib, and Tmassah (Tmessa). Small oases of Majdūl and Izām are on the south side of the dunes. East of the Murzuk Sand Sea are the Gatrun-Tajarḫī string of oases in the central part of Fezzan.

Other oases of Fezzan are Al Fogha (Al Fuqahā'), an isolated oasis south of Hūn, and the Ghāt-Barkat oases in the southwestern part of Fezzan near the Algerian border. The small oasis of Serdeles (Sardalas) is about 100 km north of Ghāt.

FIGURE 6.—Typical scene in the Ubari Sand Sea, which covers an area of about 80,000 sq km.

FIGURE 7.—Aerial view of the Wāw an Nāmūs volcanic crater in east-central Fezzan. Note the central cone and crater and the surrounding lakes.

About 150 km southeast of Tmassah, at the end of a line of oases extending from Murzuk northeastward through Tmassah, is the small settlement of Wāw al Kabīr. It is a small oasis inhabited by about 25 people, who subsist on dates and camel milk. Occasionally these people travel to Sebha for clothing and other essentials. From Wāw al Kabīr to the Tibesti Mountains, practically no life exists.

A point of special interest in east-central Fezzan is the isolated Wāw an Nāmūs volcano at about lat 24°50′ N. and long 17°45′ E. (figs. 7 and 8). The Wāw an Nāmūs crater, about 5 km in diameter, contains a central cone that rises about 180 m above the crater floor and has a secondary crater. The central cone is surrounded by five salty lakes that are fed by water from springs along their margins. The only vegetation is needly brush (reeds and cane type) bordering the lakes and a few scattered date palms. Of interest are the sulfur concentrations at Wāw an Nāmūs which are described on page 91.

THE TIBESTI MOUNTAINS

From Wāw an Nāmūs to the foothills of the Tibesti Mountains is an extensive gravel plain (Sarīr Tibesti). Utter desolation and silence best describe the area.

The Tibesti Mountains are an isolated massif in the northeast section of the Republic of Chad. The two highest peaks are about 3,400 and 3,300 m above sea level and are probably the highest points of the Sahara. The region is reportedly inhabited by nomads of the Tibu tribe whose livelihood is made by grazing of animals. They venture long trips into Sebha by way of Gatrun (Al Qaṭrūn) for trading purposes. Evidently, the Tibu tribes live on the Chad side of the Tibesti, for no human or any other life was seen during the present writer's visit to the Libyan portion of the area.

Jabal Al Harūj al Aswad and Jabal as Sawdā' were mentioned briefly earlier as the only outstanding features south of lat 30° N. Jabal Al Harūj al Aswad covers an area of approximately 35,000 sq km. It is an elevated mass of basalt, the highest part of which is an extinct volcano that rises about 600 m above the surrounding terrain. The Al Harūj al Aswad is bordered on the west by the vast gravel plains of Sarīr al Gattusa, almost equal in area to that of Harūj. The sarīr is devoid of life and vegetation, and the black basalts emerge abruptly from the comparatively featureless sarīr. Jabal as Sawdā' covers an area of about 7,000 sq km. It is also an elevated mass of basalt, the highest part of which rises 840 m above sea level. Jabal as Sawdā' is bordered on the southeast by Sarīr al Gattusa and on the west by the Hamāda al Ḥamrā' which extends beyond Ghadamēs into Algeria and Tunisia.

DRAINAGE AND CLIMATE

Fezzan drains internally into salt flats and playas scattered throughout the area. The streams are single or in small connected systems, and only ephemeral runoff occurs during rare but sometimes heavy rainstorms.

Northern Fezzan is drained by a number of south-flowing wadis into a closed basin, the Shati Valley, north of the Ubari Sand Sea. Runoff from Jabal Al

FIGURE 8.—The central cone at Wāw an Nāmūs surrounded by saline lakes. A few scattered palm trees and cane-type needly bush are found around the lakes. Hordes of mosquitoes that infest the lake area are responsible for the name (Nāmūs means mosquito).

Harūj al Aswad is to the north toward Zella and to the east into the Sarīr Calanscio. Most of the drainage from Jabal Ben Ghenema is to the northwest into another closed basin, the Murzuk, and the Acacus-Tadrart mountains drain to the east into the dunes. In the Tibesti region the runoff is shared by the Libyan depression and the Chad Basin; however, most of the present runoff is apparently to the south.

Fezzan is an arid region. Its average relative humidity is about 30 percent, but readings of as much as 90 percent have been reported at Sebha. The annual rainfall for a given station might range from 0 to 15 mm, but the average annual rainfall for the region is from 5 to 10 mm. Rain is so uncommon that many parts of the region receive no rainfall for several consecutive years; the occasional rains, however, occur as torrential downpours over small areas.

Generally the nights are cool, particularly in the winter months when the temperature may drop to as low as 0°C. Although it may not be a record, a winter temperature of −7°C has been reported at Sebha. The difference between night and day temperatures is extreme; in April of 1958 a nighttime temperature of 1°C, followed by 37°C in the daytime, was recorded in southeastern Fezzan. Summers are very hot and dry and a maximum of 55°C was recorded at Brach in June 1958. Heavy fogs covered the oasis of Brach several times during the spring of 1958. Prevailing winds are from the northeast and southwest, shifting from one direction to the other. The winds blowing north from the Sahara are intensely hot during the summer and often very cold and penetrating in the winter time.

AGRICULTURE AND VEGETATION

Agriculture in Fezzan is limited to the areas around the oases of the Shati Valley, Sebha, Wādī Ajal, Wādī Hufrah, and the Murzuk-Traghan Valley. The Shati Valley area, with Brach as the center, is the most populated and the main center of agriculture where several flowing wells furnish water for irrigation. Scattered oases of Ghāt near the Algerian border, Serdeles, Majdūl, and Gatrun in central Fezzan Province are also agriculturally important. A few other very small oases are situated in the dune areas of the Ubari Sand Sea.

The main agricultural products are dates, wheat, and barley. Vegetables such as potatoes, tomatoes, and melons are raised on a small scale, and citrus crops are grown in the Ghāt area.

With the exception of the oases mentioned above, there is scarcely any vegetation in Fezzan. Utter desolation best describes the deserts to the west, east, and south of Murzuk. Jabal Ben Ghenema seems capable of supporting vegetation periodically; but apart from this, the desert area south of lat 26° N. is almost lifeless, and a tuft of grass, an insect, or a bird is a rarity.

DESERTS OF LIBYA

Libya comprises part of the Sahara Desert, and contrary to general opinion, only 16 to 20 percent of the country is covered by sand-dune areas, notably the Ubari and the Murzuk Sand Seas in Fezzan and the Calanscio and the Rebiana Sand Seas in central Cyrenaica. A much greater part of the Libyan desert [1] is

[1] Libyan desert is herein used to include all the desert areas in Libya. The Libyan Desert, however, is only the desert area in southeastern Libya.

occupied by the hamadas (rocky plains) and the sarīrs (gravel plains).

In this paper the deserts of western Libya, which contain a part of the Libyan Sahara, are discussed. This part of the Libyan desert is one of the most fascinating areas for the study of the desert and its morphology. The great dune areas (ergs), the hamadas, the sarīrs, sebchas (salt flats), and the playas afford textbook examples of desert geomorphology.

"Climatically, deserts have been described as regions where evaporation exceeds precipitation; or, in relation to their vegetative aspects, as places where precipitation is too meager to maintain a continuous plant cover" (von Engeln, 1942, p. 401). The inadequacy of precipitation that occasions the Libyan Sahara may be due to the fact that the Sahara is a trade-wind desert. "The constant Trades are normally evaporating winds because they become progressively warmer as they descend from higher to lower altitudes and proceed from higher to lower latitudes" (von Engeln, 1942, p. 402). However, the occasional desert rainfall is of great geomorphic importance. The desert rain occurs in torrential downpour over restricted areas even though no rain may fall in many areas for years.

The surfaces of the rocks are subject to great extremes of temperature, as previously mentioned. It appears that the processes of heating, cooling, and slow chemical alteration are each in part responsible for the granular disintegration and exfoliated peeling which provide the characteristic aspect of desert weathering. Lack of plant cover results in continuous exposure. Therefore, as a result of chemical decomposition by occasional rains, high temperature variation, and constant exposure, granular disintegration and accumulation of waste are made possible. These grains in turn break down to produce fine sand which accumulates around detached boulders and at the base of the hills.

Winds of excessive velocity are a common phenomenon in the Libyan desert. These winds act effectively as a transporting medium. The sandstorms of the desert are well known to the present writer; sand and dust are lifted and conveyed by wind in sufficient volume to blacken the sky. These winds are locally called "ghibli," and men and animals caught in them are in danger of suffocation. As a result of wind erosion and the abrasive action of the sand-filled winds, eroded rocks assume fantastic and unusual forms. A typical example of wind-carved mountains is well displayed in the Ghost Mountains of the Tibesti Mountains (fig. 9).

FIGURE 9.—Wind-carved Ghost Mountains of the Tibesti Mountains. Photograph taken at about lat 22°30′ N. and long 17° E. near the Chad border.

Continuation of the processes of weathering and intermittent erosion brings about the progressive filling of the lower level basins with waste from the higher levels. By these means, longer continuous slopes are progressively developed from the highest elevation to the lowest depression in the desert. With the passage of time, the relief in the desert continues to be diminished.

SAND DUNES

A dune is generally started by the presence of some obstruction on the lee side of which the sand piles up; in the Libyan desert the irregularities of the wind currents may suffice of themselves to cause deposits of sand to pile up at certain spots (E. D. McKee, oral commun.).

In the Ubari Sand Sea the accumulation of sand, influenced by the shifting winds, generally northeast to southwest, has resulted in dunes in heaps more than 200 m high (fig. 10). Sand encroachments on the high ridges in southwest Libya (fig. 11) and similar partly covered hills south and southwest of Edri suggest that the tremendous heights and depressions in the Ubari Sand Sea, where the present writer examined them for 5 days on foot, may be attributable to the underlying rock topography.

FIGURE 10.—Aerial view of high dunes in the Ubari Sand Sea. The dunes in the right foreground are more than 200 m (about 700 ft) high. The village of Gabre Oun and the saline lake seen at the base of the dunes are about 45 km west-northwest of Umm Al Abyad. Photograph taken in October 1956.

LONGITUDINAL DUNES

The origin of longitudinal dunes is not fully solved. They appear to be the form characteristically present in the desert interior, where strong, steady winds prevail.

In the central and northeastern parts of the Ubari Sand Sea, possibly as a result of blowouts, greatly elongated parallel fixed dunes, oriented southwest to northeast, are formed (fig. 12). In between these elongated dunes, some of which are like waves in the sea, are wadis or passageways that are swept almost clear by the wind, in some places exposing the bedrock. Some vegetation exists in these channels or passageways. Locally, below the sandy cover is a phreatic zone from which all the wells obtain their water. Around these wells are settlements, oases, and gardens nourished by capillary water from this shallow water table. Some of these oases surround small saline lakes, some of which are perennial, whereas others dry up in the summer (fig. 13).

The gigantic sand-dune areas (ergs) of southwestern Libya cover an area of about 150,000 sq km, almost the size of Texas, and seem to remain fixed in position. The existence of the vegetation in the passageway and the occurrence of lakes and oases suggest the presence of an inner moisture, which along with the shifting winds prevent the shift of the sand beyond the sand-dune areas.

BARCHANES

Some dunes are high in the center, and the surface as well as the outline of the windward slope is convex. The lee slope tends to be concave because the back

FIGURE 11.—Sand encroachment on high ridges in southwest Libya. The sand has completely covered the ridge at the left and is gradually covering the entire ridge. Rock outcrops are partly exposed in the center and almost completely bare on the right side. Photograph taken along the sand areas northwest of the Tanezzuft valley about 30 km west of Serdeles.

FIGURE 12.—Aerial view of longitudinal dunes in the Ubari Sand Sea. The dunes are several kilometers long, and some are more than 100 m high. The photograph shows the parallel longitudinal dunes in the foreground. The slightly shadowed areas between the dunes are thought to be blowouts; dark spots are vegetation. Photograph taken about 30 km southwest of Brach looking northeast. Dune trends are N. 40° to 45° E.

FIGURE 13.—Aerial view of the village of Maatan near a small trona lake about 55 km northwest of Umm Al Abyaḍ. The lake dries up late in the summer, and sodium carbonate is deposited at the bottom of the lake. Note the saline residues already accumulating in April around the edges of the lake in the foreground. The sand dunes in the background are more than 100 m high.

eddy of the wind acts to hollow it out. They are probably of barchane type. According to von Engeln (1942 p. 422), "Barchanes are held to be the elementary dune form and are inferred to be the product of a moderate supply of sand and moderate wind velocities. * * * The crescent form develops because, with the uniform force of the wind approaching the dune, the sand must be moved over a longer course and to a greater height at the center than at the sides. The particle by particle migration of dune therefore proceeds more rapidly at the ends, and the characteristic barchane, sickle form results." (See fig. 14, this rept.).

Barchane-type dunes and shifting sand areas occur in several areas in the Libyan desert. Near Bu Ngem there are large areas of unstable dune areas that frequently blow over the road. They are thought to be of barchane type.

SARĪR

In some places the surface of the undissected land is made up of coarse angular and rounded pebbles (fig. 15) spread over extensive flat areas, where one can drive with ease and safety at high speeds. These extensive gravel plains are referred to as sarīr (serir). Many of these areas are in the Libyan desert: Sarīr al Gattussa bordering Jabal Al Harūj al Aswad; Sarīr Tibesti south of Wāw an Nāmūs, bordering the Tibesti foothills; and Sarīr Calanscio which covers an area of about 150,000 sq km in south-central Cyrenaica.

PLAYAS

On occasions playas are formed as a result of floodwaters which occupy wide depressions. The water penetrates through the porous sandy deposits leaving a smooth clayey surface mixed with salt crystals. Occasionally where the percentage of salts in the adjoining rocks is high, the playa lakes give rise to the accumulation of saline residues locally referred to as sebchas (sabkhahs). The surface of these sebchas is covered with crusted salts at places more than 30 cm thick (fig. 16*A*). Some of these saline residues contain a high amount of potassium and magnesium salts and may be of commercial value. Examples of this type are the sebchas of Marada and Edri.

In places the high sodium carbonate content has given rise to the formation of sodium carbonate residue, or trona (fig. 16*B*). These salt deposits are described in the section on mineral deposits.

HAMADAS

Hamadas, or stony deserts, are wide areas of flat bare rock floors which contrast with the above-mentioned sand seas of the desert. These floors are covered with coarse debris, and they may be truly called stony desert.

These hamadas are formed on the flat-lying or gently sloping sediments. The hamada surface was presumably developed by the combined action of wind and water. Many of these hamadas occur in the Libyan Desert, the more important of which are the Hamāda al Ḥamrā', which extends from south of the Jabal area of Tripolitania to northern Fezzan, and the Hamāda el Murzuk, which almost encircles the Murzuk Sand Sea.

GEOLOGY

Libya as a whole is a cratonic basin on the northern fringe of the African Shield. Precambrian rocks occur in south and southeastern Libya and in northern Fezzan. Libya contains thick sequences of moderately deformed Paleozoic rocks, and except in the northwest and northeast, Mesozoic sedimentary rocks are comparatively thin. Tertiary rocks occupy the greater part of the Sirte embayment and northern Cyrenaica.

Tertiary and Quaternary extrusive and intrusive rocks occupy large areas in the central part of the country and smaller areas in south-central Fezzan and northern Tripolitania.

FIGURE 14.—Typical barchane-type dune along the west edge of the Calanscio Sand Sea of Cyrenaica, about 30 km east of the village of Jālū (Gialo). Copied from color photograph, courtesy of Harry F. Thomas.

A

B

FIGURE 15.—Sarīr surface in Sarīr al Gattussa. *A*, Typical sarīr surface. These vast flat areas have sometimes been referred to as desert pavement. *B*, Closeup view of the pebbles on the sarīr surface shown in other photograph.

A

B

FIGURE 16.—Playa lakes in Fezzan. *A*, The accumulation of saline residues in playa lake-type depression at Edri. This salt flat (sebcha) covers an area of about 35 sq km. Note the hummocky, rough surface of the deposit. *B*, Aerial view of the saline lake at Nashnusha, about 60 km northwest of Umm Al Abyaḍ, in the Ubari Sand Sea. This lake dries up in the summer. In the background are the high sand dunes in step form several tens of meters high. To the right of center are the deposits of sodium carbonate in the bottom of the lake. The striped pattern results from troughs dug in the lake to concentrate the sodium carbonate.

Continental environments prevailed in south Libya from late Paleozoic until possibly the middle of Cretaceous time during which period several thousand meters of sediments was deposited there. The basin was active from Late Cretaceous time through Tertiary time when several thousand meters of marine sediments were deposited in the Sirte area and parts of northern Cyrenaica. The narrow coastal plains of Libya are generally mantled by marine and continental beds of Quaternary age, and the greater part of the Libyan desert is covered by immense gravel plains and sand-dune areas which were also formed during Quaternary time.

PRECAMBRIAN ROCKS

Crystalline and metamorphic rocks of Precambrian age occupy less than 1 percent of the area of Libya. They consist of para- and orthogneiss, schist, phyllite, quartzite, diorite, granodiorite, and granite. These rocks are believed to be part of the basement complex and considered to be comparable to the Pharusian (Massa and Collomb, 1960).

The main exposures are in south-central Libya west of Jabal Eghei, Tibesti area, and southeast of Tajarḥī and in the southeastern part of the country near the Sudan-Egyptian border in Jabal Awenat-Jabal Arkenu area. In northern Fezzan in Jabal Fezzan (Jabal Hasouna), Precambrian rocks are also exposed in several scattered outcrops in the middle of the Gargaf arch. The only other exposure of Precambrian rock in Libya is on the west side of Jabal Al Harūj al Aswad, north of Wāw al Kabīr in Dor el Goussa area.

Precambrian rocks in south-central Libya crop out over no more than 3,000 sq km. South of the Libyan border in the Republic of Chad (formerly Equatorial Africa), they crop out over a much greater area.

In Tibesti area, west of Jabal Eghei and southeast of Tajarḥī, these rocks consist of gray muscovite and biotite granites cut by dikes and veins of rhyolite and aplite porphyry. All these rocks are associated with strongly folded quartzites, schists, and varicolored phyllites. The granites crop out in weathered exfoliated blocks in most areas. They are porphyritic in some places, containing crystals of orthoclase as much as 1 cm long. Pegmatite dikes, some of which contain crystals of muscovite 2 to 5 cm long, occur in the area. A few dikes of dark-green gabbro intrude the granites in some parts of the western Tibesti area. The metamorphic rocks of the area generally strike almost east and dip vertically or steeply to the north or northwest. They are overlain unconformably by Cambrian and Ordovician rocks (fig. 17).

In Jabal Eghei and the eastern Tibesti areas, Precambrian rocks are locally covered by Tertiary extrusive basalt.

Only a brief geological reconnaissance study was made of the Tibesti area. Although tungsten minerals, including wolframite, and gold, cassiterite, lead-copper-silver, and uranium minerals have been reported in the Tibesti Mountains of the Republic of Chad, no evidence of such mineralization was noted in Libya by the present writer.

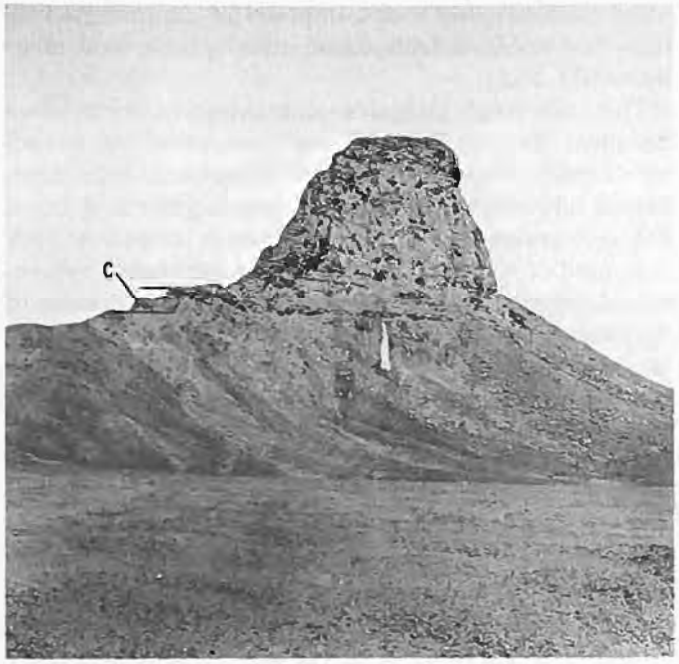

FIGURE 17.—Precambrian rocks in the Tibesti area, west of Jabal Eghei near the Chad border, discordantly overlain by Cambrian and Ordovician rocks. A basal conglomerate (C), about 4 m thick and containing large quartz pebbles and cobbles, marks the contact.

Precambrian crystalline and metamorphic rocks in southeast Libya in the Jabal Awenat–Jabal Arkenu area near the Sudan-Egyptian border cover an area of less than 1,500 sq km. They also extend into Egypt. In the Jabal Awenat–Jabal Arkenu area they consist chiefly of paragneiss and orthogneiss, quartzite, and marble intruded by muscovite and biotite granites which are in turn cut by aplitic and pegmatitic dikes. The granites contain sandstone inclusions as much as 10 cm in diameter, a feature noted west of Jabal Awenat and in a northwest-trending wadi north of Ayn Zuwayyab. Menchikoff (1927) noted stope blocks (inclusions) of crossbedded dark-colored sandstone several hundred meters thick in the granites of this area.

Immediately to the northwest of Jabal Awenat, beds of metaquartzites several hundred meters thick trend N. 40° E. and dip as much as 40° NW. These rocks, although covered by sand and gravel in the vicinity of Jabal Awenat, seem to be intruded by the granites, which at 'Ayn al Ghazāla rise to heights of several hundred meters above their surroundings (fig. 18A). In Jabal Arkenu, a complex metamorphic sequence (fig. 18B), consisting of gneiss and schists of Precambrian age, strikes almost north and dips 15° to 20° S. and SE. Here also, the granites appear to have intruded the metamorphic rocks in the central part of Jabal Arkenu.

Gallitelli (1934) regarded the metamorphic sequence of Jabal Awenat–Jabal Arkenu as Archean in age. He considered the younger granites (with inclusions) to be possibly contemporaneous with Hercynian folding during Late Carboniferous time.

Precambrian rocks in northern Fezzan are exposed in several scattered outcrops in the Jabal Fezzan area in

A

B

FIGURE 18.—Intrusion of metamorphic rocks by granite. *A*, Younger post-Carboniferous granite intruding the metamorphic rocks at Jabal Awenat in southeast Libya. Here the granite rises several hundred meters above the surrounding land surface. Note the goats at lower left. *B*, Precambrian metamorphic rocks in southwestern part of the central area at Jabal Arkenu. They are intruded by the granites in the background.

the middle of the Gargaf arch. These rocks, covering considerably less than 100 sq km, are muscovite and biotite granites cut by rhyolite, aplite, and pegmatite dikes. The granites are gray and develop an irregular weathered surface. They are exposed only in the eroded areas in the wadi beds. A few mafic dikes of nepheline phonolite intrude the granites in one small area (fig. 19).

The only other Precambrian rock exposures in Libya are on the west side of Jabal Al Harūj al Aswad, northwest of Wāw al Kabīr. These outcrops cover an area of only about 20 to 30 sq km and consist of biotite granite with syenite inclusions cut by aplite and pegmatite dikes. No evidence of mineralization was noted by the writer in the Precambrian rocks of Libya.

During the summer of 1963, Jewell J. Glass, U.S. Geological Survey, made a study of several thin sections of samples collected from the Precambrian and younger associated intrusive and extrusive rocks. Although many other samples are needed for a thorough understanding of the nature of these rocks and their relationship, the following is a summary description of the above-mentioned rocks examined under a polarizing microscope.

Study of the Precambrian metamorphic rocks of western Jabal Arkenu in southeast Libya shows (1) quartz feldspar schist with relic quartz grains in matrix of kaolinite derived from the feldspar (a few grains of magnetite remain, and the rock was perhaps originally a granite gneiss) and (2) amphibolite, a dark-grayish-green metamorphic rock composed of cummingtonite, oligoclase-andesine feldspar, apatite, quartz, and magnetite (fig. 20*A*).

FIGURE 19.—Precambrian rocks of Jabal Fezzan, exposed in the wadis; they consist of muscovite and biotite granites cut by rhyolite, aplite, and pegmatite dikes. A mafic dike of nepheline phonolite in upper center intrudes the granites. The rocks in the background are Cambrian and Ordovician sandstones unconformably overlying the basement rocks.

The associated intrusive and extrusive rocks were identified as (1) altered basalt composed of brown hornblende, orthorhombic and monoclinic pyroxene, altered labradorite, biotite, and magnetite, (2) gabbro, a coarse-grained black mafic igneous intrusive rock composed of orthopyroxene and clinopyroxene (hypersthene and augite) and of labradorite feldspar; some of the pyroxene is altered to magnetite rimmed by chlorite, (3) altered andesite, a gray fine-grained extrusive igneous rock composed of a mat of small laths of plagioclase (andesine) and small irregular grains of augite, some chlorite, and patches of carbonate, (4) granodiorite, highly metamorphosed and showing strong lineation, composed of biotite, andesite, labradorite, orthoclase, quartz, almandite garnet ($n+1.78$), sphene, and small amounts of magnetite or ilmenite, and (5) other extremely altered igneous rocks which contain fragments of plagioclase feldspar with alteration products such as carbonate, iron oxide, and siderite, and show evidence of infiltration of manganese-rich waters.

Samples collected from a deeply eroded central core of Jabal Fezzan in north-central Fezzan show that in this area the Precambrian granites are highly altered. The original quartz has been recystallized, and most of the orthoclase has changed to kaolinite although a few fragments of altered orthoclase and muscovite remain. Carbonate as an alteration product and a few grains of sphene and small patches of hematite are present.

The associated granite pegmatites in the Jabal Fezzan are composed (1) of large crystals of microcline, a few remnants of oligoclase feldspar, a few plates of biotite, and an abundance of quartz and (2) of quartz, orthoclase feldspar interlaminated with flesh-pink albite, an albite that is near oligoclase in optical properties, tourmaline that is black in hand specimen but is mingled brown and blue in thin section, spessartite garnet, and pale blue, nearly colorless apatite cutting across a large lath of albite-oligolcase.

The associated extrusive igneous rocks sampled in the area are:

1. Rhyolite, altered and stained by hematite. The groundmass ranges from glassy to finely crystalline and contains numerous inclusions of an iron-rich mineral which makes an alteration rim of iron oxide. Plates of biotite and rock fragments also occur sparingly in the groundmass. Orthoclase is the most abundant feldspar; albite is rare; and quartz is the most abundant mineral.

2. Rhyolite, highly altered; the groundmass is devitrified and shows small grains of quartz and feldspar.
3. Rhyolite, altered and stained by iron oxide. The groundmass is glass that shows only incipient devitrification. The feldspars are altered—the plagioclase to sericite and the potassic feldspar to kaolin. Quartz grains are fresh, and a few remnants of muscovite and orthoclase remain. A veinlet of hematite follows a small crevice in the rock, and some hematite is concentrated near the veinlet (fig. 20*B*).

Although other extrusive rock specimens that were examined had nearly the same characteristics as described in 1, only incipient devitrification noted in 3 is noteworthy, indicating a probable younger than Precambrian age for some of the extrusive rocks in the Jabal Fezzan area.

PALEOZOIC ROCKS

Paleozoic rocks,[3] ranging in age from Cambrian to Permian, occupy much of the southern part of Libya in Fezzan and southern Cyrenaica. In southwestern Libya they crop out along the peripheries of the Murzuk basin, in the Gargaf area, and in the Acacus-Tadrart mountains of southwestern Libya. In south-central Libya they crop out in Jabal Ben Ghenema, Dor el Goussa, Jabal Eghei, and the Tibesti Mountains; and in southeastern Libya they are present in the vicinity of Jabal Awenat–Jabal Arkenu and the hills of Jabal Dalma about 100 km north of Cufra (Kufrah). (See pl. 3.)

The Paleozoic rocks of Libya are mainly marine shale, siltstone, sandstone, limestone, and continental sandstones. In Fezzan they grade eastward from marine through mixed marine-continental to predominantly continental facies. In southern Cyrenaica,

[3] The stratigraphic classification of rocks described in this report is based on the more recent correlation chart, pl. 3. Therefore, some rock classifications may differ from those shown on the geologic map (pl. 2).

A

B

FIGURE 20.—Igneous rocks at Jabal Arkenu and Jabal Fezzan. *A*, Photomicrograph of amphibolite, from Jabal Arkenu in southeastern Libya, composed largely of cummingtonite with oligoclase-andesine feldspar and a small amount of apatite, quartz, and magnetite. × 20, crossed nicols. *B*, Photomicrograph of rhyolite from Jabal Fezzan. The groundmass is glass that shows only incipient devitrification. Other constituents are extremely altered. Plain and polarized light.

Paleozoic rocks are chiefly continental and shallow-water deposits with minor marine beds.

No Paleozoic rocks crop out in Libya north of about lat 28°45′ N. in the Gargaf area, or north of lat 26°30′ N. elsewhere in the country.

The lithologic similarity of Cambrian and Ordovician sequences overlying Precambrian rocks in widely separated areas is striking. The basal conglomerate, which everywhere marks the unconformable contact with the Precambrian, contains large pebbles and cobbles of clear white quartz. The overlying Cambrian and Ordovician sandstone and conglomerate sequences are generally white to rose colored, micaceous, and cross bedded; they are medium to coarse grained and poorly sorted, have kaolinitic cement, and are ferruginous in some places. The present writer in 1955–58 noted this unusual similarity in all the areas visited and correlated these beds by lithology and stratigraphic sequences. Massa and Collomb (1960) and later others (oil-company geologists, oral commun.) made similar correlations based on fossil identification.

Massa and Collomb (1960), on the basis of paleontologic evidence in the Gargaf area, divided the continental sequence into Cambrian and Ordovician rocks, and later Klitzsch (1963) and Burollet (1963) made the same subdivision in the Dor el Goussa area and Jabal Arkenu, respectively. Elsewhere in Libya, the oldest Paleozoic continental series overlying rocks of Precambrian age are not dated; they are here considered Cambrian and Ordovician.

CAMBRIAN AND ORDOVICIAN SYSTEMS

GARGAF GROUP

The Gargaf Group consists of intercalated continental sandstone, conglomerate, and shale; the shale beds range in thickness from slightly less than half a meter to 2 m. Unconformities of erosion and nondeposition occur commonly within the group. The group is divided into four formations (Massa and Collomb, 1960): the basal Hasouna of Cambrian age, and the Haouaz, Melez Chograne, and Memouniat Formations of Ordovician age. The estimated overall thickness of the Cambrian and Ordovician rocks is between 750 and 800 m in the Garaf area.

HASOUNA FORMATION

The Hasouna Formation of Cambrian age was identified first in the Gargaf area; it consists of a brown to yellowish-brown massive medium- to coarse-grained highly crossbedded silicified sandstone with abundant conglomeratic lenses. Kaolinitic cement and interbedded minor micaceous shale beds are characteristic. The base of the formation is marked by an arkosic conglomerate bed as much as 10 m thick unconformably overlying Precambrian rocks in Jabal Fezzan. This unit is a uniform sandy complex about 350 to 400 m thick containing *Tigillites* in its upper few meters. (*Tigillites* was a mud-eating worm that is represented by cylindrical tubes (burrows), which may be filled with sand or clay.) It is unconformably overlain by the fine-grained sandstone of the Haouaz Formation of Ordovician age. This separation of the Cambrian and Ordovician rocks is based on identification of *Tigillites* (Massa and Collomb, 1960).

Burollet (1963) recognized a 300-m sequence of the Hasouna (Cambrian) and the Memouniat (Ordovician) Formations in Jabal Arkenu; a conglomerate lies at the base. He considered the lower 100 m of sandstone containing *Tigillites* and the overlying quartzitic coarse-grained and conglomeratic sandstone to belong to the Hasouna Formation. He noted a discordance between the Hasouna and the overlying fine-grained sandstone and conglomeratic sandstones, which he considered to be equivalent to the Memouniat Formation.

Klitzsch (1963) noted thick-bedded to massive cross-bedded sandstone with kaolinitic cement in north Dor el Goussa and considered it to be equivalent to the Hasouna Formation of Cambrian age. He reported a minimum thickness of 1,700 m for the formation in the north edge of Dor el Goussa.

HAOUAZ FORMATION

The Haouaz Formation consists of fine-grained slightly crossbedded sandstone interbedded with silty micaceous gray and green shale beds, some of which contain massive *Tigillites* lenses. The Haouaz Formation is characterized by intercalations of *Tigillites* and absence of ripple marks and has a thickness ranging from 120 to 190 m (Massa and Collomb, 1960).

Massa (in Massa and Collomb, 1960) noted that the unconformable contact between the Hasouna and the Haouaz Formations is not apparent in many areas. However, the contact, an abrupt lithologic change, from coarse-grained crossbedded sandstone of the Hasouna Formation to fine-grained massive alluvial deposits of angular and subangular fresh feldspar and heavy minerals at the base of the Haouaz, can be traced for many kilometers in the Jabal Fezzan area.

In the Dor el Goussa area Klitzsch (1963) noted the Haouaz Formation, a sequence of thin- to thick-bedded sandstone, containing abundant *Tigillites*, resting unconformably on Cambrian rocks. According to Klitzsch, the Haouaz Formation is 50 m thick in Dor el Goussa but is generally absent in the eastern part of the area.

MELEZ CHOGRANE FORMATION

The Melez Chograne Formation is predominantly varicolored green and purple chloritic thin-bedded shale intercalated with angular and subangular fine-grained sandstone and siltstone. In the middle of the unit is a bed of violet-brown shale which is richly fossiliferous and contains Middle Ordovician marine fossils (Collomb, 1962). The unit is 10 to 60 m thick.

In Dor el Goussa area the Melez Chograne is a silty and sandy gray and reddish shale about 25 m thick and has fine-grained sandstone intercalations. It overlies the Haouaz Formation (Middle Ordovician) in northwest Dor el Goussa, the Hasouna Formation in the southeast, and is generally absent in the eastern flank (Klitzsch, 1963).

MEMOUNIAT FORMATION

The Memouniat Formation is a massive highly crossbedded sandstone weakly cemented by kaolinite and has minor fine-grained sandstone and micaceous shale interbeds. It discordantly overlies the Melez Chograne Formation or the Haouaz Formation where the Melez Chograne has been eroded and is absent. Where the Memouniat Formation lies on the Haouaz Formation, it is extremely difficult or impossible to distinguish between them. The unit is 100 to 140 m thick and is marked by a ferruginous sandstone bed at the top.

Klitzsch (1963) recognized the Memouniat Formation of Ordovician age in Dor el Goussa area. Here the Memouniat Formation consists of 30 m of a fine- to coarse-grained locally conglomeratic and crossbedded sandstone containing *Tigillites*. It overlies the Melez Chograne Formation (Ordovician) on the northwest and the Hasouna Formation (Cambrian) in the southeast. The base of the Memouniat is marked by about 2 m of highly ferruginous sandstone, indicating a probable stratigraphic break between the shale of the Melez Chograne Formation and the basal sandstone of Memouniat Formation (Klitzsch, 1963).

EGHEI SANDSTONE

The Eghei Sandstone (Cambrian and Ordovician undifferentiated) in south-central Libya is a massive crossbedded pebbly sandstone, locally conglomeratic, and contains *Tigillites*, *Harlania*, and *Cruziana*. It unconformably overlies Precambrian rocks in Jabal Eghei, Tibesti area.

LORI SANDSTONE

The Lori Sandstone of uncertain age (Cambrian to Devonian) (Petroleum Exploration Society of Libya, 1960) is a massive locally crossbedded friable sandstone which unconformably overlies the Eghei Sandstone. In some places it weathers to striking honeycombed pinnacles (fig. 21).

SILURIAN SYSTEM

Silurian rocks are exposed around the periphery of the Murzuk basin, on the eastern slopes of Jabal Eghei in the Tibesti area, and in south-central Cyrenaica about 100 km north of the Cufra oasis in Jabal Dalma area. The Silurian rocks consist of a series of shale and minor interbedded sandstone at the base (Tanezzuft Shale) and sandstone on top of the unit (Acacus Sandstone). These rocks form a high escarpment along the east side of Wādī Tanezzuft (fig. 22) on the west flank of the Murzuk basin and the castellated Jabal Edinen (Devil's Mountain) north of Ghāt, where they reach a thickness of about 550 m. They thicken southward to In Ezzan about 200 km southeast of Ghāt and decrease in thickness northward to Serdeles (Fürst and Klitzsch, 1963).

TANEZZUFT SHALE

The Lower Silurian Tanezzuft Shale of Llandovery Age is a sequence of green and light- to dark-gray graptolitic shales having minor beds of fine-grained

FIGURE 21.—The massive crossbedded Lori Sandstone (Cambrian to Devonian). It unconformably overlies the Eghei Sandstone (Cambrian), and in places it weathers to a peculiar honeycombed structure in pinnacle-type forms. Exposure is about 15 m high. Photograph taken in Jabal Eghei.

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FIGURE 22.—East side of Wādī Tanezzuft on the west flank of the Murzuk basin in southwestern Libya, about 15 km west of Serdeles. Photograph shows the Tanezzuft Shale overlain by the cliff-forming Acacus Sandstone, both of Silurian age. The escarpment here rises to about 400 m above the valley floor.

sandstone and siltstone. Near Ghāt, the shale is underlain by a white fine- to medium-grained sandstone. Farther west, the shales overlie a coarse-grained tan-brown conglomeratic sandstone of Cambrian and Ordovician age. Desio (1936a) found *Monograptus* in green marls overlying the Tanezzuft, which would probably place the base of the Tanezzuft Shale in the Gothlandian.

Fürst and Klitzsch (1963) stated that in northern Dor el Goussa, in central Libya, the Tanezzuft Shale probably lies conformably on the Memouniat Formation (Ordovician); and in southern Dor el Goussa, it overlies continental sandstones which are probably of Cambrian age. In the southeast part of the Murzuk basin, the Tanezzuft also lies on the Cambrian and Ordovician rocks, whereas on the southwest flank it is transgressive on Upper Cambrian rocks, and south of Ghāt it overlies Lower Ordovician strata. Massa and Collomb (1960) noted that the Tanezzuft overlies the Memouniat (Upper Ordovician) west of the Gargaf arch in the Awenat Wennin area. Other exposures of the Tanezzuft Shale are found at the base of a small hill about 10 km north of Edri (pl. 4*A*), west of the Gargaf arch, and in the Wādī Kenīr area (not shown in pl. 2), southeast of the Gargaf arch, but the contact with the older rocks has not been observed.

ACACUS SANDSTONE

The Acacus Sandstone of Late Silurian (Ludlow) age, sometimes referred to as Harlania Sandstone after Kilian (1931), forms the upper part of the Acacus Mountains in southwest Libya. It is a light-brown fine- to medium-grained massive crossbedded sandstone with minor beds of light-gray and green shales. The Upper Silurian rocks in the vicinity of Wāw al Kabīr west of the Jabal Al Harūj al Aswad consist chiefly of sandstone with minor siltstone interbeds. Fürst and Klitzsch (1963) noted that the Acacus Sandstone is about 200 m thick near Ghāt and attains a maximum thickness of about 270 m south of Ghāt; it pinches out northward toward Serdeles. They reported that the formation has a maximum thickness of 485 m in northern Dor el Goussa in the east flank of the Murzuk basin but that it pinches out a short distance to the south, and the Devonian Tadrart Sandstone overlies the Tanezzuft Shale of Early Silurian age.

DEVONIAN SYSTEM

Rocks of Devonian age are exposed on the north flank of the Gargaf arch at Awenat Wennin, on the south flank in the Shati Valley, on the western flank of the Murzuk basin in the eastern slopes of the Acacus Mountains and the Tadrart, along the entire eastern flank of the Murzuk basin, in the eastern parts of Jabal Eghei, in the hills of Jabal Dalma north of Cufra, and near the Egyptian border of southern Cyrenaica.

In the region of Awenat Wennin, Lower Devonian rocks seem to be discordant on Cambrian and Ordovician rocks. They are fine- to medium-grained subrounded poorly sorted crossbedded ferruginous sandstone. The Upper Devonian rocks are interbedded sandy clays and siltstone and yellow-brown fine- to medium-grained locally crossbedded sandstone. In the Shati Valley area the Upper Devonian rocks are faulted against Cambrian and Ordovician rocks without any apparent horizontal displacement, although several hundred meters of vertical displacement is suspected. Northwest of Guira the Upper Devonian rocks are in fault contact with the overlying Carboniferous rocks but elsewhere appear to be conformably overlain by Carboniferous beds. Here in the Shati Valley area, the Upper Devonian strata consist of about 120 m of gray, tan, and brown fine- to medium-grained well-rounded and well-sorted crossbedded sandstone interbedded with varicolored claystone and siltstone. Several intraformational conglomerates occur within the unit. Desert varnish on the outcrops gives a brownish-black appearance. In some areas south of the Gargaf, these rocks are unconformably overlain by continental limestone of Tertiary age.

In the Shati Valley area the lower beds of the Upper Devonian sequence are largely coarse-grained cross-

bedded conglomeratic beds interbedded with thin beds of quartzitic sandstone. Several worm tracks and fossil impressions associated with a light-gray fine-grained sandstone were observed in the upper part of the unit. Near the top of the unit (pl. 4*B*, *C*, *D*) in many areas is a thin bed of brownish-black fine-grained petroliferous sandstone. These beds may be correlated with the Awenat Wennin Formation of Middle and Late Devonian age.

The Devonian rocks along the east flanks of the Murzuk basin in the Wāw al Kabīr area are gray medium-grained, sugary sandstone consisting of well-sorted and well-rounded grains; they contain some unidentified black particles which may be asphalt. The contact of these rocks with the underlying Cambrian and Ordovician rocks is a northeast-trending fault with vertical dip. The upper part of the Devonian sequence consists of about 70 m of interbedded sandstone and siltstone containing fossil flora and crinoid stems and may be equivalent to the Awenat Wennin Formation, though the uppermost beds may be of Early Carboniferous age. The unit is separated from the younger Carboniferous beds by a vertical northeast-striking fault. Several northeast-striking fractures filled with highly ferruginous, hematitic, and quartzitic sandstones occur within the unit. In eastern Cyrenaica the Devonian rocks consist chiefly of sandstone containing *Spirophyton* (oil-company geologists, oral commun.). They are of Givetian to Famennian (Middle to Late Devonian) Age.

The Devonian rocks in Libya are divided into the Tadrart, Wan Kasa, and Awenat Wennin Formations.

TADRART SANDSTONE

The Tadrart Sandstone of Early Devonian (Siegenian?) age is named for the Tadrart hills[3] on the eastern parts of Jabal Acacus on the western flanks of the Murzuk basin in southwestern Libya. It is generally a dark massive crossbedded sandstone interbedded with minor ferruginous sandstone beds. It overlies the Acacus Sandstone and reaches a maximum thickness of about 350 m in Jabal Tadrart and wedges out to the north; and in the vicinity of Awenat Wennin, on the north western flank of the basin, only about 30 m is present overlying the Lower Silurian Tanezzuft Shale (Burollet, 1963).

On the eastern flanks of the Murzuk basin in northern Dor el Goussa area, Fürst and Klitzsch (1963) reported a unit equivalent to the Tadrart Sandstone with a maximum thickness of about 375 m. They further noted that, although the base of the Tadrart is predominantly continental, the upper part of the formation on the east and west flank of the basin shows marine characteristics.

WAN KASA FORMATION

The Wan Kasa Formation of Early and Middle Devonian age overlies the Tadrart Sandstone in Wādī Wan Kasa east of Ghāt on the eastern slopes of the Acacus Mountain range, and it is generally identified on the peripheries of the Murzuk basin. It consists of interbedded sandy clay, shale, and fine-grained sandstone with minor calcareous beds. Klitzsch (1963) reported a unit equivalent to the Wan Kasa Formation 70 to 120 m thick in northern Dor el Goussa area. He suggested, however, that part of this unit may belong to the overlying Awenat Wennin Formation.

AWENAT WENNIN FORMATION

The Middle and Upper Devonian Awenat Wennin Formation is best exposed in the type locality of Awenat Wennin in the northwestern part of the Murzuk basin where it attains a maximum thickness of about 300 m. It consists of interbedded varicolored silty shale, siltstone, and fine-grained sandstone (pl. 4 *E*, *F*). Overlying the Awenat Wennin are oolitic hematitic beds of Tournaisian Age (Early Carboniferous), which in turn are overlain unconformably by beds of Late Cretaceous age. A sedimentary unit of probable Paleocene age caps the sequence in this area.

On the eastern flank of the Murzuk basin, Klitzsch (1963) reported a unit 140 to 310 m thick, equivalent to the Awenat Wennin Formation, in the western flank of the Dor el Goussa.

CARBONIFEROUS SYSTEM

Carboniferous rocks are exposed east of Serdeles, in the Shati Valley area, at Awenat Wennin, and in the Wāw al Kabīr area along the eastern flanks of the Murzuk basin. They have been reported also on the eastern slopes of Jabal Eghei in the Tibesti area and in southern Cyrenaica at about 150 km north and east of the Cufra oasis (oil-company geologists, oral commun.).

The contact between Carboniferous and Devonian rocks is uncertainly known in the Shati Valley and other areas. Beds transitional from marine to shallow-water and continental deposition make it difficult to establish a definite contact. The few poorly preserved fossils that have been collected range in age from Late Devonian to Early Carboniferous.

The Lower Carboniferous rocks (Tournaisian) exposed in the Shati Valley consist of markedly lenticular shallow-water deposits typically composed of light-red and brown sandstone and greenish-gray and brown shales and limonitic claystone. The most conspicuous

[3] Tadrart is a badland type of topography on the eastern slopes of the Acacus Mountains.

unit of the series is a group of beds consisting of massive hematitic siltstone and oolitic to finely granular hematitic rock lying at or near the base. These hematitic beds are several meters thick, crop out continuously for about 100 km in the Shati Valley, and display marked facies changes. The beds, which are highly enriched in iron in the vicinity of Brach, become more lenticular eastward from a point about 50 km east of Brach. At Gotah (Quṭṭah), about 50 km west of Brach, they become more sandy, though exposures of oolitic ferruginous beds were found south of Wanzārik about 30 km west of Gotah. The total exposed section of Tournasian rocks in the Shati Valley is about 140 m. This may include some beds of Viséan Age.

The uppermost strata of the Lower Carboniferous rocks grades upward into continental beds of light-brown and gray sandstone interbedded with grayish-green shale (pl. 4*F*). An oolitic chamosite-limonite bed about 1 m thick is considered to mark the contact with the continental unit. The continental beds in turn grade upward into marine beds of Viséan Age. Dark organic shale beds at the base of the marine unit are overlain by variegated shale and interbedded gray and white sandstone (pl. 4*G*, *H*, *I*). The maximum measured thickness is about 80 m in the eastern part of the Shati Valley.

LOWER CARBONIFEROUS SERIES

The thickest section of Carboniferous rocks, exposed in the vicinity of Awenat Wennin in west-central Libya, consists of interbedded marl, shale, and sandstone. These rocks are divided into the Mrar (Murár) Formation, Dome of Collenia Beds, and the Assedjefar Formation.

MRAR FORMATION

The Mrar Formation (Lelubre, 1948) consists of interbedded siltstone, micaceous shale, and fine-grained micaceous sandstone of Tournaisian to Viséan (Early Carboniferous=Mississippian) Age. The thickness of the Mrar Formation is estimated to be 715 m (Burollet, 1963).

DOME OF COLLENIA BEDS

The Dome of Collenia Beds (Freulon, 1953), widespread in the Dimbābah area west of Awenat Wennin, consist of dolomitic marl and siltstone containing beds of Colleniaform limestones which form a rippled, domed, crusty surface. This unit is 50 m thick (Burollet, 1963) and is Viséan to Namurian in age.

ASSEDJEFAR FORMATION

The Assedjefar Formation (Lelubre, 1952) is a fine- to coarse-grained poorly consolidated crossbedded feldspathic sandstone having sandy and silty green shale interbeds. Minor beds of ferruginous sandstone are noted in the unit, and petrified wood is present locally. The upper part of the unit contains thin beds of dolomite and dolomitic limestone. It is estimated to be 200 m thick (Burollet, 1963). The Assedjefar Formation is considered to be of Viséan to Namurian Age.

UPPER CARBONIFEROUS SERIES

The Dimbabah Formation in the Awenat Wennin area (Lelubre, 1952) is considered to be of Namurian to Muscovian (Late Carboniferous=Pennsylvanian) Age. It is estimated to be about 100 m thick. At the base of the unit is a dolomitic marly limestone with minor green shale interbeds, overlain by a sandy dolomitic limestone. The top of the unit is richly fossiliferous and has yielded productids and gastropods.

The Jabal Ben Ghenema Limestone was first described by Desio (1936b, p. 337) as green and red marls having gypsum and ferruginous concretions. These marls were considered to belong to the middle Carboniferous. The same beds were found by Desio (1936b, p. 336) in western Fezzan to overlie the *Productus* (coral) limestone, which consists of white, yellow, and brown limestone, oolitic on top and richly fossiliferous, and they were considered to be of Early Carboniferous age (pl. 4*K*).

In the Wāw al Kabīr area 70 m of interbedded clays and calcareous sandstones containing crinoid stems and fossil flora underlies Upper Carboniferous limestone beds. Some of these beds are ferruginous and oolitic. The lower beds might belong to the Upper Devonian Series, but they are probably of Carboniferous age. They strike north-northeast, have variable dips as much as 20°, and are separated from the Devonian sandstone beds by a vertical northeast-striking fault (pl. 4*J*).

In Wādī Ubaraccat area (pl. 4*K*), southeast of Serdeles, oolitic beds overlie Devonian rocks, but they are not as highly ferruginous and oolitic as in the Shati Valley area (pl. 4*G*). Similar lithologic units overlying Devonian sandstones were found at Awenat Wennin escarpment.

Carboniferous rocks in southern Cyrenaica consist chiefly of continental sandstone and interbedded siltstone. In east-central Cyrenaica sandy beds containing *Lepidodendron* are considered to be of Tournaisian to Namurian Age (oil-company geologists, oral commun.).

MESOZOIC ROCKS

During the Mesozoic Era, several hundred meters of sediments was deposited in shallow and deep troughs along the Mediterranean shores. The thickest exposed Mesozoic section is in the Jabal Nefusa escarpment of

northwestern Libya. This escarpment exposes Triassic, Jurassic, and Lower and Upper Cretaceous rocks (pl. 4*L*, *M*, *N*, *O*, *P*).

A great diversity of sedimentary conditions prevailed in Libya and nearby areas during the Mesozoic Era. Marine conditions in the northern part produced widespread deposits of limestone, dolomite, and marl. In northwestern Libya, however, lagoonal or estuarine conditions locally caused the deposition of large amounts of gypsum and anhydrite. In the Sirte embayment, Upper Cretaceous rocks have been drilled at depth in some oil-test wells, but information regarding their lithology, distribution, and thickness is not generally available. In northern Cyrenaica, Upper Cretaceous rocks are exposed at several places and presumably underlie large parts of the area. A deep oil-test well about 25 km east of the Libyan border in Egypt at about lat 30°30′ N. was reported (Said, 1962, p. 292) to have penetrated about 1,100 m of Cretaceous strata, some 300 m of which is limestone and shale of Late Cretaceous age. Very probably similar rocks underlie the northern part of Cyrenaica.

During the Cenomanian to Turonian transgression, the seas extended south in western Libya to about lat 28°30′ N., where a thin layer of sediments was deposited on the Paleozoic rocks in a very shallow and flat basin. South of lat 28°30′ N. in Libya, lacustrine or marine strata of Mesozoic age have been identified in only one area northeast of Jabal Eghei, but continental beds are widespread, consisting chiefly of crossbedded sandstone and some conglomerate and clay. These beds have commonly been called "Nubian Sandstone," but in recent years attempts have been made to divide the sequence into two or more formations, restricting the term Nubian to the uppermost unit that is believed to be chiefly of Early Cretaceous age. Discussion of these continental beds follows that of the marine beds.

TRIASSIC SYSTEM

Triassic rocks representing a marine transgressive series are exposed at the base of the Tripolitanian escarpment in northwestern Libya extending from Nālūt to the vicinity of Ar Rummeyah, east-northeast of Garian. They include the Ras Hamia, Azizia, and Bu Sheba (Bu Sceba) Formations. The lower units of the Bir al Ghanam Group are also of Triassic age.

RAS HAMIA FORMATION

The Ras Hamia Formation of Early and Middle Triassic age, first described by Christie (1955) as the Butoniere after Brichant (1952, p. 4–6), is partly exposed in several domal structures in front of the Jabal escarpment. It is chiefly a dark-red fine-grained micaceous sandstone interbedded with varicolored silty clay and claystone. Its maximum exposed thickness is about 74 m at Ras el Hamia, though a considerably greater thickness has been found in drill holes (Petroleum Exploration Society of Libya, 1960, p. 44).

AZIZIA FORMATION

Overlying the Ras Hamia Formation is the Azizia Formation of Muschelkalk (Middle Triassic) Age. The base of the Azizia Formation is a red fine-grained sandstone with minor beds of limestone grading upward to dolomitic limestone. A complete section of the Azizia is not exposed anywhere; however, as a result of faulting and anticlinal folding, numerous exposures of the formation are present south and southwest of Azizia and along the Azizia-Yafran Highway. The formation is also exposed at the base of the Garian escarpment.

Southwest of Azizia the lower exposed units of the Azizia Formation are well-bedded limestone and dolomitic limestone with minor beds of shaly marl and shale. Overlying these beds is a dark-gray siliceous, cherty, dolomitic limestone. The top of the unit is a well-bedded yellow limestone with thin layers of shale and minor chert interbeds.

The Azizia Formation grades upward into a shale and sandy unit of the Bu Sheba Formation. The total thickness of the Azizia Formation is estimated at about 110 m (Christie, 1955, p. 4).

Measured section of Azizia Formation (Triassic) at km 54, Azizia-Yafran Highway

	Meters
Caliche-type alluvium	4.9
Limestone, yellowish-brown, marly	1.8
Limestone, light-gray to dark-gray, compact	3.1
Limestone, light-gray; thin shale partings	4.9
Limestone, light-gray to dark-gray, hard, massive	3.7
Marl, yellow, greenish-gray	.9
Limestone, light-gray, massive; some parts purple	3.1
Limestone, light-gray to dark-gray, compact, siliceous	3.7
Shale, yellow, marly, calcareous	1.2
Limestone, light-gray, massive, compact	3.1
Limestone, yellowish-green, marly and shaly	1.5
Limestone, yellow, light-gray	1.8
Limestone, light-gray, yellowish-brown; marl partings as much as 10 cm thick	1.5
Marl, limestone, yellowish-brown; some thin shale partings as much as 10 cm thick	1.5
Limestone, light-gray, siliceous	3.1
Base of exposed section.	
	39.8

Measure section of Azizia Formation (Triassic) at km 59, Azizia-Yafran Highway

	Meters
Surficial cover, caliche-type; alluvium	1.5
Caliche-type calcareous material	1.2
Limestone, gray, yellow, thin-bedded	1.5
Limestone, light-gray to dark-gray, massive, compact, siliceous	.5
Limestone, marly, and yellow thin-bedded shale	.3
Limestone, light-gray to dark-gray, massive, compact, siliceous	1.1
Limestone and marl, yellow, gray, thin-bedded	1.2
Limestone, light-gray to dark-gray, massive	2.3
Limestone, marl, and shale, yellow, gray, thin-bedded	1.2
Limestone, gray, massive	.9
Marl, limestone, shale, yellow	.5
Limestone, gray, massive	1.5
Base of exposed section.	
	13.7

BU SHEBA FORMATION

The Bu Sheba (Bu Sceba) Formation was first described by Christie (1955) as the Bu Sheba Group of Jurassic age, but it is now treated as a formation and is considered to be of Late Triassic age (Petroleum Exploration Society of Libya, 1960, p. 10; Burollet, 1963). It is chiefly reddish-brown to yellow crossbedded sandstone with minor pebbly conglomerate beds and changes laterally to the west into varicolored sandy clays interbedded with dolomite. The exposed thickness of the formation is about 165 m (Christie, 1955, p. 4), but the total thickness is not known. The Bu Sheba is overlain conformably by rocks of the Bir al Ghanam Group.

JURASSIC SYSTEM

Outcrops of Jurassic rocks are present at the base of the Tripolitanian escarpment from Tunisia to Yafran. Lower and Middle Jurassic rocks, constituting the Bir al Ghanam Group (shown on plate 2 as the Bir al Ghanam Gypsum and anhydrite of Late Triassic and Early Jurassic age), have been identified from the Garian area to near the Tunisian border. Upper Jurassic rocks crop out in the vicinity of Yafran and continue west to Nālūt near the Tunisian border. These, the Tījī Group (Burollet, 1963), are composed chiefly of sandstone, shale, and shaly limestone (pl. 4*Q*). Some of the continental post-Tassilian deposits in south Libya are also thought to be of Jurassic age. They are discussed on page 31.

BIR AL GHANAM GROUP

The Bir al Ghanam Group is divided into two laterally equivalent units, the Bu Ghaylan Limestone and an unnamed gypsum-anhydrite sequence (pl. 3). They are considered to be of Late Triassic and Early to Middle Jurassic age. The gypsum and anhydrite unit consists of a white and gray massive gypsum interbedded with oolitic dolomitic limestone, and minor clay interbeds. Probably lagoonal conditions prevailed which at times gave way to a shallow-water marine environment. In the Yafran area the gypsum and anhydrite unit exceeds 400 m in thickness, but to the east it grades laterally into the Bu Ghaylan Limestone. About 40 km east of Yafran, a thickness of only about 30 m of gypsum can be measured within the Bu Ghaylan Limestone, and in the next few kilometers gypsum pinches out completely. The oolitic beds are fairly persistent and can be traced from Bi'r al Ghanam (Bi'r El Ghnem) to Bū Ghaylān.

Gualtieri (1959) studied the Bir al Ghanam Group, and his lithologic description of a typical section at about km 95 on the Azizia-Yafran Highway is as follows:

Section of Bir al Ghanam Group, 0.75 km east of km 95, Azizia-Yafran Highway

	Meters
Slumped strata almost in place, estimated to be about 25 percent dolomitic limestone and 75 percent gypsum	25.00
Dolomitic limestone, gray, massive, and thin-bedded	.30
Alluvium-covered interval with sparse, small outcrops of gypsum	7.00
Dolomitic limestone, gray, massive, thin-bedded, ledge-forming	2.00
Alluvium-covered interval with sparse small outcrops of gypsum	5.10
Dolomitic limestone, gray, dense, ledge-forming	1.70
Alluvium-covered interval with sparse outcrops of white and gray gypsum containing sparse selenite crystals and sparse dolomitic limestone laminae	5.60
Gypsum, gray, argillaceous; interbedded with gray thin-bedded and laminar dolomitic limestone	1.10
Alluvium-covered interval with sparse outcrops of massive, white, and gray gypsum	7.60
Dolomitic limestone, gray, thin-bedded, oolitic	.50
Alluvium-covered interval with sparse outcrops of gypsum	5.50
Dolomitic limestone, gray, vuggy, thin-bedded; contains interbedded gypsum	1.50
Alluvium-covered interval with sparse outcrops of gray and white gypsum containing sparse to abundant selenite crystals	8.50
Dolomitic limestone, gray, thin-bedded	.50
Alluvium-covered interval with outcrops of gray and white gypsum	.35
Dolomitic limestone, gray, argillaceous, thin-bedded, platy	.15
Dolomitic limestone, gray, thin-bedded, platy	.30
Gypsum, white and gray; contains disseminated claystone films	2.55
Dolomitic limestone, gray, oolitic	.10
Gypsum, white and dark-gray; contains undulatory dolomitic limestone laminae	.75
Dolomitic limestone, gray, dense, thin-bedded, platy	.40
Gypsum, light and dark-gray; contains abundant claystone laminae and sparse selenite crystals in places	3.10
Dolomitic siltstone, light-gray, thin-bedded and laminar	1.10
Gypsum, white, massive; contains sparse selenite crystals	.15
Claystone, grayish-green; contains thin satin spar veins replacing claystone along fractures	.10

Section of Bir al Ghanam Group, 0.75 km east of km 95, Aziziа-Yafran Highway—Continued

	Meters
Gypsum, gray; contains sparse selenite crystal masses and claystone laminae	2.20
Claystone and siltstone, greenish-gray; gypsiferous at base, dolomitic at top	.55
Gypsum, white and gray; contains sparse thin claystone lenses	.35
Claystone, light-green; contains abundant satin spar veinlets	.70
Claystone, light-green and black	.60
Gypsum, white and gray; contains abundant selenite crystals; base of unit not visible	.20
Total	85.55

The Bu Ghaylan Limestone, first described by Christie (1955), overlies the Bu Sheba Formation and is probably of Late Triassic to Early and Middle Jurassic age. It is a white, gray to yellow well-bedded limestone and dolomitic limestone, about 60 m thick, exposed at Bū Ghaylān at the base of the Garian escarpment south of Tripoli. It thins out a few miles to the east and grades westward into the gypsum and anhydrite unit. Christie (1955, p. 16) suggested that earth movements occurred during the deposition of the Bu Ghaylan Limestone, as evinced by brecciation and recementation in the lower part of the unit. He further suggested (p. 17) that movements during deposition may account for the thinning of the beds to the east. Christie (1955, p. 17) stated that "the bentonitic clays that underlie the limestone series, and the rarer similar bands within it, suggest that volcanic action may have accompanied these earth movements."

TĪJĪ GROUP

The Tījī Group (not shown on geologic map, pl. 2) of Middle and Late Jurassic age was first described by Burollet (1963); it is a calcareous unit with interbedded shale and sandstone. It has been divided into the Tocbal Limestone, Giosc Shale, and Chameau Mort Sandstone, all of which are discordantly overlain by the Kikla (Chicla) Formation of Early Cretaceous age (pl. 4*Q*). The Tocbal Limestone is fine-grained locally dolomitic limestone having gypsum in the lower part and shale in the upper part. The Giosc Shale is varicolored shale irregularly interbedded with sandstone. It grades upward into the overlying Chameau Mort Sandstone, which is white and yellow and has ferruginous sandstone and varicolored shale interbeds.

CONTINENTAL ROCKS OF MESOZOIC AGE

A continental environment prevailed in Fezzan and southern Cyrenaica after the Carboniferous and continued until possibly the middle of the Cretaceous. This is evinced by the deposition of several hundred meters of chiefly continental sandstones and siltstones in broad basins. These continental rocks are found in the peripheries of the Murzuk basin and cover large areas in southern Cyrenaica. They are also present in northeast Africa from Algeria to the Red Sea and consist of a predominantly sandstone facies commonly referred to as the Nubian Sandstone, named for the Nubian Desert of Egypt.

Owing to the lack of identifiable fossils, no definite age can be given to these continental beds in Libya, but they are apparently in part correlative with the Karroo Formation (Permian and Triassic) in Southern Rhodesia and the Continental Intercalaire of the Sahara.

In this report an attempt is made to divide the continental rocks of the Fezzan and southern Cyrenaica into two rock-time units. (See pl. 2.) The older rocks, which generally overlie the Upper Carboniferous beds, are treated as Continental Post-Tassilian Group, which probably ranges in age from Permian to Early Cretaceous. The younger beds that locally contain ferns and petrified wood are termed the Nubian Sandstone and in Libya are generally considered to be of Early Cretaceous age. In general, this continental sequence can be described as several argillaceous and sandy units about 800 m thick.

CONTINENTAL POST-TASSILIAN GROUP

Beds probably belonging to the Continental Post-Tassilian sequence crop out in the lower part of the great Nubian escarpment around most of the Murzuk basin, from the vicinity of Ubari southwest and south to the Algerian border, thence through nearby parts of Algeria and the Republic of Niger; and back into Libya up the east side of Jabal Ben Ghenema. They are also exposed south of Wādī Kenīr at about lat 27°30′ N. and long 15° E. and along the Algerian border at about lat 28° N. In all the above locations they are overlain by the Nubian Sandstone.

Along the Algerian-Libyan border the Continental Post-Tassilian sequence, which may include some beds of Permian age, was divided by de Lapparent and Lelube (1948) into the Tiguentourine, Zarzaitine, and Taouratine Formations.

The Tiguentourine Formation consists of about 50 m of red and brown clay and shale that is locally dolomitic. The base of the unit is gypsiferous and unconformably overlies the Carboniferous beds.

The Zarzaitine Formation consists of about 60 m of red clay at the base overlain by a thick sequence of interbedded sandstone and clays. The top of the unit is a calcareous marl which grades upward into red and brown clay. The calcareous unit of the Zarzaitine For-

mation is considered by some to be of Muschelkalk Age (Petroleum Exploration Society of Libya, 1960, p. 14).

The Taouratine Formation is red and dark-red claystone at the base grading upward into thick coarse-grained sandstone. It unconformably overlies the Zarzaitine. On the basis of study of the animal remains in Algeria, de Lapparent (1958) considered the Zarzaitine Formation to be of probable Late Triassic age and the Taouratine Formation of probable Late Jurassic age.

In the Ubari-Serdeles region the Continental Post-Tassillian beds (unit 1, pl. 5*A*) consist of about 60 m of crossbedded sandstone in which some conglomeratic beds contain quartz pebbles as much as 2.5 cm in diameter. This grades downward into a yellow-brown calcareous claystone and red siltstone which unconformably overlie the Carboniferous beds that are fossiliferous and limonitic on top. Overlying unit 1 is a sequence of sandy and variegated shale and claystone (unit 2, pl. 5*A*). Near the base of unit 2 is a varicolored violet and gray claystone that contains inclusions and concretions of clay, some of which are ferruginous.

These beds grade upward into a sequence of interbedded siltstone and sandstone that is locally crossbedded and is considered to be the Nubian Sandstone of Early Cretaceous age. In this region no definite contact between the two units can be seen, although it appears that a slight unconformity may be present at the base of the massive sandstone (pl. 5*A*).

The present writer also considers the red beds of clay and siltstone at the base of the Ubari escarpment to be possibly Permian to Jurassic in age, whereas the upper units are considered to be of Early Cretaceous age.

A composite section from Murzuk to the east of Ubari is shown on plate 5*B*, and another composite section from Majdūl to Wāw al Kabīr is shown on plate 5*C*.

Between Gatrun and Wāw al Kabīr, in the southern parts of the Jabal Ben Ghenema, and between Majdūl and Wāw al Kabīr, in the eastern part of the Majdūl escarpment and on the west side of Dor el Goussa, the older continental beds (provisional unit "1") or the Continental Post-Tassilian beds are found unconformably overlying the Upper Carboniferous beds. In these areas they consist of pink and yellow sandstone marked at the base by about 20 m of highly crossbedded conglomeratic sandstone (fig. 23*A*) having well-rounded quartz cobbles as much as 10 cm in diameter. The beds strike about N. 50° E. and dip about 2° NW. The conglomerate unit marks the contact between Upper Carboniferous marine beds and the Continental Post-Tassilian sequence. This can be seen both in the southern part of Jabal Ben Ghenema and west of Wāw al Kabīr where the Upper Carboniferous rocks are exposed (pl. 5*C*). Another conglomerate bed (fig. 23*B*) several meters thick marks the base of the overlying Lower Cretaceous Nubian Sandstone.

A

B

FIGURE 23.—Continental Post-Tassilian Group and Nubian Sandstone in south-central Libya. *A*, The basal conglomerate of the Continental Post-Tassilian beds lying on rocks of Carboniferous age in eastern Fezzan about 35 km northwest of Wāw al Kabīr on the north side of the desert track. *B*, The Nubian Sandstone overlying the Continental Post-Tassilian beds, which are here lighter in color and markedly crossbedded, about 80 km northwest of Wāw al Kabīr near the desert track to Majdūl.

Unlike the Ubari-Serdeles region, a time break in the sequence appears to be present here at the base of the conglomerate bed. This break between the two units was observed east of the Majdūl (see composite section, (pl. 5*C*) and Jabal Ben Ghenema.

In Wadi Kenīr, about 90 to 100 km northeast of Sebha, the older continental beds consist of a series of varicolored fine- to medium-grained sandstone and interbedded silstone and clay. The base of the unit contains gypsum and gypsiferous clays (pl. 5*K*). These beds overlie the marine beds of Carboniferous (Viséan) age and are considered to be the older continental beds of Permian to Jurassic age. The beds are essentially flat lying but have a slight regional southeasterly dip; however, some local northwesterly dips indicate the presence of structural irregularities. The lithologic characteristics of these beds are similar to those of the Tiguentourine Formation described earlier (p. 31).

At most areas the uppermost beds of the outcrops of the continental sequence have a nearly black desert varnish; they are quartzitic conglomerate or quartzite having clear quartz pebbles cemented by a ferruginous and quartzitic cement. The present writer has given the name "duricrust," after Pettijohn [4] (1957, p. 355–356) to this upper bed which is generally not more than 2 m thick. Following peneplanation, the quartzitic beds were probably formed from a laterite by a process of percolation, the same as the duricrust in Australia and Saudi Arabia.

NUBIAN SANDSTONE

The upper part of the continental sequence of Early Cretaceous age, termed the Nubian Sandstone, is widespread in southern Libya and was studied at several locations in Fezzan and southern Cyrenaica. It is probably equivalent to the Kikla Formation in Tripolitania (p. 34). These continental beds are overlain by marine Upper Cretaceous beds in northwestern Fezzan, at Bir el Gaf (Bi'r al Qāf), and in Tripolitania along the Jabal Nefusa.

At Bir el Gaf, the northern limit of the exposures, these beds are transgressively overlain by the Paleocene and Upper Cretaceous marine beds. Here the Nubian consists chiefly of purple, brown, fine- to medium-grained quartzitic ferruginous sandstone and contains some conglomerate beds (pl. 5*D*). The base of the unit is a hard grayish-white siliceous sandstone.

South and southeast of Sebha the Nubian Sandstone consists chiefly of a sequence of yellowish-brown to red quartzitic sandstone with some conglomerate. It grades upward into a more loosely cemented crossbedded sandstone, which is conglomeratic along the crossbeds, and thin beds of quartzitic sandstone and quartzite (pl. 5*E*, *H*).

Southwest of Sebha on the road to Ubari, about 57 km west of Umm Al Abyāḍ (pl. 5*F*, *G*), is a sequence chiefly consisting of interbedded yellowish-brown fine-grained sandstone, claystone, and siltstone at the base grading upward into highly crossbedded sandstone on top. About 30 km farther east, the somewhat younger beds are chiefly crossbedded sandstones at the base locally containing petrified wood (figs. 24 and 25), and these grade upward into interbedded sandstone, conglomeratic sandstone, and thin beds of clay and claystone (see pl. 5*H*). The beds in the area generally strike about northeast and have a low southeasterly regional dip.

In the Majdūl area the section illustrated on plate 5*I* is considered to be Nubian Sandstone. The rocks consist essentially of interbedded sandstone and conglomeratic units having cement that is more calcareous than in other areas. The unit is capped, as in many other areas, by a desert-varnished hard massive conglomeratic and quartzitic sandstone that is generally white to gray where freshly broken. The beds generally strike northeast and dip less than 2° NW.

The Nubian Sandstone covers most of southern

FIGURE 24.—Petrified wood in the Nubian Sandstone about 50 km west of Umm Al Abyāḍ on the road to Ubari. Locally such petrified wood is abundant, trunks as much as 60 cm in diameter being common.

[4] "In the arid regions the soils are enriched in lime (pedocals). A *caliche* or duricrust (Woolnough, 1928) may be formed. A duricrust is a peculiar type of deposit which is formed on a peneplain that is marked by sharply defined alterations of saturation and desiccation. It is an armorlike deposit produced by upward capillary migration of ground waters during the arid period. From these ground waters are precipitated aluminous, ferruginous, siliceous or calcareous materials."

FIGURE 25.—Intricate crossbedding in the Nubian Sandstone (Lower Cretaceous) in the hill near Umm Al Abyāḍ southwest of Sebha.

Cyrenaica. A typical section of the rocks at Rebiana in the Rebiana Sand Sea is illustrated on plate 5*J*. In this area the rocks consist of white, gray, yellow, and brown fine- to medium-grained sandstones having minor sandy clay interbeds. The sandstone beds, some of which are crossbedded and contain conglomeratic layers, are generally loosely cemented with calcareous material. The base of the unit is marked by a varicolored claystone interbedded with thin layers of fine-grained sandstone. This unit is much thicker than shown on the section, and it is exposed in deep wadi cuts. The top of the unit is marked by a conglomerate having carbonate aggregates and sand pebbles well cemented with calcareous material. This calcareous conglomerate capping was not found elsewhere in Libya.

The much thinner Kikla Sandstone, exposed in the high Jabal escarpment of northern Tripolitania, is probably a northern tongue of the Nubian Sandstone. If correct, this correlation indicates that the Nubian environments almost reached the sea during a part of Early Cretaceous time.

CRETACEOUS SYSTEM

LOWER CRETACEOUS ROCKS

The only exposures of Lower Cretaceous rocks in northern Libya are in the Jabal escarpment of Tripolitania. They include the Cabao (Kabaw) and the Kikla (Chicla) Formations in Tripolitania.

CABAO FORMATION

The Cabao Formation, first described by Burollet (1963), extends from Nālūt to near Yafran. It consists chiefly of interbedded gray sandstone and green siltstone, and shale that is red toward the base, though in the Nālūt-Uazzan area the upper part of the unit is interbedded with limestone. It is discordantly overlain by the Kikla Formation and was considered by Burollet (1963) to be of Wealden Age.

KIKLA FORMATION

The Kikla Formation was first described by Christie (1955) and considered to be of Wealden Age. It is a red crossbedded sandstone about 70 m thick, consisting of pebbly conglomerate interbedded with varicolored shale and clay. The present writer believes that the Kikla is a northern tongue of the Lower Cretaceous continental sequence (the Nubian) in Fezzan and southern Cyrenaica. The Kikla Formation is exposed from the Tunisian border to about 30 km east of Garian. It unconformably overlies the Cabao Formation (Lower Cretaceous) and Jurassic and Triassic rocks. It was considered by Burollet (1963) to be part of the Cenomanian and Turonian cycle and to be of Albian, probably late Albian, Age. It is overlain by the Ain Tobi Limestone Member of the Nefusa Formation.

UPPER CRETACEOUS ROCKS

The Upper Cretaceous rocks in northwest Libya include the Nefusa, the Mizda, and the Zmam Formations of the al Hamra Group, which ranges in age from Cenomanian to Maestrichtian. They form the Hamāda al Ḥamrā' plateau and are exposed in the cliffs of the Tripolitanian Jabal from Tunisia to Tarhuna. They are also exposed in Wādī Soffegin area east of Beni Ulīd. Several small and scattered outcrops of Upper Cretaceous rocks are present in Cyrenaica in northeast Libya.

In northern Cyrenaica, Upper Cretaceous rocks are exposed in two small areas on the Jabal al Akhḍar uplift a few miles south of Barce and Slonta (Suluntah) where their total outcrop area is less than 300 sq km. They are also present at the base of the escarpments along the shore between Tocra and Tolemaide and just east of Ra's el Hilāl about 20 km east of Apollonia, and at the base of the upper escarpment about 15 km east of Barce. Some petroleum geologists (oral commun.) have questioned the presence of Cretaceous beds at the three escarpment localities, but others feel that the Cretaceous rocks are present; this second interpretation was accepted for the geologic map (pl. 2). The Upper Cretaceous rocks of Cyrenaica include the Jardas (Gerdes) al Abid and the Tocra Limestones.

The Jardas al Abid Limestone (Petroleum Exploration Society of Libya, 1960, p. 28) is a sequence of interbedded hard limestone, yellow and gray marl, and marly limestone having echinoids and lamellibranchs. Fossil evidence indicates a probable Turonian or Senonian Age. These rocks crop out in the two isolated areas south of Barce and Slonta.

The Tocra Limestone (Petroleum Exploration Society of Libya, 1960, p. 49–50) is light colored and has nodules of chert. Its fossils, chiefly lamellibranchs, have been interpreted as indicating Maestrichtian Age. Rocks that are probably of the same or similar age are present at all three of the escarpment localities.

NEFUSA FORMATION

In Tripolitania the Ain Tobi Limestone, Yafran (Jefren) Marl, and Garian Dolomite Members are assigned to the Nefusa Formation. Christie (1955) assigned them to the Cenomanian, but they are now considered to be Cenomanian to Turonian in age (Petroleum Exploration Society of Libya, 1960, p. 37).

The Ain Tobi Limestone Member of Cenomanian Age is massive well-bedded limestone and dolomitic limestone about 90 m thick. It is locally detrital and oolitic and, in the middle of the unit, is marked by a hard siliceous cherty limestone bed containing *Ichthyosarcolites* (Christie, 1955, p. 18). A few intraformational conglomerates are locally present in the unit.

The Yafran Marl Member, Cenomanian to Turonian in age, consists of greenish-gray interbedded shale, marl, and yellow argillaceous limestone. The marls are soft and somewhat gypsiferous from Yafran westward. In the vicinity of Nālūt the marls are interbedded with massive beds of gypsum, several meters thick, in the Nālūt escarpment. The thickness of the unit is estimated to be 80 m (Christie, 1955, p. 19). The contact with the Garian Dolomite Member is gradational and poorly defined.

The Garian Dolomite Member of Turonian Age is white massive locally siliceous dolomitic limestone containing chert nodules in some places. An average thickness of 70 m is estimated for the Garian Dolomite, though some of the lower units measured may belong to the Yafran Marl Member (fig. 26*A*, *B*).

MIZDA FORMATION

In this paper the Mizda Formation of the al Hamra Group includes the Tigrinna Marl, Mazuza Limestone, and Thala Members after Jordi and Lonfat (1963). It is considered to be from Turonian to Campanian in age (pl. 3 and p. 37).

The Tigrinna Marl is treated herein as the lowest member of the Mizda Formation. Christie (1955, p. 4) first described the Gasr Tigrinna Formation southwest of Garian as "Soft marls with lesser red and yellow limestone bands, white porous limestone, white limestone with chert interbeds" and assigned them to the Cenomanian and Turonian. The Tigrinna Marl Member consists of a sequence of interbedded dolomitic limestone, dolomite, and gypsiferous shale. South of Garian toward Mizda, the Tigrinna becomes more gypsiferous, having gypsum interbeds as much as 2 m thick. Overlying the Tigrinna is massive irregularly crossbedded limestone which may be equivalent to the

A

B

FIGURE 26.—Jabal Garian and Jabal Nefusa Mesozoic escarpments. *A*, Jabal Garian Mesozoic escarpment on Garian road, showing succession of the Nefusa Formation (Upper Cretaceous) and the Kikla (Lower Cretaceous) in the foreground. From bottom to top: Kikla Sandstone, Ain Tobi Limestone Member, and Yafran Marl Member. Village of Bū Ghaylān is on the lower right. *B*, Jabal Nefusa escarpment east of Giado. The Kikla and Cabao (Kabaw) Formations of the lower slopes are overlain by the Ain Tobi Limestone Member which is overlain by the Yafran Marl Member.

Mazuza Limestone Member. This strikingly crossbedded limestone is also present southeast of Beni Ulíd in Wādī Soffegin area and also northwest of Al Kussabat (fig. 27). Overlying this crossbedded limestone is a series of interbedded green and gray shales and gypsiferous dolomitic limestone capped by a chalky dolomite that contains chert. This unit forms the upper part of the Mizda Formation and is probably equivalent to the Thala Member of the Mizda Formation. (See pl. 3).

ZMAM FORMATION

The Zmam Formation, described by Jordi and Lonfat (1963), "represents the last sedimentary cycle of the Hamada Group. Within this unit lies the Cretaceous-Tertiary boundary. * * * In western part of the Hamada where no younger deposits have been laid down, the Zmam Formation outcrops over large areas; in the eastern part, this unit is overlain by the Surfa Formation, the first cycle of the Waddan Group."

Jordi and Lonfat (1963) divided the Zmam Formation into Lower Tar Marl, Upper Tar Marl, and Had Limestone Members. The Lower Tar Marl is a marl and shale sequence that is dark green at the base and red and fossiliferous on the top, grading upward into 12 m of yellow calcareous mudstone. Jordi and Lonfat (1963) reported that the exposed section of the Lower Tar Marl is about 80 m, but a thickness of 230 to 240 m has been drilled. The Upper Tar Marl was described by Jordi and Lonfat (1963) as marls and calcareous mudstone and shaly intercalations. The base of the unit is marked by a fossiliferous limestone called the "Socna Mollusc Bed." The total thickness of the unit is about 70 m. The Had Limestone consists of three thick beds of dolomite and dolomitic limestone that are separated by chalky marl and have a combined thickness of about 50 m.

FIGURE 27.—Crossbedded Upper Cretaceous limestone about 10 km northwest of Al Kussabat, Tripolitania. Photograph taken looking south. Courtesy of Harry F. Thomas.

The Gheriat Limestone (Petroleum Exploration Society of Libya, 1960, p. 21), which consists of light-gray detrital dolomitic limestone with some crossbedding, is transgressively overlain by the Shuwayrif Limestone of Paleocene age. The Gheriat Limestone is probably equivalent to the Had Limestone Member of the upper Zmam Formation described by Jordi and Lonfat (1963).

A series of white chalky limestone and soft yellow limestone and the interbedded clay and limestone near Bi'r Tala (Bi'r Talah) in the south flanks of Wādī Soffegin are also probably the lateral equivalent of the upper Zmam Formation (pl. 4*B*). They overlie a greenish-gray glauconitic limestone and white soft marls, which contain phosphatic nodules in Wādī Soffegin area and were considered by Lipparini (1940) to be of Maestrichtian Age. They are probably the same rocks that were described by Desio (1943) as the Dor Tala series.

TERTIARY ROCKS

CRETACEOUS-TERTIARY BOUNDARY

Rocks of Paleocene age were not recognized in Libya by the earlier investigators. In recent years, however, oil-company geologists have studied the Cretaceous-Tertiary contact in detail and have reported Paleocene and lower Eocene rocks in Tripolitania and in central and eastern Libya.

The larger commercial phosphate deposits have been discovered in the upper Cretaceous and lower Eocene sediments in several places in north Africa. Phosphate has also been reported in the Maestrichtian rocks in Beni Ulíd–Wādī Soffegin area of Tripolitania (Lipparini, 1940, p. 249), where it is associated with a glauconitic marly limestone and occurs in nodules in a white soft marl.

In a search for commercial phosphates in Libya, the present writer studied (1955–58) the areas where the Upper Cretaceous rocks are known to occur. Along the courses of Wādī Soffegin and Wādī Zamzam and near Gheriat, Sināwan, and Shuwayrif, a younger sequence was noted that consists of dark clay, marl, and limestone beds overlying the rocks of Maestrichtian Age, and was provisionally assigned to the Danian. In practically all the areas studied, the glauconitic limestone, which marks the phosphate level of Maestrichtian Age in the Wādī Soffegin area, is present and

is overlain by several hundred meters of younger sediments.

Jordi and Lonfat (1963) considered the Cretaceous-Tertiary boundary to be within the Zmam Formation. They noted that the Zmam Formation crops out over large areas in the western part of the Hamāda al Ḥamrā' but that in the eastern part the Zmam Formation is overlain by the Surfa Formation (Paleocene), the first cycle of the Waddan Group. They considered the Lower Tar Member to be of Maestrichtian Age (Late Cretaceous) and suggested that the Cretaceous-Tertiary contact lies within the Upper Tar Member of the Zmam Formation. The following section (table 1) is adapted after Jordi and Lonfat (1963).

Early Tertiary rocks of Paleocene age are now known to cover the greater part of the Hamāda al Ḥamrā' of northwestern Tripolitania, to crop out in small areas of east and central Libya, and to be present in the subsurface of the Sirte embayment. Eocene seas extended through central Libya far into the Sahara tableland to the Tibesti foothills, where a thin layer of sediments was deposited in a shallow basin on the Precambrian and Paleozoic rocks. During the Oligocene and Miocene Epochs, the seas were less extensive but in the Sirte embayment reached to about lat 28° N. and at times covered large parts of northern Cyrenaica.

TABLE 1.—*Stratigraphic division of Upper Cretaceous and lower Tertiary rocks in northwestern Libya*

[Modified from Jordi and Lonfat (1963). Dashed rules indicate gradational or covered contacts]

System	Group	Formation	Member
Tertiary	Jabal Waddan Group	Beshima Formation	Rouaga Chalk Member.
			Kheir Marl Member.
		Surfa Formation	"Operculina" Limestone Member (*Operculinoides*).
			Gelta Chalk Member.
			Bu Ras Marl Member.
Upper Cretaceous	Al Hamra (Hamada) Group	Zmam Formation	Had Limestone Member.
			Upper Tar Marl Member.
			Socna Mollusc Bed.
			Lower Tar Marl Member.
		Mizda Formation	Thala Member.
			Mazuza Limestone Member.
			Tigrinna Marl Member.
		Nefusa Formation	Garian Dolomite Member.
			Yafran Marl Member.
			Ain Tobi Limestone Member.

During the Tertiary Period, several thousand meters of sediments ranging in age from Paleocene to Pliocene was deposited in a deep basin at the present site of the Sirte area, the Sirte basin, which probably extended south and southeastward from the Gulf of Sirte into central Cyrenaica. From the Eocene to the Miocene, several hundred meters of sediments was also deposited in northern Cyrenaica. Other Tertiary strata ranging in age from Miocene to Pliocene also are exposed in the coastal areas west of the Gulf of Sirte as far as Homs and extend westward below the Gefara of northwestern Tripolitania. The known thickness of the Tertiary strata is on the order of some hundred of meters, but in the structurally disturbed northern part of the Sirte embayment these beds are several thousand meters thick.

The Tertiary rocks generally consist of marine sequences of limestone, dolomite, marl, shale, and relatively minor beds of calcareous sandstone. Fossils are present at many places and are abundant in some layers. Many of the strata grade southward into strata of lagoonal or continental origin. Several scattered occurrences of Tertiary continental rocks are in Libya, and they are discussed on page 41.

PALEOCENE ROCKS

Paleocene beds cover the greater part of the Hamāda al Ḥamrā' plateau from Wādī Zamzam to the vicinity of Sināwan at about long 11° E. and extend south to about lat 29° N. They are exposed along the Hun graben faults and farther south in a long narrow strip west of the Al Harūj al Aswad. Other Paleocene rocks have been identified near Jabal Dalma area near the Egyptian border between lat 26° and 27° N. (oil-company geologists, oral commun.) and are overlain by Tertiary continental rocks. South and east of Jabal Al Harūj al Aswad, some of the beds mapped as Eocene may include some rocks of Paleocene age.

The Paleocene rocks include the Bu Ras Marl, Gelta (Qaltah) Chalk and *Operculinoides* Limestone Members of the Surfa Formation, and the Kheir Marl Member, the lower member of the Beshima Formation (Jordi and Lonfat, 1963), all of which belong to the Jabal Waddan Group. The thickness of the Paleocene is estimated as about 350 m.

Bu Ras Marl Member is a cream-colored chalky limestone interbedded with marl and calcareous shale. The Gelta Chalk Member is a white soft friable chalky limestone and marl. The *Operculinoides* Limestone Member is a yellow, gray partially dolomitic limestone having beds of *Operculinoides* and *Lockhartia*. The Kheir Marl Member of the Beshima Formation is a greenish-yellow gypsiferous marl. In the area south of Shuwayrif, southeast of Mizda, the Gheriat Limestone (Maestrichtian to Paleocene), the probable equivalent of the Had Limestone Member of the Zmam Formation, is transgressively overlain by a soft gypsiferous chalky dolomitic limestone, the Shuwayrif Limestone, which is probably equivalent to the Gelta Chalk Member, the middle member of the Surfa Formation.

EOCENE ROCKS

In Tripolitania, Eocene rocks crop out in the Sirte area and extend to the south in Fezzan near the Tibesti foothills, where they overlie Precambrian igneous and metamorphic rocks. In northern Tripolitania they include the upper units of the Jabal Waddan Group (Ypresian) and the Wādī Thamit Group of Lutetian and Priabonian Age. No Eocene rocks crop out west of long 14°45′ E.

JABAL WADDAN GROUP

The lower Eocene part of the Jabal Waddan Group includes the Kheir Marl, *Flosculina* Limestone, and Rouaga Chalk Members of the Beshima Formation (Jordi and Lonfat, 1963), the Bin Isa Chalk, *Orbitolites* Limestone, and the Bir Ziden Limestone. These upper units of the Jabal Waddan Group are interbedded white, yellow, chalky, locally cherty and dolomitic limestone and yellowish-green gypsiferous marl. South of Jabal Waddān, toward Al Fogha and Wāw al Kabīr, they are near-shore or continental facies and become more shaly, marly, sandy, and gypsiferous (pl. 5 *L*, *M*, *N*).

Some of the near-shore or continental beds in south-central Libya are probably of late Eocene, or Priabonian Age. The Eocene deposits in southern Libya are marine, near-shore, and continental beds which cannot be identified with certainty. They are probably of early to late Eocene age, though some may be of Paleocene age.

Eocene rocks of marine origin in Cyrenaica crop out along a narrow belt extending from Al Abyār to Derna on the northern flank of Jabal al Akhḍar, where they attain a thickness of about 200 m. They also occur in two upland areas, south of Barce and Slonta.

At the base of the Jabal al Akhḍar escarpment, the Eocene beds overlie Cretaceous rocks without apparent discordance. Marchetti (1934, p. 310) noted that the contact between Cretaceous and Eocene rocks is distinct at Wādī Bakur (Bacur), at Tolemaide, and between Ra's el Hilāl and Wādī al Athrun (Atrun), where flint-bearing Eocene limestone conformably overlies marly fossiliferous limestone of Cretaceous age.

The Eocene strata of Cyrenaica first described and named by Gregory (1911) include the Cirene (Cyrenaica) Group consisting of the Apollonia, Derna, and Slonta Formations (Petroleum Exploration Society of Libya, 1960, p. 22, 47).

The lowest member of the Beshima Formation, the Kheir Marl, is a greenish-yellow gypsiferous marl of Paleocene age. The *Flosculina* Limestone Member is a white and yellow chalk having minor beds of black cherty limestone; the Rouaga Chalk Member is a white chalky limestone that weathers to reddish brown and grades upward into a cherty limestone on top. The Bin Isa Chalk is a white friable chalky, gypsiferous marl, which contains black chert nodules and is capped by the yellow and white *Orbitolites* Limestone. In the southern part of Jabal Waddān, the Bin Isa Chalk and *Orbitolites* Limestone become more gypsiferous and are called Jir (Gir) Gypsum. The Bir Ziden (Desio, 1943, p. 75) consists of a sequence of white limestone and calcareous algae of Ypresian Age. It is considered to be the upper unit of the Jabal Waddan Group.

WĀDĪ THAMIT GROUP

Middle Eocene rocks consist chiefly of yellowish-green marl, shaly calcareous sandstone, and coquinoidal dolomitic limestone which is argillaceous or chalky in many places and locally contains chert nodules. The lower units of the Wādī Thamit Group, the Al Gata and Tmed al Ksour Chalks, which overlie the *Orbitolites* Limestone, are mostly of Lutetian Age and belong to the middle Eocene.

The Al Gata Chalk is yellowish-green marl interbedded with yellow soft dolomitic, argillaceous, and coquinoidal limestone. It overlies the *Orbitolites* Limestone and is of early Lutetian Age. The Tmed al Ksour Chalk is white massive compact fossiliferous chalk which is slightly shaly and has beds of brown flint or chert.

The upper unit of the Wādī Thamit Group, the Qararat al Jifah Marl, is probably upper Eocene and is of Lutetian and Priabonian Age. It consists of interbedded greenish-gray marl, sandy shale, and fossiliferous limestone. It is overlain by the Dur al Abd Formation of upper Eocene to Oligocene age. A composite section of the middle and upper Eocene rocks in Wādī Thāmit is shown on plate 5*O*.

APOLLONIA FORMATION

The Apollonia Formation was named by Gregory (1911, p. 593, 598) and placed in the lower Eocene. Stefanini (1921) supported Gregory on the evidence of *Nummulites globulus*, *Plecanium niloticum*, and *Nummulites subdiscorbina* and placed the Apollonia in the Ypresian. However, because fossils of definite Lutetian Age have reportedly been found in the lower members of the formation, it is now considered to be of middle Eocene age (Petroleum Explor. Soc. Libya, oral commun.).

The Apollonia Formation crops out along the lower escarpment at Cirene and Apollonia and consists of a massive siliceous limestone having chert nodules. It has a marked stepped appearance and looks chalky at the base. It extends continuously between Derna and Bersis, about 10 km south of Tocra, and forms the base of the first escarpment. Here at Tocra it is a massive compact siliceous limestone having shell-rich beds; the top of the unit is a flint-bearing breccia.

DERNA FORMATION

The Derna Formation (Lutetian) was described by Gregory (1911, p. 579) as the Derna Limestone. It extends from Wādī el Hassien, east of Derna, west to the vicinity of Benina (Banīnah) near Bengasi. Near Derna it forms the lower part of the escarpment; farther west it forms the first terrace of the escarpment; and near Barce it extends into the base of the second escarpment. Gregory (1911, p. 598) assigned the Derna Limestone to the middle Eocene and reported a thickness of about 115 m (380 ft) for the formation.

The Derna Formation consists of a basal bed of hard siliceous, semicrystalline limestone, a middle unit of soft white to creamy limestone that has yielded *Nummulites gizehensis* together with algae and echinoids, and an upper unit of white to soft creamy somewhat porous coralline limestone. These beds are exposed by Wādī Al Cuf and other wadis forming deep indentations into the Jabal.

SLONTA FORMATION

The Slonta Formation is a part of what Gregory (1911, p. 582) called the Slonta Limestone. It is beige-white porous marly and chalky limestone overlying the coralline limestone of the Derna Formation. It is south of Slonta and on top of the middle Eocene near Derna. The Slonta Formation or Limestone is of upper Eocene, probably of Priabonian Age.

OLIGOCENE ROCKS

Rocks of the Oligocene Series in Libya crop out in Cyrenaica and in the Sirte basin and include Dur al Abd and Grier Bu Hascisc Formations. Though not very thick, the Oligocene rocks cover a large part of the Jabal al Akhḍar in Cyrenaica and the escarpment west of Marada.

The Oligocene deposits were laid down in shallow seas (shallower than the Eocene) and partly under lagoonal environments. The lower part of the Oligocene rocks is lithologically similar to the upper Eocene rocks and is a shallow-water marine facies consisting of gray and yellow limestone and sandy marl. The top of the unit, in most places, is calcareous sandy and gypsiferous marl characteristic of lagoonal and estuarine conditions. The total thickness of the Oligocene rocks is estimated to be about 150 m.

In the Sirte embayment the Oligocene Series has been divided into Dur al Abd and the overlying Grier Bu Hascisc Formations, both of which were first described by Magnier and Duval (in Petroleum Exploration Society of Libya, 1960, p. 18, 29). The Dur al Abd Formation is a white, gray, and yellow dolomitic limestone with thin beds of fossiliferous limestone. The middle of the unit is intercalated beds of light-green clay and gypsum. The formation is considered to be Oligocene or upper Eocene in age. The Greir Bu Hascisc Formation consists mainly of green shale interbedded with minor beds of fossiliferous limestone. The upper part of the unit is white soft coquinoid dolomitic limestone.

West of Marada the Oligocene is a littoral lagoonal facies consisting of calcareous, sandy, marly, and gypsiferous rocks. South of Marada, some of the near-shore and continental beds northeast of Jabal Al Harūj al Aswad and southwest of Jabal Zaltan (Zelten) consisting of limestone and calcareous sandstone are thought to be of Oligocene age (oil-company geologists, oral commun.)

In Cyrenaica, Oligocene rocks partly cover the Eocene rocks of Jabal al Akhḍar, extending south from the high areas along the escarpment, and consist of a white soft sandy limestone at the base overlain by a coralline limestone. At Cirene they crop out in a narrow belt along the upper escarpment. West of Cirene, near Oberdan, the northern boundary swings southwest and extends along the top of the escarpment almost to Barce. About 10 km east of Cirene the boundary swings south, and a progressively wider outcrop of Oligocene rocks forms the surface of the highest part of Jabal al Akhḍar from Slonta through Marāwah (Marawha) and Taknis. At Cirene the Oligocene is gray, yellow calcareous marl at the base grading upward into a soft sandy, marly limestone, from which flow the springs at the Cirene ruins. It rests on the Eocene rocks with indication of a break in sedimentation in some places. Locally in the south near Jardas al 'Abīd (Gerdes el Abíd), it appears to be

transgressive onto the Cretaceous rocks, but some Eocene rocks have been identified there.

MIOCENE ROCKS

Miocene rocks in Libya cover a wide belt extending east from the Homs-Zliten area across the Sirte and northern Cyrenaica to the Egyptian border. West of Homs they crop out only in the Gharabulli area and are covered by Quaternary deposits elsewhere. Most of these rocks belong to the Aquitanian, Burdigalian, Helvetian, and Tortonian Stages of early and middle Miocene age. The total thickness of the Miocene is estimated to be about 700 m.

Lower and middle Miocene rocks cover the greater part of northern Cyrenaica. Practically the entire south slope of the Jabal al Akhḍar almost as far south as the Calanscio Sand Sea consists of rocks of middle Miocene age. The rocks are white, yellow, and gray sandy marl and limestone that in places is granular or locally crystalline. Several nonmarine, near-shore, or continental beds consisting of calcareous marl and sandy calcareous beds along the eastern edges of the flows of Jabal Al Harūj al Aswad and Jabal Zaltan are probably lower and middle Miocene in age. These beds cannot be identified with certainty, though some are thought to be continental equivalents of the marine Fortino Formation (oil-company geologists, oral commun.) of Tripolitania.

LOWER MIOCENE ROCKS

The lower Miocene rocks in the Sirte area of Tripolitania are richly fossiliferous gray limestone, marl, and shale that in places grade downward and laterally into a basal coarse sandy fossiliferous limestone of the Fortino Formation, which is mainly of Aquitanian Age (Petroleum Exploration Society of Libya, 1960, p. 35).

Beds of early Miocene age (Aquitanian-Burdigalian) include the Cirene Limestone and the Beddahach Formation in Cyrenaica. The Cirene Limestone,[5] a soft white and gray limestone, which extends eastward almost to Derna, is Aquitanian in age and probably equivalent to the lower units of the Beddahach Formation.

The Beddahach Formation forms the upper parts of the banks of Wādī Derna and is probably of Aquitanian Age. It is a white fossiliferous detrital limestone that is generally chalky and marly in the upper part and more massive and dolomitic in the lower part. The upper part of the unit is considered to be of Burdigalian Age (Petroleum Exploration Society of Libya, 1960, p. 36).

[5] The use of this name given by Gregory (1911) has been discontinued (Petroleum Exploration Society of Libya, 1960, p. 15).

MIDDLE MIOCENE ROCKS

Middle Miocene rocks crop out along the coast near Homs and extend eastward to Cyrenaica as the Marada Group. West of Homs they are only exposed in the vicinity of Gharabulli but extend under the plains of the Gefara to the Tunisian border. The middle Miocene rocks are represented by a sequence of yellow compact marly and argillaceous limestone in the lower part, grading upward into a succession of white, gray, yellow marl interbedded with minor beds of fine-grained sandstone. The upper part of the unit is a yellow, white sandy limestone grading upward into a white compact siliceous limestone having chert nodules (pl. 5*P*). The green clay and shale found at depth in the water well in the Tripolitanian Gefara are probably of early to middle Miocene age.

The Marada Group, forming the northern cliffs of the Marada depression, displays the stratigraphic series of middle Miocene rocks: greenish-gray shale and clay, sandy clay, marl, gypsum, and yellow sandy limestone.

The middle Miocene rocks in Cyrenaica include the Porto Bardia, Maalegh, and Giarabub Formations and the Benghasi Limestone.

The Porto Bardia Formation (Porto Bardia Series of Desio, 1928, p. 85), which is probably equivalent to the Benghasi Limestone, is a marine sandy fossiliferous limestone intercalated with argillaceous and gypsiferous current-bedded sandstone. It forms the high cliffs near Port Bardia near the Egyptian border and is early Helvetian or Burdigalian in age (Petroleum Exploration Society of Libya, 1960, p. 40). The Benghasi Limestone is a massive white sandy fossiliferous limestone that crops out in the cliffs southeast of Bengasi. Desio (1935) considered that the sandy limestone and the calcareous sandstone which form the coastal plain of Bengasi were deposited in a transitional period between early and middle Miocene times.

The Maalegh Formation, first described by Desio (1935), in Wādī Maalegh overlies the Burdigalian Beddahach Formation. It crops out west of the Gulf of Bomba and consists of a fine- to medium-grained detrital limestone.

The Giarabub Formation (used only locally), described by Desio (1935, p. 94) as Giarabub Series, forms the banks of Wādī Giarabub and consists of interbedded light-yellow limestone and green gypsiferous shale. The base of the unit is Langhian in age, overlain by beds of Helvetian Age.

UPPER MIOCENE ROCKS

The upper Miocene rocks in Cyrenaica are exposed south of El Agheila and also crop out almost continuously from about long 20° E. eastward to near

Giarabub along lat 30° N. They consist chiefly of marl, limestone, gypsiferous shale, clay, calcareous sand, and conglomerates of marine and continental origin; maximum thickness is about 80 m. They include the limestone with *Alveolina bradyi*, the Fuehat[6] and Regima Limestones,[6] and the lower part of the Sahabi Group.

The limestone containing *Alveolina bradyi* is a massive white compact semicrystalline limestone. The Fuehat Limestone is a sandy white limestone capped by a hard greenish-gray limestone. The Regima Limestone is white soft fossiliferous limestone which contains a bed of white granular crystalline gypsum several meters thick.

The base of the Sahabi Group, in the Sirte area of Cyrenaica, is a regressive lagoonal series of gypsiferous shale interbedded with thinly bedded, hard white fossiliferous limestone that has yielded upper Miocene (Tortonian) fossils. These marine beds are overlain by Pliocene continental beds containing amphibious terrestrial vertebrates.

PLIOCENE DEPOSITS

The continental environment that was established in late Tertiary (Pliocene) time continued through most of the Quaternary period. Lack of fossils makes it almost impossible to distinguish between the Quaternary and the continental Pliocene deposits. Only a few scattered beds in restricted areas have been reported to be of Pliocene age; these are of continental or shallow-marine origin. In Tripolitania Pliocene beds—largely continental sandstones, eolian sands cemented to sandstone, and well-cemented river conglomerate in alluvial fans and terraces—were first reported by Lipparini (1940, p. 229).

In the Homs-Zlīten area, Lipparini found and identified Pliocene beds resting on marine Miocene rocks and covered by Pleistocene deposits. They are reported to crop out between Homs and Zlīten, extend east toward Miṣurata, and connect with the conglomerate fans of Wādī Soffegin to form the southwest bank of the Tauorga sebcha down to Buerat. They also extend south from between Zlīten and Miṣurata to Bi'r Dufan (Bi'r Dhu'fān) area where, as sand and gypsum deposits, they overlie the Upper Cretaceous beds. These Pliocene deposits continue farther into the Wādī Soffegin area and, as thick conglomerates, cover the Upper Cretaceous rock terraces from Shumaykh to Tauorga (Tāwurghā), not shown on (pl. 2).

Near Wādī Umm El Lebd the Pliocene conglomerates consist chiefly of limestone pebbles and cobbles embedded in a detrital limestone matrix, though quartzitic and chert pebbles and cobbles and thin lenticular sandstone beds are present. On the west side of Wādī Maymūn, these conglomerate beds are composed of limestone, quartz, and claystone fragments in a calcareous matrix. Between Wādī Maymūn and Wādī Gobbin, these calcareous conglomerates contain limestone boulders as much as 20 cm in diameter.

Pliocene deposits in Cyrenaica are restricted to areas southeast of Bengasi, near Sahabi, southwest of Agedabia, and south of El Agheila (Desio, 1935, p. 95). The Sahabi Group is chiefly upper Miocene rocks overlain by Pliocene continental deposits. They consist of gypsiferous green shales interbedded with thinly bedded hard white fossiliferous limestone. Sand and gravel deposits in the erosional cavities have yielded a rich fauna of amphibious vertebrates. Petrocchi (1943, p. 162) believed that these continental vertebrates are of Pliocene age.

In the other locality at Sebcha Mugtaa el Giofer (Sabkhat Maqta' al Jufar) south of El Agheila, Desio (1935, p. 95) identified Pliocene marine beds at the base of the escarpment in a light-green soft calcareous sandstone.

In Fezzan several continental deposits are Miocene to Quaternary in age; some might be of Pliocene age.

TERTIARY CONTINENTAL ROCKS

Scattered continental calcareous sandstone, gypsum, calcarenite, marl, and limestone crop out in the areas of the Hun graben (pl. 5*Q*) in Jabal Dalma area near the Egyptian border and along the eastern edges of the Al Harūj al Aswad volcanic flows. On the basis of stratigraphic positions, some of the beds east of the Al Harūj al Aswad have been placed in the middle and lower Miocene and Oligocene Series by oil-company geologists (oral commun.).

Continental beds along the Egyptian border are reported to overlie beds of Paleocene age (oil-company geologists, oral commun.) and therefore are of post-Paleocene age (or probably of Oligocene age).

In Fezzan, continental limestones unconformably overlie the Paleozoic rocks and the Lower Cretaceous Nubian Sandstone in the Shati Valley area and the Murzuk basin. These are light-gray, yellow locally sandy limestones, which in places contain nodules of chert and flint. In many areas they are underlain by a calcareous basal conglomerate as much as 2 m thick which contains large quartz pebbles and a few basalt fragments.

Presence of the basalt fragments in this basal conglomerate indicates that the deposition occurred after the onset of the Tertiary volcanic period. Since the

[6] The use of these names, given by Desio (1935), has been discontinued (Petroleum Exploration Society of Libya, 1960, p. 24, 44).

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plagioclase basalt. In the Beni Ulīd area the extrusive rocks are plagioclase-olivine basalt with augite, ilmenite, magnetite, and apatite as accessory minerals. In the Mizda area the rocks consist of plagioclase basalt and augite andesite. Lipparini (1940, p. 221–301) reported trachytic phonolite and alkaline trachyte between Garian and Mizda.

SOUTH-CENTRAL LIBYA

In south-central Libya (in Jabal Eghei and the Tibesti), volcanic rocks occupy an area of about 8,000 sq km. They generally overlie lower Eocene rocks (fig. 28*A*) in Jabal Eghei, but in small scattered areas in the Tibesti region, they overlie Precambrian or lower Paleozoic rocks. Farther south, these extrusive rocks cover vast areas in the northern part of the Republic of Chad. They consist of plagioclase-olivine basalt and nepheline basalt. The accessory minerals are augite, magnetite, iddingsite, and natrolite. Other associated accessory minerals are carbonate and minor inclusions of apatite (fig. 28*B*). In the western Tibesti region, the present writer noted dark-green dikes of gabbro intruding Precambrian rocks, and Dalloni (1948) reported numerous similar dikes of gabbro farther south in the Republic of Chad, some very thick.

QUATERNARY DEPOSITS

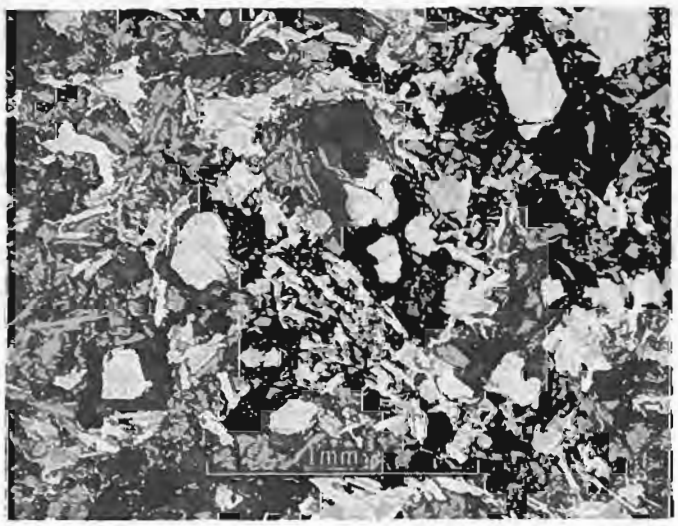
The Pleistocene and Holocene deposits in Libya cover an estimated area of about 400,000 sq km; they form the Libyan desert, the dune areas, the immense gravel plains, and the Mediterranean coastal plains. They consist of clayey eolian sand; locally cemented, calcareous, and commonly dolomitic sandy or brecciated surface incrustations; caliche; red earth (terra rosa); eolian sand; alluvium; sand and associated fine sediments; saline deposits in the undrained depressions (sebchas); and the poorly consolidated surficial deposits of local origin composed of gravel with some silt and sand that make up the sarīr or the desert pavement.

TRIPOLITANIA

The Pleistocene deposits of Tripolitania consist of a clayey sand locally cemented to sandstone, and they occupy two basins separated by hills of Miocene rocks in the Homs-Zliten area. These deposits have an estimated thickness of about 50 m and mostly overlie the Miocene marly clays in the coastal area; farther south they overlie the Mesozoic formations. They decrease in thickness eastward from Pisida along the Tunisian border to the Homs-Zliten area, where rocks of Miocene age crop out. From Zliten they thicken to the east toward Misurata and the Tauorga sebcha, a depression that is filled with Quaternary continental sediments and extends south to Buerat. East of Buerat these Quaternary (Pleistocene) deposits extend along the coast of the Gulf of Sirte to Cyrenaica, covering a belt 5 to 30 km wide.

The Gargaresh (Qarqarish) stone, long quarried for building stone at Gargaresh on the west edge of Tripoli, is considered to be of Pleistocene age. It forms a coastal ridge that rises as much as 50 m above

A



B

FIGURE 28.—Volcanic rocks at Jabal Eghei. *A*, Volcanic rocks (hill) overlying lower Eocene sedimentary rocks at north end of Jabal Eghei. The upper fifth of the hill is basalt. *B*, Photomicrograph of augite-olivine basalt from Jabal Eghei. Some of the olivine grains are rimmed by iddingsite pseudomorphs after olivine. × 45, crossed nicols.

amount of authentic information is limited and is restricted to certain areas, these continental limestones are classified as undifferentiated continental Tertiary on plate 2. The writer believes that these deposits are of Oligocene age, a concept also accepted by some oil-company geologists (oral commun.).

VOLCANIC ROCKS

Volcanic rocks in Libya, chiefly extrusive basalts, cover a total area of about 50,000 sq km. They occur in northeast and northern Fezzan at Al Harūj al Aswad, Jabal as Sawdā' and Jabal Fezzan; in the Garian-Mizda-Beni Ulīd area in northern Tripolitania; and in Jabal Eghei of the Tibesti region in south-central Libya. Only a few scattered areas elsewhere in the Tibesti region of Libya are covered by extrusive basalts. North of Brach is an outcrop too small to be shown on plate 2; other outcrops occur south of Jabal Awenat near the Egyptian border and the famous Wāw an Nāmūs volcano in east-central Fezzan. Farther south in northern Chad vast areas are covered by extrusive basalts.

The present writer recognizes three periods of volcanic activity, dating from post-Eocene to Holocene. He believes that, in general, they were related to movements along deep-seated fractures perhaps associated with the great orogenic pulse of the Alpine cycle.

NORTHEASTERN AND NORTHERN FEZZAN

Jabal Al Harūj al Aswad and Jabal as Sawdā', the two volcanic massifs in northeast and northern Fezzan, cover an area of about 40,000 to 45,000 sq km. They are considered to be chiefly post-Eocene eruptions, possibly of Oligocene age.

In Jabal Al Harūj al Aswad extrusive basalts, about 10 to 20 m thick, cover an area of approximately 35,000 to 40,000 sq km and overlie the lower Eocene and Upper Cretaceous rocks on the west side of the flows. They are overlain by patches of lower and middle Miocene rocks on the northern part, indicating possibly an Oligocene age. North and northeast of Al Harūj al Aswad near the village of Zella, several volcanic cones occur which seem to have erupted through the older lavas; this evidence suggests a second period of eruption, possibly during Quaternary time. The Jabal as Sawdā' and Jabal Fezzan volcanic flows are probably of the same age as the Al Harūj al Aswad flows. These basalts overlie the Upper Cretaceous and Paleocene beds of eastern Hamāda al Ḥamrā' and cover an area of about 7,000 sq km.

The extrusive rocks of the region generally consist of plagioclase-olivine basalts, some of which are vesicular, and augite andesite. Associated minerals are ilmenite, hematite, calcite, apatite, nepheline, and augite. Iron minerals noted by the writer of the present report on the west side of Al Harūj al Aswad as replacement in the Eocene rocks seem to have formed through percolation and leaching, forming a lateritic deposit of hematitic sandstone.

NORTHERN TRIPOLITANIA

The volcanic rocks of northern Tripolitania extend over a total of about 3,000 sq km in the Garian, Mizda, and Beni Ulīd area. The tectonic activity of the Jabal Nefusa, in Late Cretaceous time, gave rise to a tremendous northwest-trending fracture zone, parallel to the anticlinal axis of the Garian-Yafran arch, extending from the Garian area to Tarhuna. These fractures made way for the uprising magma possibly during post-Eocene time. Along the axes of the folds are numerous eruptive areas, some of which make up the extensive basalt flows southeast of Garian and northeast of Mizda. Also numerous dikes of nepheline phonolite occur in the area.

Between Garian and Tarhuna are several parallel northwest-trending fault fractures filled with intrusive basalts.

Christie (1955, p. 21–22) reported extensive flows of basalt southeast of Garian as "small crosscutting intrusions of basalt, and larger intrusions of phonolite." He (p. 21) reported that basalts flowed down Wādī Ghan (Uadi Gan), lat 32°13′ N., long 13°07′ E., and now rest on a crust of hardpan and caliche that had formed previously in the wadi bed. He believed that they postdate the topographic features and must be very young, possibly of early Quaternary or late Pliocene age.

Christie (1955, p. 22) also described the intrusive phonolites in the Garian area as being much more silicic than the basalt, less dense, and lighter in color. He reported that lathlike crystals of feldspar up to 1 cm are common, and crystals of hornblende are rare. The rocks are sheared and foliated parallel to the walls of intrusion and the enclosing rocks are generally bowed up. He stated that "the phonolite was intruded as a viscous mass, and deformed the surrounding rocks during emplacement. No extrusives corresponding to these rocks have been seen."

South of Garian, in the headwaters of the Wādī Megenin watershed and in Beni Ulīd region, the present writer noted previously unreported flat-lying sills in the Upper Cretaceous beds, some of which are exposed in deeply eroded surfaces. In the Garian area the extrusive rocks are plagioclase-olivine basalt. As in the extrusive rocks of northern Fezzan, the accessory minerals are augite, apatite, ilmenite, and hematite. The intrusive masses are nepheline phonolites and

the present sea level and consists of a detrital foraminiferal limestone composed of shell fragments and quartz sand which appear to have been blown up in dunes and later cemented. Dune ridges of this type occur along many parts of the Libyan coast, including Sirte and El Agheila, and in Cyrenaica at Ra's el Hilāl, a few kilometers northwest of Beda, Apollonia, and Derna.

Although the Quaternary deposits are largely of continental origin, there was a marine incursion during the Tyrrhenian Stage of Pleistocene time. These intercalated marine beds form the base of the present cliffs along the Mediterranean shore and have been also reported in several dug wells as far south as Suq as Sabt, 35 km south of the present shoreline (Lipparini, 1940, p. 221–301).

In the coastal plains of Tripolitania, the Holocene deposits are represented by a desert crust, sebcha, soils, dunes, and alluvium of variable thickness. They overlie the Pleistocene deposits, which are visible along the coast to the Homs-Zliten area.

The following classification of Quarternary rocks of Tripolitania, translated from Italian, is adapted from Lipparini (1940).

Quaternary rocks of Tripolitania

[Adapted from Lipparini (1940)]

Age	Facies		Description
	Continental	Marine	
Holocene		Flandrian	Weak marine transgression shown by present shoreline (cutting coastal dune features and encroaching on the cliff of lower Gefara).
	Wurmian		Red calcareous crust containing windblown sand grains.
			Reddish earthy argillaceous sand, slightly iron rich, with *Helicella lineata* and *Hellicella pyramidata* (steppe fauna).
			Marine sand with terrestrial fossil Mollusca (*Heliz melanostoma*, *Eobania* vermiculata, *Rumina decollata*); retreating phase (fauna circum-Mediterranean).

Quaternary rocks of Tripolitania—Continued

Age	Facies		Description
	Continental	Marine	
Pleistocene	Riss-wurmian	Tyrrhenian	"Panchina" 4–40 m above the present sea level, with *Cerithium protractum*, *Tellina cumana-aioda*, *Trochula dalat*, *Tapis pullastra sazatilis*, and *Mytilus senegalinsis* (equivalent to the *Stimobus bubonius* beds in Italy).
Pliocene	Rissiano		Reddish argillaceous sand with *Elemina desertorum* Forsk.
			Continental formations in Gefara, undifferentiated from Quaternary.

CYRENAICA

The coastal plains of Cyrenaica are covered with Quaternary marine fossiliferous limestones, which have a maximum thickness of about 15 m. In the Bengasi area they attain an elevation of about 20 m above sea level and overlie the marine Miocene beds. North and east of Bengasi these marine Quaternary limestones are overlain in most places by fairly well cemented crossbedded continental dune deposit. However, to the south and west of Bengasi the limestones are overlain by yellowish-green and red clays representing a brackish littoral facies.

Alluvial and eolian deposits of Quaternary age, as dunes and gravel plains (sarīrs), cover large parts of southern Cyrenaica and in most places completely mask the underlying beds.

Other Quaternary deposits in Cyrenaica include the coarse gravels and alluvial deposits of Wādī Gattar, the sebchas (salt flats), and the terra rosa (red earth), which is a lateritic deposit covering large parts of the Jabal area of Cyrenaica. In parts of Cyrenaica a veneer of boulder-bearing limestone extending a few hundred meters inland is probably of Quaternary age. Notable exposures of this rock are along the coast road between Apollonia and Derna.

The Quaternary rocks of Cyrenaica include the *Cardium* beds, the Panchina Stone, and the *Cerithium volgatum* Sands.

The *Cardium* beds[7] (Desio, 1935, p. 95) consist of friable detrital calcareous sandstone, which is probably equivalent to the Gargaresh stone of the Tyrrhenian Stage in Tripolitania (Petroleum Exploration Society of Libya, 1960, p. 6). Near Agedabia, the Agedabia Sandstone (Gregory, 1911, p. 607) was described as Agedabia Formation by Desio (1935, p. 87). It is composed largely of fragments of pelecypods and gastropods, mostly types still living. The widely used Panchina building stone,[7] which is quarried around Bengasi, extends over almost the entire coastal area. This building stone is also a detrital calcareous sandstone that probably corresponds to the *Cardium* Beds and the Agedabia Sandstone (Petroleum Exploration Society of Libya, 1960, p. 34).

The *Cerithium volgatum*[7] Sands (Desio, 1935, p. 348) is a well-bedded sandstone containing marine mollusks. Near Bengasi it is overlain by crossbedded continental sandstone of Holocene age.

In southern Cyrenaica from about lat 30° N. to the Sudan border, the Calanscio and the Rebiana Sand Seas cover the greater part of the area. These windblown sands were probably deposited over a longer period than the Quaternary, but they are generally considered to belong to that period. These great sand areas are probably remnants of the Oligocene continental and marine sandstones, which were largely destroyed by erosion.

The vast gravel plain of the Sarīr Calanscio is probably also the result of destruction in place of local rocks (probably Oligocene) by a combination of weathering processes.

Sebchas occur in many parts of Libya. In Cyrenaica they are along the coast and in the desert interior in several depressions (fig. 29). These surficial deposits of recent origin, some of which are commercially important, are discussed along with other saline deposits in the section "Mineral resources."

Gregory (1911) recognized three units of the Quaternary deposits: a basal limestone containing *Cerastoderma edule* (*Cardium edule*); a middle unit, calcareous tufa of Derna; and an upper unit consisting of sand dunes, lagoonal clays, alluvium, and delta fans (Little, 1945, p. 41). In 1959 the Names and Nomenclature Committee of the Petroleum Exploration Society of Libya adapted from the works of Gregory and Newton (1911), Desio (1935), Marchetti (1938), and Stefanini (1930) the following classification for the Quaternary deposits of Cyrenaica, comparable to the classification adapted from Lipparini for Tripolitania:

Quaternary rocks of Cyrenaica

Holocene	Sand dunes, lagoon clays, alluvium, and delta fans.
Wurmian	Calcareous tufa of Derna with *Hygromia sordulenta* and *Helicella tuberculosa*.
Tyrrhenian	Cream-colored, shelly limestone with pseudo-oolitic grains, containing *Cerastoderma edule*, *Cerithium* cf. *C. vulgatum*, *Columbella rusticus*, *Cheliconus mediterraneous*, *Ostrea edulis*, *Glycymeris glycymeris*, *Mactra stultorum*, *Jagonia pecten*, and *Loripes lacteus*.
Sicilian	Marls and compact limestone from west of Tolemaide and the plain east of Bengasi with *Cerastoderma edule*, *Cardium tuberculatum*, *Glycymeris pilosa*, and *Paludestrina* sp.

FIGURE 29.—Typical view of a sebcha, salt flat, formed in the depressions in the desert interior. The white is a crust of salt formed by evaporation. Photograph taken at Marada by Harry F. Thomas.

FEZZAN

The two great sand seas of Ubari and Murzuk cover a large part of Fezzan and were probably formed in Quaternary time. Quaternary lakes occupied much of Fezzan during pluvial stages of the Pleistocene and were partly responsible for the accumulation of fresh water in the Devonian and Nubian (Lower Cretaceous) aquifers, which are the major source of the underground water supply in Fezzan.

Fossils collected from the sandy marls overlying the Nubian Sandstones in the Murzuk-Traghan Valley are a fresh-water fauna of Pleistocene to Holocene age. Other fossils collected from several localities in the Shati Valley area indicate that the deposits are of salt-

[7] The use of these names is discontinued or recommended only for local use (Petroleum Exploration Society of Libya, 1960).

lake or estuarine origin and could be as old as late Tertiary (fig. 30).

The gravelly and stony plains of Sarīr al Gattusa along western Jabal Al Harūj al Aswad and of Sarīr Tibesti (Serir el Tibesti) extending all the way to the Tibesti foothills are the result of disintegration of rock in place since the regression of the Tertiary seas.

Other Quaternary deposits in Fezzan are the salt flats (sebchas) that have been formed in several depressions in the Shati Valley area, near Sebha, and at Trāghan, Umm al Arānīb, Tmassah, Gatrun, and south of Ghāt. Several lake-bottom deposits of sodium carbonate in the Ubari Sand Sea are also considered to be of Holocene age.

WĀW AN NĀMŪS VOLCANO

South of Jabal Al Harūj al Aswad at lat 24°50′ N., long 17°45′ E., is the Wāw an Nāmūs volcano, whose crater is about 5 km in diameter and about 150 m deep. In the center of this crater a volcanic cone, surrounded by five salt lakes, rises to a height of about 30 m above the rim of the crater. Another smaller crater (fig. 31), about 40 m deep, is in the center of this cone. Sulfur is deposited on its walls. Pea-size grains of black lapilli and volcanic ash about 10 cm thick cover the sandy surface of the crater wall and about 100 sq km of the surrounding area. This black volcanic ash consists of basalt and contains about 30 percent of olivine crystals. The central cone consists of consolidated spatter which includes coarse crystalline bombs composed chiefly of olivine crystals. Other volcanic bombs, as much as 10 cm in diameter and composed almost entirely of olivine crystals, are strewn over the crater floor. The rocks generally consist of olivine-nepheline basalt. The olivine is in the form of idiomorphic unaltered crystals, which have been cemented by materials deposited from magmatic solutions. The freshness of the olivine crystals is noteworthy.

FIGURE 30.—Outcrops of coquina, composed of mollusk shells of salt- or brackish-water types of late Tertiary or Quaternary age. The coquina occurs in small scattered outcrops whose various dimensions range from a few meters to several hundred meters; these outcrops unconformably overlie rocks of various ages. Photograph taken about 40 km west of Brach, near Tārūt in the Shati Valley area, Fezzan. Shells in center of photograph are about 2 cm long.

FIGURE 31.—A crater about 40 m deep in the central cone at Wāw an Nāmūs. Volcanic bombs as much as 10 cm in diameter, entirely of olivine crystals, are strewn over the floor.

The annular depression around the central cone at places extends below the water table so that lakes and ponds are formed. The water in the lakes is very salty (table 2), and salt crusts are formed around the shores of the lakes, though some comparatively fresh water (table 2) enters the lakes from seeps along their shores.

To the north and northwest of Wāw an Nāmūs volcano are several other volcanic craters and cones which are thought to have been contemporaneous with the Wāw an Nāmūs eruption during late Quaternary time.

TABLE 2.—*Analysis of water from Wāw an Nāmūs lakes and springs*

[Values in parts per million. Collected April 1960]

	Lake water (pH 8.6)	Spring water (pH 7.8)
SiO_2	82	34
$Al_2O_3+Fe_2O_3$	4	Trace
Ca	20	113
Mg	194	87
Na	20,200	998
K	586	17
Chlorides (as NaCl)	32,500	1,810
CO_3	308	Trace
HCO_3	3,360	708
SO_4	14,000	905
Cl	19,700	794
Dissolved solids	56,800	3,270

BRACH AREA

Another small but significant basalt flow not shown on plate 2 occurs about 20 km north of Brach. This flow consists of plagioclase-olivine basalt with associated augite, iddingsite, aplite, carbonate, and magnetite.

The proximity of this extrusive unit to the Shati Valley iron deposits and its east trend parallel to the fracture pattern in the area is significant. Nearby in the Shati Valley, northeast of Brach, fractures are filled with highly manganiferous material, and the beds are highly enriched with iron. This might be a result of magmatic waters rising along fault fractures.

GEOLOGIC HISTORY

Libya, interior Algeria, and the western desert of Egypt are on the northern fringes of the African Shield and extend over a stable platform area of cratonic basins. These cratonic basins contain thick sequences of moderately deformed Paleozoic rocks and, with the exception of the basins in northwest and northeast Libya, a comparatively thin sequence of Mesozoic sedimentary rocks. That these basins were active as recently as Tertiary time is shown by the presence of thick accumulations of Tertiary rocks in the Sirte area and northern Cyrenaica. Moreover, a slight marine incursion during Quaternary time deposited sediments in the Mediterranean coastal area (pl. 6).

Early in the Paleozoic Era, continental environments prevailed in most of Libya, and a sequence of preponderantly continental sandstones was deposited in several basins during the Cambrian and Ordovician Periods. The Early Silurian transgression in the southwest is marked by a basal conglomerate. During Silurian time, conditions created by Caledonian disturbances resulted in deposition of thick layers of marine sediments in southwest Libya. The regression of the seas at the end of the Silurian Period is marked by littoral facies and was followed by deposition of continental sandstones during Early Devonian time. Renewed transgression occurred during Devonian time, but in Late Devonian and Early Carboniferous times, shallow-water sediments were deposited. During Carboniferous time, marine and continental environments alternated; and by the end of Carboniferous time, continental environments prevailed over all southern Libya and continued possibly until about the end of Early Cretaceous time.

During Mesozoic time an almost uninterrupted sequence of rocks ranging from Triassic to Cretaceous in age was deposited in a marginal trough that extended through northwestern Libya. A marine transgression in Late Cretaceous time extended far onto the platform below the 29th parallel, and Paleocene seas invaded most of northern Libya. Near the end of Cretaceous time, movements and deformations occurred. One of the effects of the movements was the formation of the Hun graben and the Sirte embayment, which probably made a passageway for the Eocene seas that extended at least as far south as lat 23° N., near the Tibesti Mountains and probably into central Africa. Tertiary marine sedimentary rocks ranging from Paleocene to Miocene in age were deposited in the Sirte area and include the greater part of the rocks exposed in northern Cyrenaica. The Quaternary rocks in the northern part of Libya are principally continental deposits, but there was one slight marine incursion during the Tyrrhenian Stage. The Quaternary deposits of the interior consist principally of sand.

PRECAMBRIAN

During Precambrian time a series of clastic sediments of unknown thickness was folded and metamorphosed and later intruded by granitic rocks. According to Little (1945, p. 18), the metamorphic series of the Jabal Arkenu–Jabal Awenat area were considered by Gallitelli (1934) to be of Archean age and to be intruded by granitic rocks, some of which are of Late Carboniferous age and possibly contemporaneous with late Hercynian folding. Burollet (1963), however, considered this metamorphic series to be of Pharusian age and suggested rhyolite-andesite intrusion followed by granite-syenite intrusion in post-Carboniferous time. The Precambrian rocks of south-central and west-central Libya at Jabal Eghei and Jabal Fezzan are part of the basement complex, probably of Pharusian age, and are intruded by aplite and pegmatite dikes of probable Precambrian age. Klitzsch (1963) suggested that the metamorphic series of the Dor el Goussa area is also probably of Pharusian age and is intruded by Precambrian granitic rocks.

PALEOZOIC

By the beginning of the Paleozoic Era, large parts of Libya had been peneplaned as evinced by Precambrian rocks wherever exposed. This long period of erosion was general throughout north Africa from the Atlantic Ocean to the Red Sea. Everywhere in Libya a basal conglomerate at the base of the Cambrian section contains large rounded clear quartz pebbles and boulders. This indicates the existence of similar environments at the beginning of the Paleozoic throughout Libya.

Paleozoic rocks ranging in age from Cambrian to Permian are exposed in many parts of southern Libya below the 28th parallel. In southwestern Libya the Paleozoic section grades eastward from a marine to a mixed marine-continental facies and finally into a facies that is predominantly continental, so that in southeastern Libya the Paleozoic rocks are mostly continental complexes.

Cambrian and Ordovician rocks are exposed in southern Libya in the periphery of the Murzuk basin, in Jabal Eghei, in the Tibesti area, in the Jabal Awenat-Jabal Arkenu area, and in the Jabal Dalma area.

According to Klitzsch (1963), a deep basin developed in the Dor el Goussa area, along the western and southern edges of the present basement exposures, and several hundred meters of coarse clastic sediments from east and southeast was deposited in this basin. These clastic sediments were folded during Cambrian time as indicated by the angular unconformity between the Ordovician and the Cambrian rocks. Faulting also occurred in Late Cambrian time. In southeastern Libya Cambrian rocks were deposited on peneplaned highly folded Precambrian rocks and are discordantly overlain by the Ordovician rocks (Burollet, 1963). During post-Carboniferous orogenies, these rocks were uplifted to their present positions (fig. 32), several hundred meters above the surrounding land surfaces. In the Gargaf area the Cambrian rocks are also unconformable with the Precambrian rocks.

The Cambrian and to a lesser extent the Ordovician sandstones are marked by a kaolinitic cement, which probably is the alteration product of the feldspars of the older rocks, derived from the positive areas of the Hoggar (Ahaggar), the Tibesti, Jabals Awenat and Arkenu, and possibly the Sirte.

At the close of Ordovician time, large parts of Libya underwent peneplanation, which was general throughout the African Sahara from the Atlantic Ocean to the Red Sea, followed by the Tassilian (Silurian) transgression, one of the most extensive Paleozoic marine incursions of Libya.

FIGURE 32.—Cambrian outlier on top of Precambrian metamorphic rocks at Jabal Arkenu in southeast Libya. In the background are the granitic rocks.

The Silurian seas were widespread in southwest Libya and extended southward into Niger and eastward as far as Dor el Goussa northeast of the Murzuk basin. A Silurian transgression also probably occurred in southeast Libya in the Cufra basin by way of Egypt.

An Early Silurian transgression is indicated by shallow-water marine beds, including a basal conglomerate in the Murzuk basin. During Silurian time thick layers of marine sediments including graptolitic muds were deposited in the Murzuk basin, while the Sirte, Jabals Arkenu and Awenat, the Tibesti, and Hoggar (Ahaggar) remained as positive areas.

In the eastern flanks of the Murzuk basin, Klitzsch (1963) reported Silurian shales having fine-grained sandstone intercalations in the lower and upper parts. He suggested a Late Cambrian uplift in northern Dor el Goussa, and an Early Silurian subsidence that continued into Devonian time only to be interrupted by the Caledonian uplift south of the Dor el Goussa area.

The regression of the Silurian seas is marked by a littoral facies in the Murzuk basin that grades eastward into an alteration of continental and littoral beds. In the Murzuk basin some of the marine Silurian and part of the marine Devonian strata probably wedge out to the east.

In Late Silurian or Early Devonian time, new subsidence in the Murzuk basin resulted in the deposition of the Tadrart clastic sediments on the western and eastern flanks of the Murzuk basin, whereas on the north flanks of the basin Middle Devonian marine rocks discordantly overlie the Ordovician and Silurian rocks (Massa and Collomb, 1960). Renewed marine transgression during Middle Devonian time was widespread. During this period the Tihemboka anticlinal area, west of the Murzuk basin near Edjeleh in Algeria,

emerged, creating two marine basins. The Devonian seas extended deep into the Murzuk basin and probably into southeastern Libya, covering almost all south-central and western Libya with the exception of the Tibesti and the Gargaf, which had become emergent during the Caledonian disturbances. The Devonian marine rocks are well exposed in the Tadrart badlands on the high eastern slopes of the Acacus Mountains, in the Wan Kasa, and Awenat Wennin area northwest of the Gargaf anticline. Beds formed during the marine regression are on the south slope of the Gargaf anticline.

Transgression of the seas south of the Gargaf anticline took place again in Late Devonian time or at the beginning of the Carboniferous Period, but by the end of Viséan time, emergence of the land and regression of the seas gave rise to the deposition of continental sandstones which became general during succeeding Namurian time.

Carboniferous seas extended over the greater part of south and western Libya. Lower and Upper Carboniferous rocks are exposed in the periphery of the Murzuk basin consisting of sandstones and siltstones of distinct shallow-water type at the base and of marls and limestones in the upper part.

MESOZOIC

Continental environments prevailed in Fezzan and southern Cyrenaica from Carboniferous time until possibly the end of Early Cretaceous time. Meanwhile marine sediments were being deposited in northern Libya, with the exception of the positive areas of Sirte which remained high during most of the period. These predominantly arenaceous deposits are covered by marine beds of Cretaceous age near Awenat Wennin but are well exposed in south and southeastern Libya where they discordantly overlie the Paleozoic sedimentary rocks. During Mesozoic time a marginal trough extended through northwestern Libya and southern Tunisia, in which was deposited an almost uninterrupted sequence of Mesozoic rocks at the present site of Jabal Nefusa. A similar basin in northeastern Libya, Cyrenaica, probably developed at the same time. However, in northwestern Libya in the Jabal Nefusa–Jabal Garian area, an uplift in Early Cretaceous time caused erosion of some of the Lower Cretaceous (Wealdian) and Jurassic rocks (Burollet, 1963).

Triassic rocks representing a marine transgressive series of the Alpine type (Lipparini, 1940, p. 228) are exposed in Tripolitania and are composed principally of gray and dark-gray limestones with subsidiary shale. The upper part of the series is composed of anhydrite, shale, and dolomitic limestone. In southern Libya these beds are represented by a continental facies of siltstone and crossbedded sandstone. Not much is known about the extent of the Triassic seas; but they probably extended deep into the Hamada basin, possibly to about lat 30° N. and possibly also in parts of northern Cyrenaica. Rocks of Jurassic age are represented by the massive beds of gypsum and anhydrite interbedded with subsidiary dolomitic limestone and shale units near Yafran grading eastward into a dolomitic limestone. Continental and lagoonal conditions probably alternated with shallow marine environments during the Jurassic Period in northern Libya, while a continental environment prevailed in southern Libya. These shallow-water and lagoonal deposits probably extended south into the Hamada basin as far as the 30th parallel.

In Early Cretaceous time, continental environments were established almost throughout Libya. Rocks of Wealden to Albian Age consist of soft pale-yellow claystone, marls interbedded with gypsum, and crossbedded conglomeratic sandstone. These deposits are probably of continental origin.

During Cenomanian (Middle Cretaceous) time, renewed marine transgression moved the shoreline as far south as lat 29° N., and interbedded dolomitic limestones and marls with minor gypsiferous beds were deposited over the entire area. Another marine transgression in Senonian (Late Cretaceous) time extended farther south onto the platform below the 29th parallel, and a series of limestones and varicolored shales with interbedded dolomitic limestones were deposited.

Near the end of Cretaceous time, the strata were deformed in a vast anticlinal swell that trends northwest to southeast, and the Sirte area gradually was submerged probably for the first time.

One of the effects of these movements was the formation of a northwest-southeast trough, the Hun graben and the Sirte embayment, which probably formed a passageway for the seas to extend deep into the Tibesti tableland and probably farther south into Africa in early Tertiary time.

At the end of the Cretaceous, an Aptian transgression of the seas from the north reached its southernmost extent in early Maestrichtian time. The Tar Marls (Jordi and Lonfat, 1963) were deposited in this widespread sea which covered the greater part of the present Ḥamāda al Ḥamrā'.

CENOZOIC

Late Cretaceous or early Paleocene reactivation of the old highs, Gefara in the north and Gargaf in the south, caused the retreat of the seas eastward. During this period Upper Cretaceous and Paleocene rocks (Upper Tar Marl and Had Limestone Members of the

Zmam Formation) and progressively younger beds were deposited from the edges toward the center of the basin. A second transgression in late Paleocene, covered only the eastern part of Hamāda al Ḥamra in this area but extended eastward into the Sirte embayment as far as lat 24° N. and possibly as far as lat 26° N. in central Cyrenaica.

Eocene sediments were deposited in seas that invaded Libya in the Sirte area at least as far south as lat 23° N. near the Tibesti where beds of Eocene age are found on crystalline basement rocks. Following the Eocene, the seas progressively regressed during the Tertiary Period as a result of several oscillations. Thus, toward the Mediterranean coast, progressively younger Tertiary sediments of Oligocene and Miocene age were deposited.

The Tertiary sedimentary rocks include fossiliferous limestones, calcareous sandstones, marls, and argillaceous beds.

Tertiary marine sedimentary rocks of Eocene, Oligocene, and Miocene ages were also deposited in northeastern Libya and include the greater part of the rocks exposed today in Cyrenaica. The Oligocene rocks consist of a marine sequence that is shallower than that of the Eocene rocks and lie conformably on the Eocene rocks to the north in the area of Tolemaide; to the south near Al Abyār, the Oligocene rocks appear to be transgressive on Cretaceous rocks. In the northeastern part of Cyrenaica, Oligocene and Miocene beds appear conformable but to the northwest Miocene beds rest directly on Eocene rocks. In Cyrenaica orogenic movements beginning in Oligocene time continued into late Miocene or later resulting in some warping.

None of the older Tertiary rocks are exposed in western Tripolitania, but Miocene sediments deposited in transgressive seas occur for a distance of about 30 km south of the present shoreline. These Miocene rocks, represented by thick claystone beds which are directly overlain by the Pleistocene deposits of the coastal plains, progressively decrease in thickness to the south.

Volcanic activity in the eastern and northern parts of Fezzan occurred after the Eocene regression.

In general, volcanic activity in Libya probably was concurrent with movement along deep-seated fractures, perhaps in connection with the great orogenic pulse of the Alpine cycles.

Quaternary rocks in northern Libya are principally continental deposits, with the exception of those rocks produced by a marine incursion during the Tyrrhenian Stage, which extended as far as 35 km south of the present shoreline in northwest Libya (Lipparini, 1940, p. 254). The Quaternary deposits of the interior consist principally of sand (fig. 33), but fresh-water lakes covered part of the central Fezzan with Murzuk-Traghan Valley being the center. Brackish- or salt-water lakes covered the area south of the Gargaf and the present Ubari Sand Sea. (See fig. 33.)

The sand deserts of Libya lie in broad basins of tectonic origin that are also basins of interior drainage. In these broad basins are local areas of considerable relief and extent and numerous smaller subbasins of various depths and sizes. The desert sands are principally fine-grained quartz generally coated with iron oxide which has a characteristic eolian polish. Associated minerals include orthoclase, glauconite, magnetite, epidote, and mica. Gravel-covered plains, known as sarīrs (serirs), were probably formed by the disintegration of bedrock during the Quaternary period.

The volcanic cones at Wāw an Nāmūs and north of Jabal Al Harūj al Aswad are probably very recent. Christie (1955) reported basalt flows in the present-day wadis, near Garian, evidence indicating a very recent origin.

TECTONICS AND GEOMORPHOLOGY

Early in the 20th century, Italian, French, and English geologists made detailed geologic studies of Libya. Their works are recorded in many publications; Hill (1959, p. 30–42) has given reference to these works.

Some of the earlier studies dealing with geomorphology and tectonics in Libya are the works of Gregory (1911), Desio (1928), Sandford (1933), and Marchetti (1934). Lipparini's (1940) "Tettonicae Geomorfologia

FIGURE 33.—A typical aerial view of the sand dunes in Fezzan. Photograph taken between Brach and Ubari in the middle of the Ubari Sand Sea, which covers an area of about 80,000 sq km.

della Tripolitania" is the most recent and accurate regional account of the northwestern part of the country. Little (1945), in his "Handbook on Cyrenaica," discussed the geology and structure of Cyrenaica. Lelubre (1952) discussed the geology of southern Libya at some length in "Aperçu sur la Géologie du Fezzan." Freulon and Lefranc (1954) also discussed the structure and stratigraphy of the northern Fezzan. Hey (1956) combined the earlier works of Gregory, Desio, and others with geological information published by Marchetti (1938) and with his own personal observations and study in "The Geomorphology and Tectonics of the Jabal al Akhḍar (Cyrenaica)."

The geology and structure of Libya have been also under intensive study by several oil companies since 1953, but few results of those studies have been released. The most recent publications and detailed accounts of the geology and structure of some parts of Libya were presented at the first Saharan Symposium, April 1963, in Tripoli, notably by P. F. Burollet, M. Fürst, E. Klitzsch, and H. A. Jordi and F. Lonfat.

The limited scope of the investigations undertaken by the present writer, as well as time and other factors, did not permit detailed study of the structure and geomorphology of this vast desert country of about 1.6 million sq km. The following brief account of these features is mostly based on the literature cited above and on personal observations made during geological reconnaissance and study of available aerial photographs of some parts of the country. An attempt is made, however, to point out significant physiographic and tectonic features (see pl. 6) and to give a brief account of some aspects of the desert morphology (p. 15–18).

Northwestern Libya is marked by a flat coastal plain, the Gefara, that rises gently to the south and ends at a north-facing escarpment several hundred meters high, the Jabal escarpment. This escarpment arcs eastward for about 300 km, from Nālūt, near the Tunisian border, where the Gefara is about 140 km wide, to Homs where the hills come down to the coast. Structurally, this coastal plain is a basin, the Gefara-Gabese basin, that extends into eastern Tunisia (oil-company geologists, oral commun.).

Not much is known about the extent of sedimentation and accumulation of the older rocks in the northern Gefara. Water-well information indicates that the early Tertiary rocks of Paleocene to Eocene and Oligocene age are absent and that the Miocene beds overlie rocks of Cretaceous age. In Late Cretaceous time the Gefara acted as a stable platform so that a thinner sequence of the Upper Cretaceous sediments were deposited in the Gefara area. The Miocene seas only extended as far as 35 to 40 km south of the present shoreline at Tripoli to the line of east-west faulting north of Azizia (Lipparini, 1940, p. 240). South to southwest of Azizia, as a result of anticlinal swelling, faulting, and subsequent erosion, rocks of Triassic age protrude through the thin surficial cover and form buttes. Jurassic rocks are also exposed at the foot of the Jabal escarpment from near Garian to Nālūt.

The north face of the western part of the Jabal escarpment is steep and is cut by numerous wadis. Lipparini (1940, p. 240) suggested, and the present writer agrees, that after the uplift, pre-Miocene east-west faulting occurred somewhat north of the present Jabal escarpment and that the original fault scarp has since been cut back to the present position by headward erosion. Continental Quaternary deposits now cover the fault trace in the Gefara.

The western part of the Jabal escarpment of Tripolitania from Nālūt to Yafran is called Jabal Nefusa, followed by Jabal Garian, and then Jabal Tarhuna, and, from Tarhuna to Homs, the Msellata (Lipparini, 1940, p. 223).

According to Burollet (1963) the Jabal area was uplifted during the Hercynian folding, followed by intense erosion before the Permian and Triassic sedimentation. During the Mesozoic the area was generally subsident, but erosion following an uplift during Early Cretaceous time resulted in the destruction of some of the Jurassic and Lower Cretaceous beds.

The main structural feature of the Jabal area is the vast anticlinal swelling, the Garian-Yafran arch, that trends northwest-southeast and reaches its highest point west of Garian. The swelling ends near the Sirtica to the east. This emergence of the land or the Jabal uplift occurred at the end of Cretaceous time and was accompanied by northwest-southeast faulting. The aerial photographs show a system of northwest-southeast fault fractures parallel to the anticlinal axis between Garian and Tarhuna, and farther east in Beni Ulīd–Wādī Soffegin area, this system of northwest-southeast fracturing is well defined.

Another effect of this movement was the formation of the Hun graben faults that also trend northwest and separate the eastern part of the Jabal area and Hamada from the Sirte.

Parallel to the general trend of the main Jabal structure and along the axes of the folds are numerous Tertiary igneous masses consisting of extrusive and intrusive basalts and phonolites. The alinement of these rocks with the tectonic axes suggests that they are probably related to a deep-seated phase of the orogeny.

According to Burollet (1963), during and after the Miocene, downwarping in the Gefara was accompanied

by faulting and folding in the Garian area. Also during Quaternary time more volcanic activity occurred in the Garian area, and lavas flowed down the present wadis.

The Jabal area slopes gradually to the south into a desert of rocky plains which farther south grades into a gravel plain. The Hamada area (p. 7) extends from about lat 31°30′ N. from the slopes of the Jabal area to about 28°30′ N. and from the Tunisian border eastward to the Hun graben. The area slopes gradually to the south from Nālūt to Ghadamēs and rises eastward from Nālūt to the Garian area. The inner part of the Hamada is a flat, broad basin bordered by elevated areas; the eastern part of the area is deeply cut by numerous northeast-draining wadis. The monotonous Hamada surface of northwestern Libya is interrupted by the vast volcanic mass of Jabal as Sawdā' that rises more than 300 m above the surrounding land surfaces. These eruptive masses are alined with the fault-fracture zones and the volcanic flows of the Jabal area near Garian and are probably of the same age. The southern limit of the Hamada is a line of precipitous cliffs that border the northern edges of the Ubari Sand Sea of Fezzan and Gargaf. The western part of the area is referred to as the Hamāda al Ḥamrā' (p. 7), but structurally the entire area is referred to as the Hamada basin. The basin is bounded on the north by the Garian-Yafran arch, on the east by the Hun graben, and on the south by the Gargaf arch. The Hamada basin widens and deepens to the west into Algeria, forming one of the largest basement depressions in Africa. This basin contains thick sequences of sedimentary rocks ranging in age from early Paleozoic to early Tertiary.

With the exception of an obvious flattening of the beds south of the Jabal anticline, no major structural features are in evidence; however, many subsurface structural features have been found by geophysical means (oil-company geologists, oral commun.). Several northwest-southeast trending fractures and faults occur in the area, but no major fault system is recognized on the surface.

Southwestern Libya south of the Hamada is marked by two large sand areas, the Ubari and the Murzuk Sand Seas. These sand seas are separated by the great Nubian escarpment, which originates near Sebha and extends without interruption, gradually rising to heights of more than 400 m at Ubari. This escarpment, rising to still greater heights, swings south at about long 11°30′ E., eventually reaching the southern Libyan boundary, and in so doing forms the western limit of the Murzuk Sand Sea, the Mesach Mellet.

In the southwestern part of the Murzuk Sand Sea, the north-south Acacus Mountain range rises more than 600 m above the valley of Wādī Tanezzuft. No direct evidence of faulting has been found, but these sheer cliffs extend for more than 100 km, interrupted only by an offset about 30 km north of Ghāt. However, the linearity of the cliffs is so strikingly suggestive of a fault scarp that many geologists have thought a fault must be present, and this interpretation was adopted in compiling the geologic map (pl. 2). Erosion of the Tanezzuft valley has beheaded a number of east-draining wadis on top of the Acacus escarpment, wadis that now have the appearance of hanging valleys when viewed from the Tanezzuft valley (fig. 34). The Tadrart badlands form the high eastern slopes of the Acacus Mountains.

The main structural feature of southwestern Libya is the Murzuk-Djado basin which lies between the broad arches of the African Shield of the Ahaggar in southeastern Algeria and the Tibesti Mountains of the northern Republic of Chad. The basin is delimited on the north by the Gargaf arch, a major east-west structural feature, which is an undulating area of low relief except for the high ranges of Jabal Fezzan that rise more than 300 m above the surrounding land surfaces. On the west, north of the Hoggar area, is the Edjeleh anticline, a north-south structural feature just west of the Algerian-Libyan border, in which the upwarped basin strata separate the Murzuk basin from its western extension, the Polignac basin. The Murzuk basin contains thick sequences of predominantly clastic Paleozoic rocks and some marine beds.

Northeast of the Murzuk basin is the Brach-Ben Ghenema uplift, a northwest-trending structural feature (Fürst and Klitzsch, 1963) that separates the basin from the small Dor el Goussa basin. The eastern limit of the Murzuk basin is the Jabal Ben Ghenema, a high, rugged mountainous massif. This and the Dor el Goussa form the more prominent part of the northeast-trending ranges in south-central Libya. Several northeast-trending faults in the same mountainous area extend north from the Republic of Niger to about the Jabal Al Harūj al Aswad volcanic flows.

Farther east is the Tibesti-Harūj uplift (Fürst and Klitzsch, 1963), an area of present moderate relief between the Jabal Ben Ghenema-Dor el Goussa area and the Jabal Eghei that extends from the Tibesti area to the Jabal Al Harūj al Aswad, Sarīr Tibesti. This seems to have been a vast low area on the crest of a broad anticline, and it was into this low area that the Eocene seas penetrated so deeply into the tableland.

Farther east in south-central Libya are the Jabal Eghei and the Tibesti Mountains massifs that in the

FIGURE 34.—Beheaded wadis on top of the Acacus Mountains in southwestern Libya that look like hanging valleys. Photograph taken at about 50 km north of Ghāt looking east. In the foreground is the Tanezzuft valley.

northern Chad rise to the highest points in the Sahara, just more than 3,400 m (about 11,200 ft.) above sea level. These mountain massifs continue for several hundred kilometers into the Republic of Chad and form the western limits of the Cufra basin. The Cufra basin extends across southeastern Libya to the Egyptian-Sudan border and from the Jabal Dalma area, north of Cufra, southward into the Republic of Chad (fig. 39). Not much is known about the extent of sedimentation in this basin, but the basin probably contains a thick sequence of predominantly clastic sediments and some marine beds.

In the northeastern part of Libya, in northern Cyrenaica, the high Jabal al Akhḍar plateau is limited on its north and west side by abrupt slopes in the form of successive faultline escarpments and terraces, which were formed by later processes of marine erosion (Hey, 1956). This high upland slopes gradually to the east, forming a hamada-type surface, the Marmarica, between the high mountain areas and the Egyptian border. Farther south the Jabal area slopes to the south, forming a hamada-type surface, Baltat, which grades southward into the vast desert area of Cyrenaica that extends beyond the distant southern border of Libya. This monotonous desert is broken only by the small scattered but high mountains of Jabal Dalma area, in east-central Libya and the Jabals Arkenu and Awenat near the Sudan-Egyptian border.

The Jabal al Akhḍar plateau is a northeast-trending anticline, which plunges sharply to the northeast and gradually to the southwest. There are northerly dips north of the axis, but the strata generally dip to the south; to the southwest the dips gradually decrease, so that near the Sirte area the beds lie almost flat, but in the areas of folds and faults variable dips may be observed.

Orogenic movements that probably began in Oligocene time continued into Miocene time and were probably responsible for the exposure of the Cretaceous inliers at Gesscia and Jardas al 'Abīd.

Migliorini (1925) described a gentle anticlinal fold (to the south of the Gulf of Bomba and not on the trend of the Jabal al Akhḍar anticline) the axis of which runs almost parallel to the coast and passes through a point about 5 km southwest of Tobruk.

Several faults occur within the Cyrenaica area, but the presence of two major faults that follow or parallel the upper and lower escarpments has been a subject of controversy among oil company geologists. However, many geologists suggest, and the present writer believes, that the Jabal escarpments are actually faultline escarpments and that the terraces were formed later by processes of marine erosion. It is thought that a major fault follows the lower escarpment to the northeast of Benina and can be traced to Tolemaide; another fault follows the upper escarpment and can be traced from the Barce area both to the southwest and to the northeast. This concept was adopted in compilation of the geologic map of Libya (pl. 2). Other faults run parallel to the coast between Derna and the Gulf of Bomba and between Cirene and El Atrun (Al Athrūn). In the eastern Cyrenaica, Marmarica, two major east-west faults parallel the coast and extend almost to the Egyptian border. These faults follow the escarpment lines and are probably responsible for the present relief in the area.

Broadly speaking, northeastern Libya south of the Jabal al Akhḍar is a basement platform, the Cyrenaican platform, on which Paleozoic, Mesozoic, and Tertiary sediments were deposited.

The Sirte area, in north-central Libya, is a steppe (high plain) with many fault-controlled hills and ridges more than 100 m above the general land surface and many north-trending wadis. South of this plain the volcanic massifs of Jabal Al Harūj al Aswad rise more than 300 m above the land surface. The Sirte area is tectonically a northwest-trending elongated basin with major structural features trending northwest. It is delimited on the west by the Hun graben, which separates it from the Jabal area and the Hamada basin. The Sirte basin extends from the Gulf of Sirte southeastward into the Sarīr Calanscio and the Calanscio Sand Sea in central Cyrenaica where it forms the southern and western boundaries of the Cyrenaica platform. Several northwest-trending faults in the area

probably reflect the original block faulting of the basement rocks beneath the basin. This basin was probably formed initially during Late Cretaceous time and is filled by several thousand feet of sediments ranging in age from Late Cretaceous to late Tertiary.

MINERAL RESOURCES

IRON AND MANGANESE DEPOSITS

SHATI VALLEY IRON DEPOSIT

LOCATION AND ACCESSIBILITY

The only known large iron deposit occurs in Carboniferous strata in the central part of the Shati Valley area in north-central Fezzan. The valley is an east-trending depression about 180 km long and between 10 and 15 km wide. It is bounded on the north by the Gargaf, a region of extremely precipitous ground having steeply sloped hills. To the south, the valley is bordered by the Ubari Sand Sea.

About 100 km of secondary road connects the area to the newly completed paved Fezzan road, at a point about 500 km from the coast. In general, the area to be crossed is fairly level, with the exception of Jabal as Sawdā' which is but slightly elevated. Distance to the nearest potential ports, the little towns of Sirte and Buerat, is about 530 km airline.

NATURE OF INVESTIGATIONS

Occurrence of iron ore on the surface near Mahruga in the Shati Valley was first reported by Desio (1943, p. 265). Desio described the occurrence as hematite beds 1 m thick in Paleozoic rocks. He also stated that the occurrence is too far from commercial facilities for practical utilization.

Muller-Feuga (1954, p. 311–320) outlined the geology of the Shati Valley, gave a brief description of the iron deposit, and presented the results of chemical and differential thermal analyses and photomicrographs of selected specimens. Some of the results of this work are incorporated later in this report. Muller-Feuga reported that the deposit extends over large areas and is made up of several beds that crop out between Guira and Ashkada. He noted an oolitic zone about 1 m thick that can be easily followed and estimated a visible tonnage of 5 to 10 million tons. He stated, however, that taking into account the possible vertical and lateral extension of the beds, the estimated tonnage could be increased tenfold. He concluded that owing to transportation costs from Fezzan, no deposit, even if it were large, could be exploitable.

The present writer visited the Shati Valley area early in 1955 during a geologic reconnaissance of Fezzan. Iron-rich material was noted from dug wells near Tārūt, grab samples of which analyzed 45 percent iron. Later investigations indicated the presence of extensive iron-bearing beds several meters thick. Detailed study of the area was made from January 1957 until July 1958 in cooperation with the Libyan government. A geologic map (pl. 7) of the entire Shati Valley area was made at a scale of 1:40,000.

STRATIGRAPHY AND STRUCTURE

The Shati Valley is bordered on the north by the Gargaf arch, an east-trending anticline that constitutes part of the northern boundary of the Murzuk basin. Here, the Paleozoic rocks have a general easterly trend and consist of Cambrian and Ordovician, Devonian, and Carboniferous rocks. The succession of the older to younger beds is from north to south. Tertiary continental limestone, 10 to 15 m thick, discordantly overlies the Devonian and Carboniferous rocks. The valley floor is composed principally of surficial Quaternary deposits of gravel, alluvium, and sand. Carboniferous rocks crop out through this surficial cover in some places (pl. 7).

The uppermost strata of the Lower Carboniferous rocks (Tournaisian) consist of markedly lenticular shallow-water deposits of light-red and brown sandstone, gray and brown shale, and limonitic claystone. These beds grade upward into continental beds of light-brown and gray sandstone interbedded with green and gray shale. An oolitic chamosite-limonite bed about 1 m thick occurs near the contact of the continental unit. These continental beds grade upward into marine beds of Viséan Age. Dark-colored organic beds at the base of the marine units are overlain by variegated shale and interbedded gray and white sandstone. The most conspicuous unit of the Carboniferous rocks is a group of hematitic beds, near the base, that constitute the iron deposits of the Shati Valley area (see pl. 4*G*).

The basalt flows 10 km north of Brach were probably associated with the Jabal as Sawdā' Tertiary volcanic activity, which might be responsible for the later introduction of manganese minerals into the iron-bearing beds along fault fractures.

The main structural feature is an east-trending anticline, the Gargaf arch, north of the area. The rocks of the region strike about N. 80° to 85° E. and dip 1° to 3° S., but local flexures are numerous, and beds may be found with greater or lesser dips. East of the area the beds strike northeast, and west of Gotah they strike east, swinging to a northwesterly trend farther west.

The fault and fracture system in the area is generally parallel to the strike of the beds and is probably related to the Gargaf arch. Major faults are nearly vertical, but the vertical displacement along them has not been determined. Small faults and fractures are common in

the vicinity of larger faults. Minor folding may be observed near Sheb (As Shabb), Duessa (Ad Duwāysah), and west of Gotah. Slumping, associated with vertical fractures that parallel the strike of the beds, is evident north of Guira. Some fractures are filled with indurated sandstone and stand out as conspicuous dikelike prominences (fig. 35). Two thin sections of these fracture fillings show (Jewell J. Glass, written commun., 1963) that the sandstone is composed of dusty angular to subangular poorly sorted loosely packed quartz grains. Interstices are filled with limonite and hematite. Patches of carbonate and a black material, probably manganese oxide, occur sparingly. The quartz grains have been enlarged by authigenic outgrowth, a thin line marking the boundary between the old dusty quartz and the clean clear outgrowth.

FERRUGINOUS ROCKS

The iron-bearing beds of the Shati Valley are in the lower 50 m of the Tournaisian strata. These rocks consist of a shallow-water deposit of markedly lenticular character typically composed of light-red and brown sandstone and greenish-gray and brown shale and claystone, commonly limonitic. The most conspicuous unit, the group of beds consisting of massive hematitic siltstone and oolitic to finely granular hematitic rocks, constitute the iron deposits of the Shati Valley area. These hematitic beds persist with remarkable regularity

FIGURE 35.—Dikelike fracture filling in the Shati Valley area in a wadi about 15 km east of Tārūt; note the slight vertical offset of the iron-bearing beds. Photograph taken looking west.

FIGURE 36.—Part of a hematitic bed exposed north of the road about 42 km east of Brach, near Sheb and the eastern limit of the explored area; the outcrops can be followed about 15 km farther east.

for about 100 km along the valley from a point west of Gotah to more than 50 km east of Brach (fig. 36). Farther east the beds thin out and become irregularly lenticular; to the west of Gotah, transition into a ferruginous sandstone facies takes place.

The iron-bearing beds are exposed in a zone 2 to 3 km wide. Because the iron is believed to have been deposited over a large area, it may persist some distance farther south under the cover of younger strata. (See pls. 4*G* and 7).

Surface outcrops and drill-hole data indicate that the thickness of the iron-bearing beds is variable. At Tārūt in the western part of the area, they are about 10 m thick (fig. 37). In the central part of the deposit, the beds are 2 to 3 m thick and are intercalated with shale and siltstone (fig. 37*C*). In the eastern part of the deposit, a massive hematitic bed as much as 11 m was penetrated during drilling. The average thickness of the iron-bearing beds within the whole area described is thought to be about 5 m.

TEXTURE AND MINERALOGY

The ore [8] is oolitic or granular to compact and in places occurs as an irregular permeation or interstitial filling of clastic rocks. Oolitic ore is the most common.

Oolites are chiefly composed of hematite and chamosite and to a lesser extent of limonite and siderite. The larger oolites are as much as 2 mm in diameter and are spherical or ovoid. Almost all the thicker ore

[8] In this report the word "ore" is used in the same sense as in "Webster's New International Dictionary," 1928, p. 1517, which defines ore as "a native compound containing one or more metals."

A

B

C

FIGURE 37.—Exposures of hematite-bearing beds in Shati Valley, Fezzan. *A*, Panoramic view of the hematite-bearing beds near Tārūt that constitute the ore bed. The base of the zone is obscured by alluvium. The buttes are capped by a Tertiary continental limestone that unconformably overlies the Carboniferous rocks. Note left center where erosion has removed the bed. *B*, Hematitic beds about 2 m thick exposed in wadi cuts southwest of Tārūt about 40 km west of Brach. Drilling in this area penetrated about 10 m of iron-bearing beds that averaged over 45 percent iron. The thin white beds are gypsum. *C*, Iron-bearing beds north of Brach. The ledge-forming dark bed is richly hematitic; the light-colored beds beneath it are quartzose siltstone and hematitic claystone.

beds are oolitic, with variation in oolite size, and in places the oolites grade into a finely granular material. A thin section of a core sample from the western part of the area shows some of the oolites to be composed of concentric bands of hematite and limonite in a nearly opaque matrix of hematite and limonite (fig. 38*B*). In another sample from the west-central part of the area, siderite makes up the major part of the groundmass, and a few patches of manganese oxide are present. Apparently the rock was once oolitic, but some of the oolites have disappeared and left open cavities. Some of the holes are filled with chamosite. A few grains of quartz are scattered through the groundmass, and one large quartz grain can be seen in the center of the thin section. (See fig. 39*C*.)

ORE MINERALS

The ore minerals vary in kind and form in different parts of the deposit. They are, in order of their abundance, hematite, goethite or limonite, chamosite, and siderite. They all occur in oolitic form embedded in a matrix of ferruginized claystone or siltstone. The hematititic ore is dark red or purple. but shades of brown, yellow, and orange are common where the ore is altered to limonite. The chamositic ore is grayish green. Jewell J. Glass (written commun., 1956) identified (1) Chamositic oolites and oolites of limonite or goethite in a matrix of chamosite, (2) oolitic hematite in siderite-chamosite matrix, (3) hematite-impregnated concretions in claystone, (3) clayey shale impregnated with limonite and hematite, (5) oolitic hematite rock with inclusions of white kaolinite, (6) hematite as an alteration product of siderite-chamosite, and earthy limonite as alteration of the original hematite, and (7) pseudomorphous limonite after oolitic chamosite and siderite. (See figs. 38, 39, 40).

From cores and petrographic analysis of several core samples of different boreholes the following observations are made:

1. In the eastern part of the deposit, the ore minerals are chiefly hematite, limonite or goethite, and chamosite. These minerals occur as oolites in a matrix of one or more of the same minerals. The oolites apparently become gradually smaller downward, giving way to a finely granular material with few or no oolites.
2. In the central part of the area, from west of Brach to the vicinity of Mahruga, siderite is the chief ore mineral, with lesser amounts of chamosite, limonite, and hematite. Oolites of siderite occur in a matrix of siderite. (See pl. 8.)
3. In the western part of the area, hematite and limonite are most abundant, both as oolites and in the matrix. Oolites become smaller downward and give way to a granular or to an earthy material. However, the graduation in oolite size is not as pronounced as is in the eastern part of the area.

Muller-Feuga (1954) made differential thermal analyses of several outcrop samples in the area. Samples were taken from the sandy base, the oolitic beds, and the granular material on top. He reported the presence of stilpnosiderite and geothite in the lower beds and of oxides, goethite, and hematite partially hydrated in the upper and middle beds. Most of the analyses indicated traces of aluminum monohydrates. He further reported that petrographic analyses and polished sections indicated the presence of boehmite. The analyses quoted by Muller-Fuega averaged about 5.5 percent Al_2O_3. This corresponds very closely to the analyses of several hundred samples collected by the writer.

The present writer believes that alumina is present in the ore as a normal constituent of chamosite, but elsewhere it probably occurs as an ingredient of some clay mineral such as kaolinite or maybe boehmite.

ASSOCIATED MINERALS

North of Guira, near Dabdab, 14 km northeast of Brach, numerous veinlets of manganiferous material occur along a fracture zone. The manganiferous veinlets cut across the beds in an area of about 1 km long and 100 m wide; here the beds have become dense and are indurated over a visible thickness of about 25 m. Locally, the oolitic structure has been retained within the hematitic lenses. Diamond-drill hole 21 in this area (pl. 9) was not completed, and therefore no assay values were obtained for the area. Qualitative chemical analyses of grab samples indicate a manganese content.

Manganiferous seams up to 1 cm thick are found west of Sheb and north of Brach, and they are also related to fault fractures in the area. Manganiferous sandstones that may contain as much as 2 percent manganese also occur below the iron-bearing beds in the central part of Shati Valley.

In most areas the strata at the base of the iron-bearing beds are highly impregnated with a petroliferous material in the form of a tarlike substance or asphaltite. This same material is found, sparsely or in abundance, in other strata below the iron-bearing horizon, and also occurs as "dead" oil in some of the surface outcrops. (See "Petroleum resources," p. 93.)

Vertical tubules noted in most of the cores are filled with a clay mineral, probably kaolinite, that is ferruginized. Locally these tubules are associated with gypsum.

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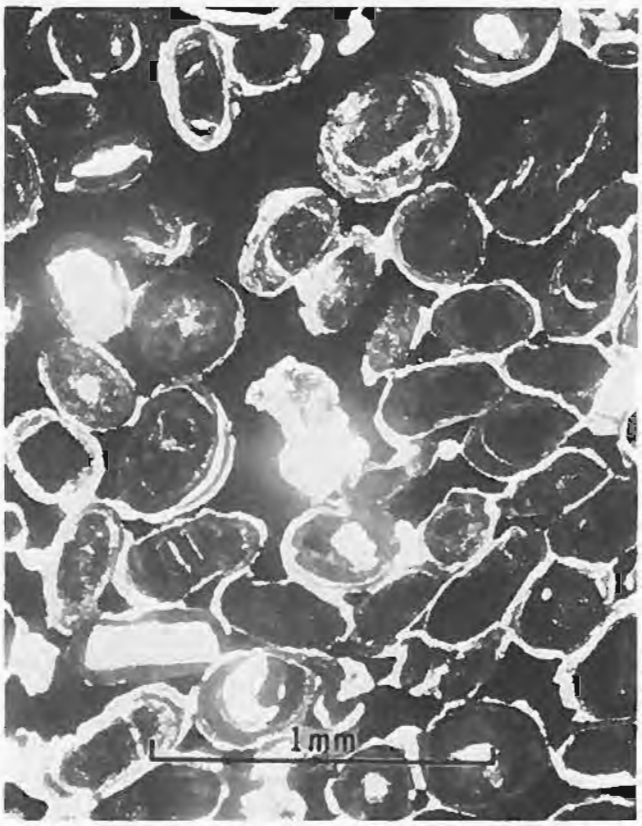

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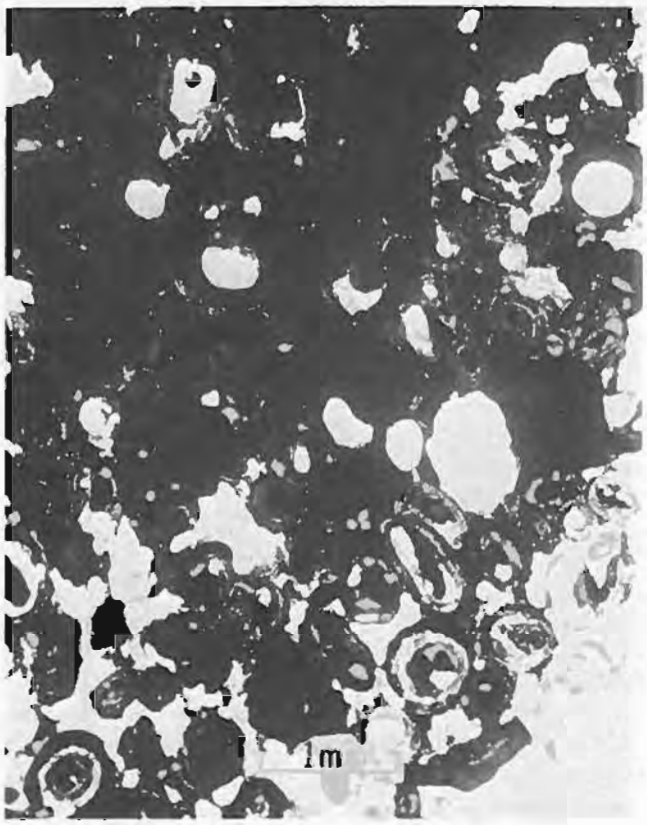

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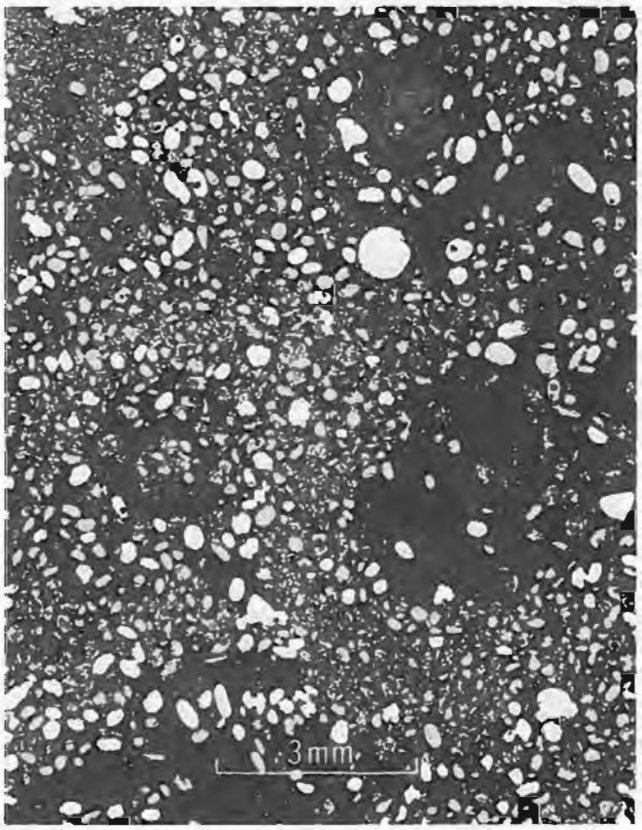

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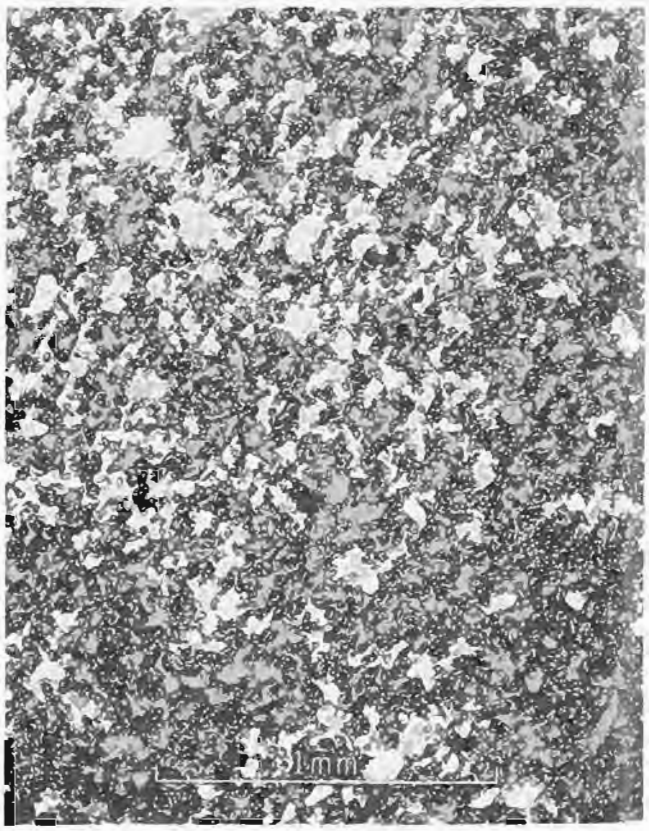

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IMPURITIES

Quartz is the main impurity of the ore and is present in varying proportions. It occurs as sparsely scattered quartz grains embedded in hematitic rocks or in abundance in ferruginous siltstone and sandstone units. These sandstones differ in degree of impurity, in texture, and in cementing material. Jewell J. Glass (written commun., 1963) reports that:

1. Commonly the texture of the rock is smooth, and the composition is homogeneous; the sand grains are medium, well sorted, and closely packed; the cementing material is hematitic or limonitic.
2. Locally the sandstones are composed of heterogeneous quartz and detritus, cemented by limonite. The detritus includes mineral grains of volcanic origin and from sedimentary sources, such as mud rock.
3. Near Tārūt, in the western part of the area, arkosic sandstone is common. The quartz is poorly sorted and is composed of subangular grains. Other minerals are orthoclase, oligoclase, and a few plates of muscovite, all bound in a matrix of ferruginous clay and chamosite.
4. Sideritic sandstone is common in the west-central part of the area described.
5. Locally in the west-central part of the area, the sandstone consists of well-sorted angular to subangular sand grains. The grains are loosly packed, and the interstices are filled with manganese oxide.

Phosphorus and sulfur are present in the ore in appreciable quantities. The ore ranges from 0.1 to 2.0 percent P_2O_5 and rarely as much as 4.0 percent P_2O_5.

The ore over the entire area averages about 0.8 percent P_2O_5.

FIGURE 38.—Iron ores in Shati Valley area, Fezzan. *A*, Photomicrograph of goethite ironstone from outcrops south of Tārūt. Dark-brown oolites show indistinct concentric banding and nearly opaque nuclei of concentrated goethite. Some oolites are detached from the matrix by shrinkage; plain polarized light. *B*, Photomicrograph of hematite ironstone from 9- to 10-m depth in drill hole 8 near Tārūt. The oolites are red, concentrically banded with brown limonite, and translucent in thin section. The matrix is nearly opaque hematite and limonite; crossed nicols. *C*, Photomicrograph of siderite-chamosite ironstone from 11- to 12-m depth in drill hole 11 south of Mahruga. The groundmass is granular reddish-brown siderite with fine to coarse grains of quartz. The oolites are greenish-gray chamosite; crossed nicols. *D*, Photomicrograph of siderite ironstone from 34- to 35-m depth in drill hole 14 northeast of Agar (Āgār). The siderite consists of reddish-brown granules of iron carbonate, dotted sparsely with manganese oxide and interstitial chamosite; plain polarized light.

In some parts of the area, chemical analyses show a downward increase of phosphorus content of the ore. No phosphatic minerals were identified in this section, and the phosphorus is thought to be supergene.

The ore ranges from a trace to 3.5 percent elemental sulfur and averages about 0.3 percent sulfur over the entire ore body.

Gypsum and pyrite are present in the ore and account for the greater part of the sulfur. Locally beds of gypsum, as much as 1 cm thick, occur within the hematitic beds in the outcrop (fig. 37*B*); and in some of the core samples gypsum is noted in association with the tubules previously mentioned. Pyrite is found sparsely or in abundance and is invariably associated with petroliferous or with carbonaceous material. Pyrite occurs more abundantly in or near the strata that are impregnated with asphaltite. With very few exceptions, the samples showing high sulfur content of the ore are within 1 or 2 m of the surface (table 4). From this zone downward, the analyses show a decrease in sulfur content of the ore.

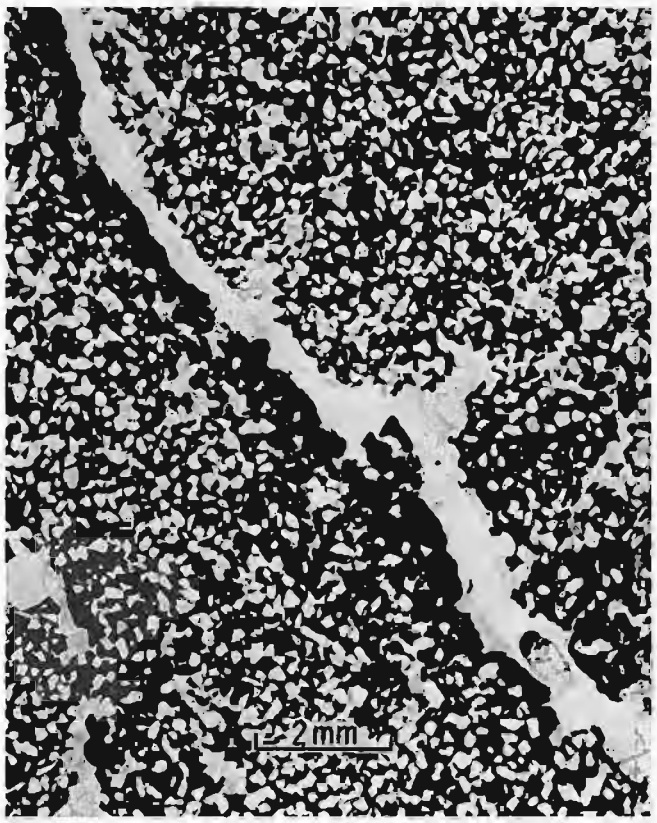
Gypsum in the ore is thought to be supergene and is probably formed by capillary migration long after the iron deposition. Also, sulfur was probably introduced along with petroliferous material and deposited as pyrite. The presence of organic matter may have induced the precipitation of some of the pyrite (Castano and Garrels, 1950, p. 755).

GENESIS

The iron deposit of the Shati Valley area is comparable to those deposits described as marine oolitic iron ores. Lindgren (1933, p. 272–273), summarizing previous work, described the Clinton iron ores as beds and lenses deposited in a shallow-water marine environment. They are composed of ferruginous clastic rocks and oolitic hematite embedded in a calcite matrix. He noted that the deposit also contains ores composed of marine fossil fragments coated with or replaced by hematite.

In discussing the minette deposit of Lorraine, France, Lindgren (1933, p. 275–277) cited the work of Cayeux, who described the ores as being oolitic and composed of limonite, siderite, chlorite, and hematite in a complex relationship. The ore was noted as occurring in somewhat lenticular beds.

In the Wabana iron deposit in Newfoundland, originally studied by O. A. Hayes and referred to by Lindgren (1933, p. 277–278), the ore is represented as being composed of fine-grained oolites of hematite and chamosite or alternating layers of hematite and chamosite. The oolites occur in a chamosite, hematite, quartz, or siderite matrix.



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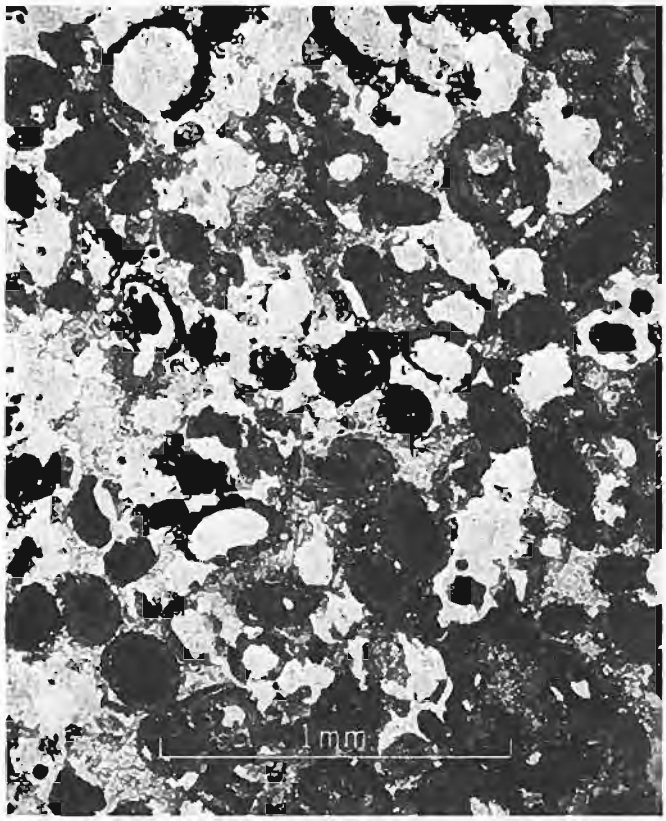

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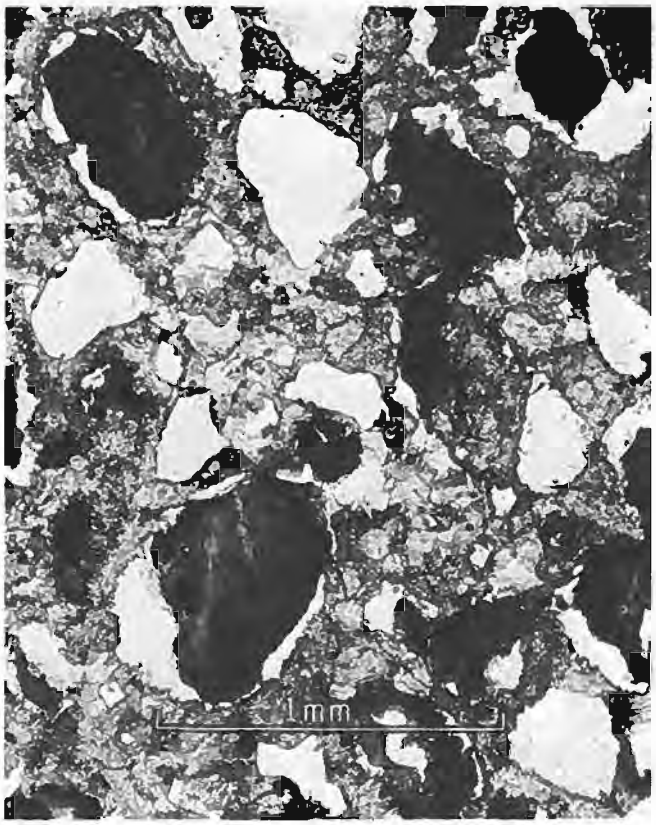

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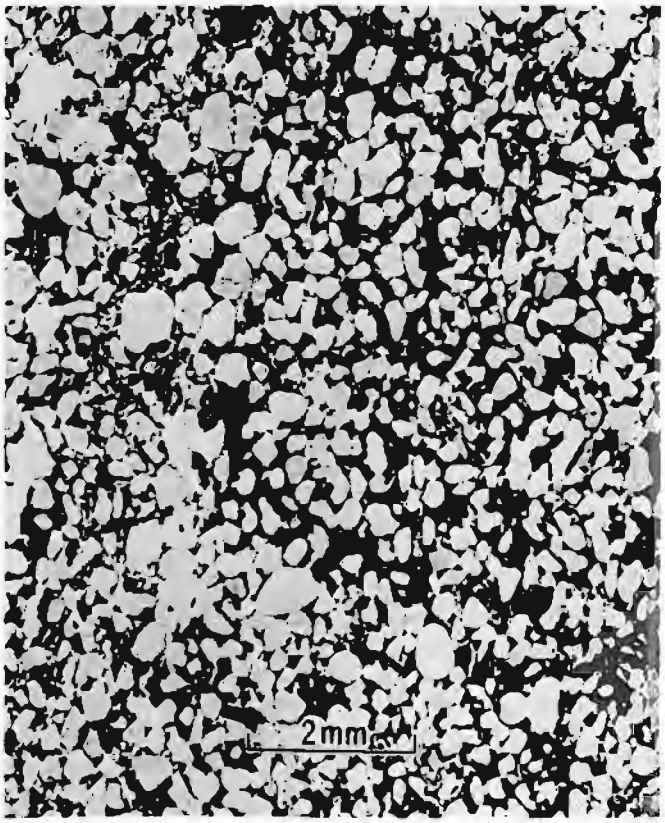

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The general similarity of mineral types and sedimentary structures of the marine oolitic iron deposits described above to that of the Shati Valley deposit is evident. No volcanic activity can be related or is associated in time or space with the iron deposit. Tertiary volcanic activity probably had little influence, for it occurred long after the iron was deposited. The only possible effect of the Tertiary volcanic activity would be introduction of manganese minerals along faults and fractures into the hematitic beds in some parts of the Shati Valley area.

The present writer believes that the iron was deposited by direct sedimentation in a shallow-water or near-shore environment over large areas.

The Lower Carboniferous rocks of Tournaisian Age occur in southwestern Libya around the Murzuk basin (fig. 41), an area of about 200,000 sq km. In the northern part of the Murzuk basin, the Tournaisian rocks are exposed in the Shati Valley area and at Awenat Wennin. In the western part of the basin, they crop out east of Serdeles and continue southeastward toward the southern boundary of the basin; near long 14° E. the beds swing northeastward and are well exposed at Jabal Ben Ghenema in the eastern part of the basin.

The lower Tournaisian rocks, well exposed in the Shati Valley area, consist of markedly lenticular shallow-water strata. In this area, for about 180 km, the oolitic structure of the hematitic beds or lenses can be seen throughout the entire exposures. Other exposures of the lower Tournaisian rocks at Awenat Wennin, southeast of Serdeles, and at Jabal Ben Ghenema are also shallow-water or near-shore facies. These outcrops, several hundred kilometers apart (fig. 41), display oolitic structures and are ferruginous. The continuity of an oolitic ferruginous zone over such a large area is remarkable.

The present writer believes that the iron was deposited over a very large area, probably at least throughout the margins of the Murzuk basin. Subsurface information obtained from private oil companies shows that at least one well (fig. 41) penetrated a highly ferruginous bed in the Tournaisian rocks in the northeastern part of the Murzuk basin. Practically all the water wells drilled in the Shati Valley area have also penetrated a highly ferruginous bed at depth.

The older strata of Cambrian and Ordovician age surrounding the Murzuk basin are generally clastic sedimentary rocks, mostly sandstones that are somewhat ferruginous. Today, in most areas, these older strata overlie the basement metamorphic and granitic rocks. The Cambrian and Ordovician ferruginous sandstones could have been the source rock from which the iron was derived and carried into the Murzuk basin by rivers and streams.

Therefore, it is assumed that the Early Carboniferous seas in southwestern Libya contained much more iron than the present-day oceans, and the iron was probably deposited over a large area and under a shallow-water marine or near-shore environment. The shorelines fluctuated back and forth, and the facies changes and formation of the more ferruginous beds such as the Shati Valley iron deposit was probably due to this oscillation.

Available data are insufficient to present a clearcut picture of the conditions under which the Shati Valley iron deposits were formed. Examination of outcrops by the present writer, description of rocks, and determination of the ore minerals by Jewell J. Glass in 1963 show an interesting pattern of mineral distribution in the Shati Valley area. (See pl. 8.) Whereas hematite, limonite, and chamosite are the chief ore minerals in the eastern and western limits of the explored area, siderite both as oolites and as matrix is the main mineral constituent in the central part. Hematite and chamosite were seemingly deposited closer to the shoreline and in a shallower water than siderite.

The present writer believes that—

1. The Shati Valley iron is syngenetic and was deposited by direct sedimentation under shallow-water or near-shore marine environments.
2. The iron in the form of ferrous bicarbonate in solution or as hydrosol in colloidal suspension was derived from the weathered land surfaces and transported by rivers or streams into the basin.

FIGURE 39.—Iron ores in Shati Valley area, Fezzan. *A*, Photomicrograph of sandstone from 36- to 37-m depth in drill hole 15, north of Agar. Spaces between loosely packed grains of sand are filled with manganese oxide. The quartz sand is well sorted, angular to subangular; crossed nicols. *B*, Photomicrograph of hematite-siderite ironstone, from 17- to 18-m depth in drill hole 16 west of Brach. The siderite grains are compacted and form a matrix for hematite oolites. The cavities are filled with fine-grained siderite; plain polarized light. *C*, Photomicrograph of siderite-hematite ironstone, from 14- to 15-m depth in drill hole 16 west of Brach. The coarse granular siderite matrix contains large oolites of hematite, some of which are partly replaced by siderite and some partly enclosed by pale-green chamosite. The cavities are filled with colorless siderite and pale-reddish-yellow chamosite; plain polarized light. *D*, Photomicrograph of hematitic sandstone from 2- to 3-m depth in drill hole 18 north of Brach. The quartz grains are well sorted and rounded to subrounded, loosely packed and cemented by dark-red hematite; crossed nicols.

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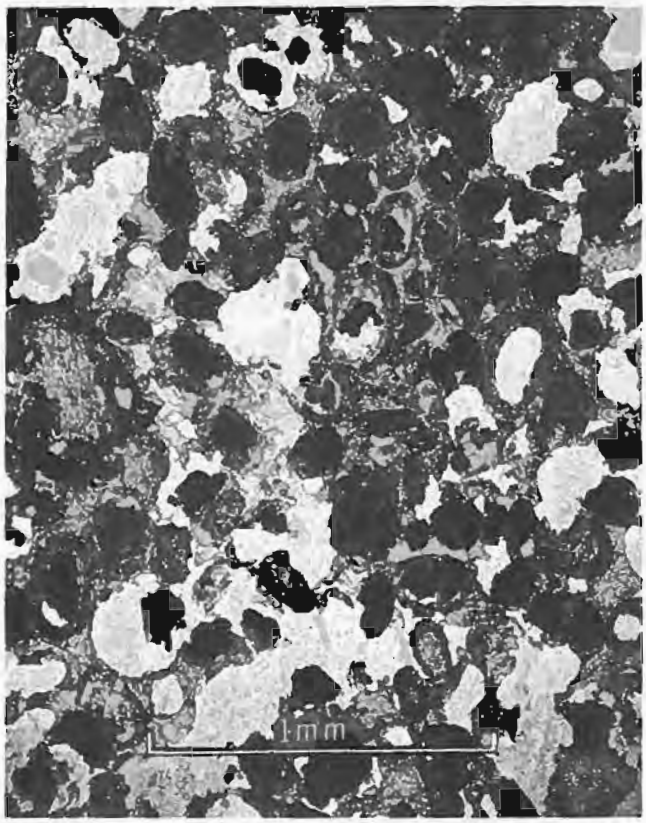

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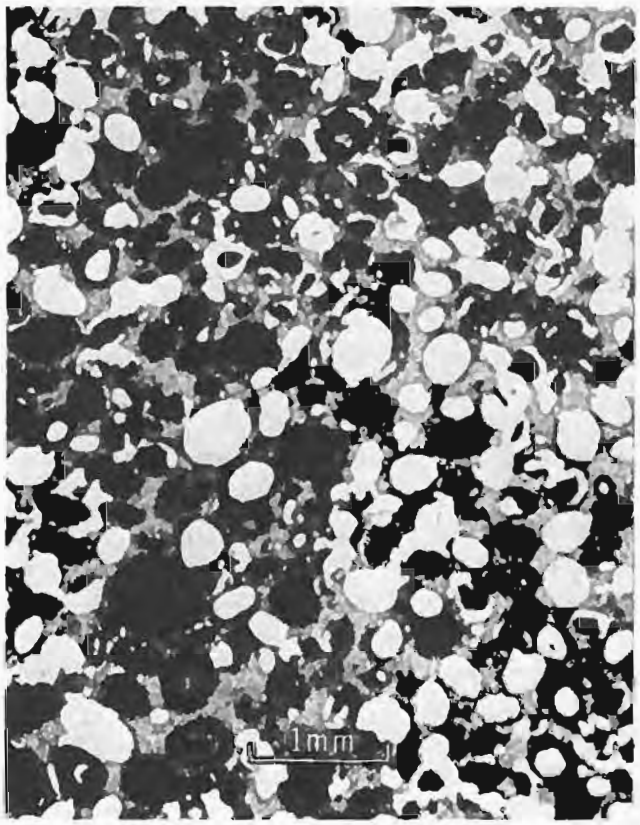

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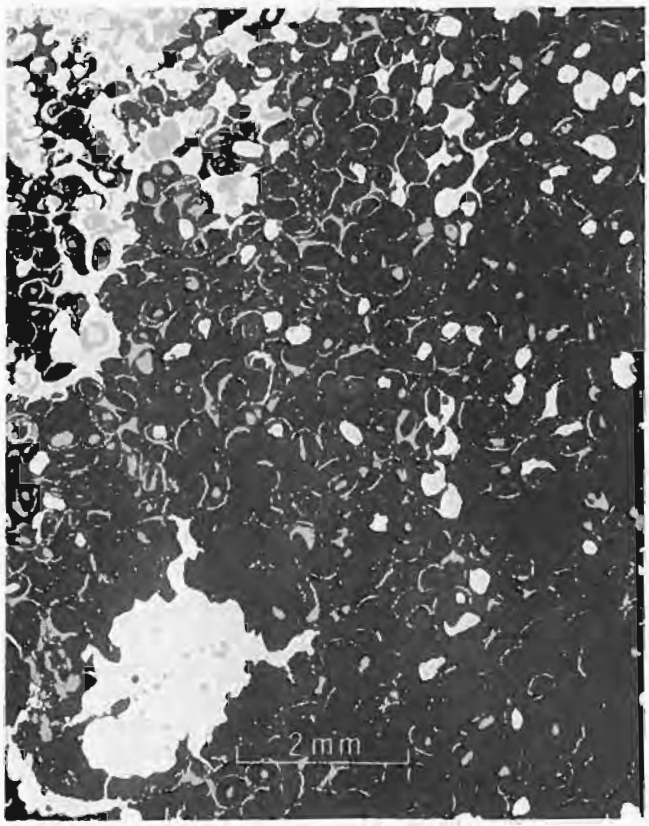

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3. Upon reaching a marine or near-marine environment, a series of complicated chemical reactions took place; hematite and colloidal iron silicate, some of which later oxidized to hematite, precipitated, or—accepting Alling (1947, p. 1012) sequence of deposition—
   (*a*) Iron-bearing waters introduced iron compounds into the pore spaces between detrital grains.
   (*b*) Iron was deposited as limonite.
   (*c*) Alumina and silica were introduced by the waters, depositing chamosite and hematite.
4. In the central and deeper part of the basin, siderite was deposited as a primary mineral.
5. The oolitic structure of the rocks is probably the result of wave and current action on the materials while in colloidal state.
6. The irregular permeation of hematite through some of the rocks may be a diagenetic replacement, as described by Alling (1947, p. 1015).

EXPLORATION AND GRADE OF ORE

Preliminary exploration of the Shati Valley iron deposit was done in 1955–56 by pitting in the Tārūt area and the collection of many samples along the entire exposures. In 1957–58, 42 test holes were drilled along the strike of the iron-bearing beds. Drilling was done by an inexperienced crew. Test holes were drilled about 2 km apart along the strike of the beds. Most of the drilling sites were selected on the basis of geological information so as to obtain core samples of the ore body with a minimum of drilling through the overburden. In some holes difficulties in drilling and inadequate samples necessitated drilling another hole near the original site. Some holes were drilled several meters deep into the bedrock in order to check the nature of the underlying beds; some sites were selected so as to collect samples of the overlying ferruginous beds as well as the main ore body; some sites were selected so as to determine the width of the ore body and the variation in grade and mineral content of the ore. Near Tārūt, in the western part and in one of the richer zones, several holes were drilled in an almost circular pattern to determine the variation in grade or mineral content. Three test holes were drilled in the western, central, and eastern parts of the ore body to collect special samples. These samples were sent by the Geological Department of the Libyan Government to Fried, Krupp Rohstoffe of West Germany for examination. Logs of 33 drill holes and detailed results of the chemical analyses have been reported (Goudarzi, 1962a).

Systematic sampling of test pits was unsuccessful, but grab samples of the materials range from 40 percent to 45 percent iron.

Outcrop samples in the area average about 45 percent iron in the western part, 40 percent in the west-central part, 45 percent in the central part, and 45 percent in the eastern part of the area. In general, the western and the eastern parts of the ore body are richer and thicker than the central part. (See pl. 9.) These zones contain about 525 million metric tons of iron ore averaging about 49 percent iron.

No definite pattern of vertical variation in grade of ore has been established. The chemical analyses of the cores and the average grades of various intervals are given in table 3. The average composition of these intervals is given on plate 9 and in tables 3, 4, and 5.

ORE RESERVES

The reserves reported here are indicated and inferred ore. The terms "indicated" and "inferred" conform to standard usage of the U.S. Geological Survey. They are defined as follows:

Indicated ore is ore for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projection for a reasonable distance on geologic evidence. The sites available for inspection, measurement, and sampling are too widely spaced, or otherwise inappropriately spaced, to outline the ore completely or to establish its grade throughout.

Inferred ore is ore for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition for which there is geologic evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred ore should include a statement of the special limits within which the inferred ore may lie.

FIGURE 40.—Iron ores in Shati Valley area, Fezzan. *A*, Photomicrograph of hematite ironstone from 1- to 2-m depth in drill hole 23 near Ashkada. Quartz grains cemented by hematite in a groundmass of hematite. The light-colored areas are quartz grains cemented by chamosite; plain polarized light. *B*, Photomicrograph of goethite-siderite ironstone from 9- to 10-m depth in drill hole 23 near Ashkada. Oolites of goethite are set in a matrix of reddish-brown fine-grained siderite, mottled with grayish-green chamosite. The oolites are brown, concentrically banded, and have dark-brown nuclei; plain polarized light. *C*, Photomicrograph of chamosite-limonite ironstone from 3½-m depth in drill hole 26 in eastern part of the deposit. This ore is greenish-gray chamosite mottled with oolitic hematite. The cavities are filled with nearly colorless chamosite; plain polarized light. *D*, Photomicrograph of oolitic goethite from 9½-m depth in drill hole 27 in eastern part of the deposit. The oolites are packed together in a dense mass and have opaque nuclei; the matrix is pale-grayish-green chamosite. The concentric bands are pale-brown limonite. Crossed nicols.

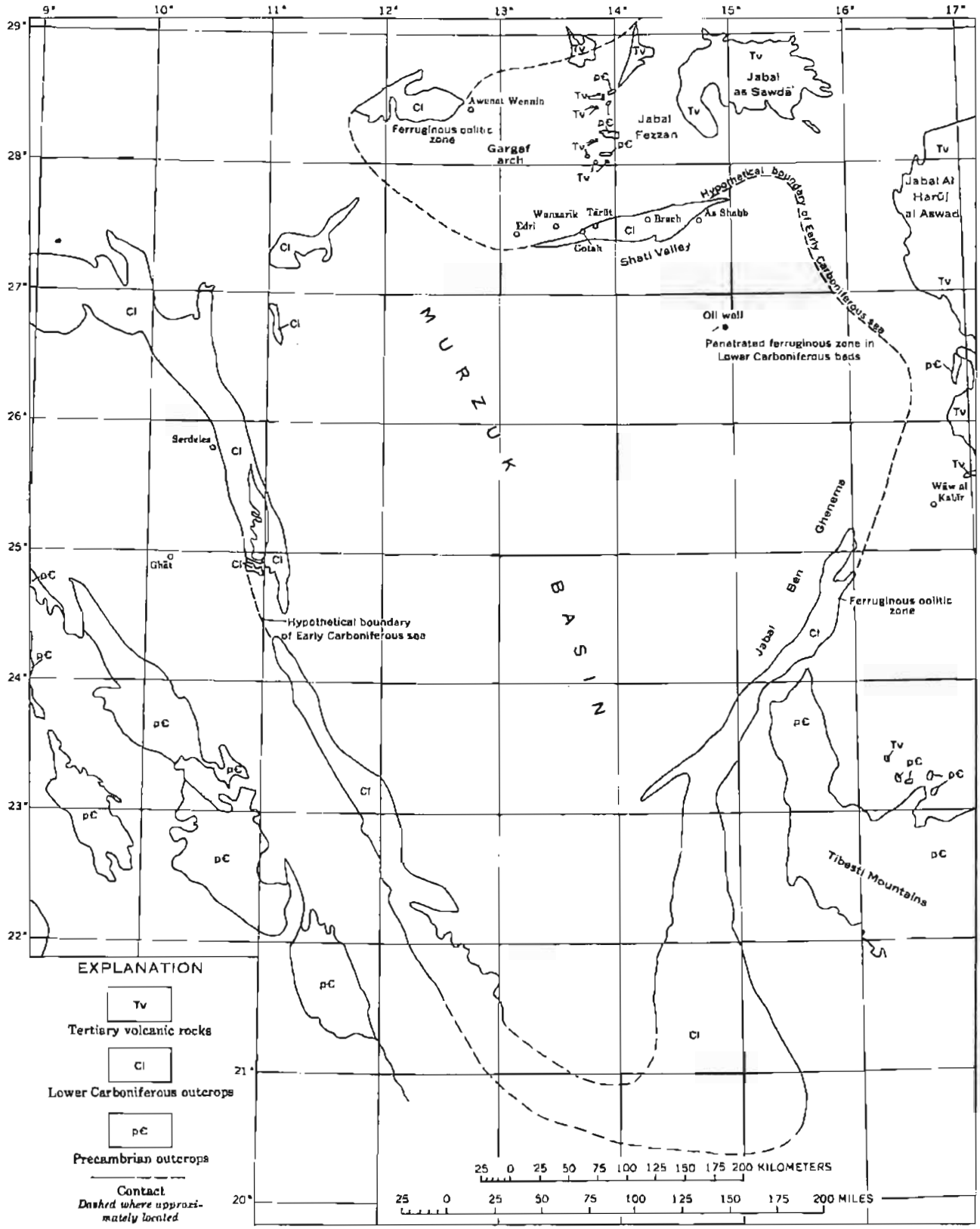

FIGURE 41.—Hypothetical boundary of the Early Carboniferous sea in the Murzuk basin, southwestern Libya and adjoining areas.

INDICATED ORE

Calculation of the Shati Valley indicated ore reserves and the determination of ore-block boundaries are based on drill-hole information, on surface outcrops, and on knowledge of the area gained in the course of geologic mapping. The amount of erosion which the iron-bearing beds have undergone was estimated so that a closer estimate of the reserves could be made.

The distribution and the concentration of iron ore along the outcrops, though differing somewhat, are fairly uniform over a large area. This fact, combined with the remarkable persistence of the iron-bearing beds throughout the deposit, seems to warrant the assumption that assay values and measured thicknesses of the cores can be extrapolated between drill holes.

The area is divided into 12 blocks; the width of each block is based on the north-south extent of the ore exposures plus an additional width for the ore underlying the strata to the south, within depths that would probably permit economic recovery. In most areas a maximum thickness of about 10 m of overburden to be removed is used in establishing the southern limits of the ore block. (See pls. 8 and 9.)

The thickness and grade of the ore in respective blocks are based on assay values of the cores. The thickness and assay values are assumed to extend proportionately between drill holes and throughout the entire area of the block, except where erosion has removed the bed. The average specific gravity of the ore, based on many determinations, is 2.72.

Plate 9 shows the location of the drill holes and includes columnar sections of thickness, lithology, and assay information for each of the cores in a typical area. (See also table 3.) Figure 51 also shows the assumed ore boundaries and the areas where the ore bed has been wholly or partly removed by erosion.

To outline any deposit, there must be a dividing line or a cutoff grade. In estimating the indicated reserves of the Shati Valley, all thicknesses and assay values of sampled intervals were considered. Generally, the lower cutoff grade for the vertical limits of the ore was placed at 25 percent iron. Above this limit combinations of grades and thicknesses were used in arriving at an average grade for a certain interval. (See table 3.)

A system of ore-reserve calculations practiced by many mining companies is used herein. For example, core X in block Y is divided into five sample units—A, 1, 2, 3, and B. In the calculations,

T_1, T_2, etc. equals thickness of units 1, 2, etc.

G_1, G_2, etc. equals grade of units 1, 2, etc.

g_1 equals average grade of units 1 and 2 combined.

g_2 equals average grade of units 2 and 3 combined.

t_1 equals combined thickness of units 1 and 2.

t_2 equals combined thickness of units 2 and 3.

A and B units assay less than 25 percent iron and therefore are not included. Computing for the total thickness (T) and average grade (G) of ore,

$$T_1+T_2+T_3=T$$

and

$$\frac{T_1\times G_1+T_2\times G_2+T_3\times G_3}{T_1+T_2+T_3}=G \text{ for the total thickness } (T)$$

$$\frac{T_1\times G_1+T_2\times G_2}{T_1+T_2}=g \text{ for thickness } t_1=T_1+T_2$$

$$\frac{T_1\times G_2+T_3\times G_3}{T_2+T_3}=g \text{ for thickness } t_2=T_2+T_3$$

TABLE 3.—*Analyses of core samples and grade of ores, Shati Valley iron deposits*

[Asterisk (*), composite grade for depth and thickness shown]

Depth (meters) From	Depth (meters) To	Thickness (meters)	Fe	SiO_2	P_2O_5	S	Al
		Drill hole 1					
0.00	0.64	0.64	28.14	37.81	1.49	2.06	3.78
.64	3.48	2.84	18.96	57.91	1.27	.83	4.35
3.48	3.73	.25	30.71	33.09	4.04	.04	5.54
3.73	4.17	.44	9.57	73.19	1.01	.06	2.54
4.17	5.00	.83	43.84	21.31	1.94	.21	4.56
5.00	5.78	.78	20.04	49.63	.86	.59	6.78
5.78	6.00	.22	41.89	22.57	1.37	.19	5.47
6.00	8.80	2.80	23.61	46.84	1.13	.54	5.12
8.80	9.00	.20	38.66	24.89	3.18	.20	5.06
*4.17	9.00	4.83	27.90	40.90	1.32	.41	5.33
		Drill hole 2					
0.00	1.00	1.00	44.94	16.52	1.22	1.65	1.56
1.00	3.00	2.00	41.44	20.27	1.03	.47	3.97
3.00	4.00	1.00	40.61	24.30	.63	.65	2.56
4.00	5.00	1.00	38.05	25.93	1.53	.56	4.82
5.00	6.00	1.00	38.90	31.04	.69	.90	.67
6.00	7.00	1.00	35.72	24.89	.82	1.92	4.41
7.00	8.00	1.00	45.85	14.55	.94	.18	4.70
8.00	9.00	1.00	45.79	20.40	1.40	.38	1.08
9.00	10.00	1.00	47.20	13.72	.87	.46	3.49
10.00	11.00	1.00	45.57	16.97	.75	.46	3.28
11.00	11.53	.53	40.86	25.84	1.14	.28	3.12
*7.00	11.00	4.00	46.10	16.43	1.06	.32	3.10
*.00	11.53	11.53	42.00	19.30	1.04	.78	3.14
		Drill hole 3					
0.00	1.00	1.00	28.86	35.88	1.95	2.48	3.47
1.00	2.00	1.00	41.64	29.86	.11	Tr.	Tr.
2.00	2.50	.50	41.47	28.02	.35	Tr.	2.62
2.50	4.00	1.50	35.75	36.51	.20	Tr.	.60
4.00	5.00	1.00	30.07	42.91	.23	Tr.	2.70
5.00	6.00	1.00	49.92	13.57	.16	Tr.	2.77
6.00	7.00	1.00	47.68	12.74	.15	Tr.	5.32
7.00	8.00	1.00	44.55	17.46	.33	Tr.	4.06
8.00	9.00	1.00	50.27	9.67	.31	Tr.	3.96
9.00	9.90	.90	54.48	8.61	.10	Tr.	1.48
9.90	10.37	.47	24.43	46.43	.12	Tr.	3.26
10.37	10.58	.21	42.59	15.95	.16	Tr.	7.60
10.58	11.63	1.05	20.79	50.22	.62	Tr.	4.42
*5.00	9.90	4.90	49.30	12.46	.21	Tr.	3.56
*1.00	10.58	9.58	42.74	23.70	.20	Tr.	2.66
		Drill hole 4					
0.00	0.60	0.60	25.21	38.95	0.28	None	3.87
.60	2.00	1.40	44.00	18.07	.80	...do.....	4.50
2.00	3.00	1.00	36.65	27.18	.16	...do.....	5.69
3.00	4.00	1.00	40.97	21.13	.59	...do.....	4.67
4.00	5.00	1.00	40.90	21.64	.49	...do.....	4.72
5.00	7.00	2.00	35.31	29.22	.35	...do.....	5.49
7.00	8.00	1.00	41.74	22.06	.55	...do.....	3.26
8.00	9.00	1.00	45.33	17.80	.54	...do.....	2.85
9.00	10.00	1.00	48.74	10.82	.72	...do.....	4.00
*7.00	10.00	3.00	45.34	18.89	.61	...do.....	3.37
*.60	10.00	9.40	41.12	21.74	.72	...do.....	4.52

TABLE 3.—*Analyses of core samples and grade of ores, Shati Valley iron deposits*—Continued

Depth (meters) From	Depth (meters) To	Thickness (meters)	Fe	SiO_2	P_2O_5	S	Al
Drill hole 5							
0.32	1.63	1.31	37.40	21.72	0.71	0.32	6.27
1.63	2.11	.48	35.08	24.33	.85	1.30	5.10
2.11	2.64	.53	42.34	14.78	.86	.21	6.70
2.64	5.00	2.36	33.26	29.78	1.60	.42	4.94
5.00	7.50	2.50	35.59	28.90	1.77	.57	3.82
7.50	10.40	2.90	42.26	17.19	1.19	.77	4.62
10.40	11.45	1.05	45.50	11.86	1.06	1.51	6.28
11.45	12.28	.83	30.07	40.55	1.18	.51	2.01
12.28	13.54	1.26	20.79	58.22	.77	.73	1.71
*10.40	11.45	1.05	45.50	11.86	1.06	1.51	6.28
*7.50	11.45	3.95	43.20	16.86	1.15	.97	5.06
*.32	11.45	11.13	33.35	22.70	1.30	.66	4.97
Drill hole 6							
0.00	2.00	2.00	33.54	31.90	1.01	1.62	3.65
2.00	4.00	2.00	31.33	33.69	2.46	1.56	3.85
4.00	6.00	2.00	32.61	29.82	1.88	1.87	3.41
6.00	7.73	1.73	30.71	30.85	1.70	1.97	4.17
7.73	9.00	1.27	45.80	13.05	1.07	.92	4.25
9.00	10.00	1.00	49.01	14.03	1.08	1.88	1.52
10.00	11.00	1.00	46.42	17.55	1.14	1.50	2.11
11.00	12.65	1.65	50.16	14.11	1.34	.82	1.05
12.65	13.50	.85	30.15	39.77	1.81	1.40	2.50
*7.73	12.65	4.92	48.04	14.62	1.11	.99	1.18
*.00	12.65	12.65	38.29	24.99	1.52	1.45	2.28
*.00	7.73	7.73	32.09	31.66	1.74	1.75	2.98
Drill hole 7							
0.22	1.70	1.48	21.07	41.39	0.94	3.99	2.94
1.70	2.20	.50	41.42	23.73	.99	.43	2.93
2.20	4.46	2.26	31.05	42.07	1.49	.98	1.36
4.46	6.65	2.19	27.39	49.90	.80	.52	.74
6.65	7.85	1.00	34.74	36.54	.91	.55	2.25
7.85	9.00	1.35	44.80	14.65	.92	.52	4.40
9.00	10.00	1.00	48.91	10.56	1.19	.42	2.53
10.00	11.60	1.60	50.78	10.32	.68	.28	2.54
11.60	12.15	.55	30.79	29.25	1.08	1.37	6.75
*7.85	11.60	3.95	48.26	11.84	.90	.39	3.17
*1.70	7.85	5.95	31.18	44.86	1.10	.69	1.41
*1.70	11.60	9.90	38.00	31.70	1.00	.57	2.12
Drill hole 8							
0.00	1.00	1.00	7.66	72.76	0.39	2.46	1.54
1.00	2.00	1.00	22.95	40.91	.97	3.44	5.18
2.00	3.00	1.00	32.70	36.11	1.36	1.02	1.67
3.00	4.00	1.00	31.02	34.44	.97	1.16	3.73
4.00	5.66	1.66	32.73	34.23	.90	1.14	3.97
5.66	6.20	.54	44.53	20.63	.97	.52	1.86
6.20	6.70	.50	34.47	31.36	1.14	.69	3.70
6.70	8.00	1.30	23.56	46.27	.67	.51	4.32
8.00	9.00	1.00	40.27	21.90	1.68	.85	3.98
9.00	10.00	1.00	38.99	27.11	1.09	.73	3.39
10.00	11.00	1.00	33.62	32.80	1.03	.85	4.17
11.00	12.00	1.00	36.75	27.59	1.03	.52	4.56
12.00	12.70	.70	33.23	31.43	.46	.52	5.56
12.70	13.70	1.00	48.46	11.59	.25	.25	4.74
*12.70	13.70	1.00	48.46	11.59	.25	.25	4.74
*8.00	13.70	5.70	38.75	25.15	.94	.59	4.32
*2.00	13.70	11.70	35.15	30.55	.94	.76	3.85
Drill hole 9							
0.00	0.40	0.40	10.65	70.54	0.82	0.62	2.28
.40	.83	.43	17.97	58.60	.84	.97	2.74
.83	3.00	2.17	25.90	44.59	.70	.29	3.90
3.00	9.65	6.65	9.30	76.50	.40	.58	1.55
*.83	3.00	2.17	25.90	44.59	.70	.28	3.90
Drill hole 10							
0.00	1.00	1.00	16.57	53.42	0.37	None	2.80
1.00	2.00	1.00	42.51	21.82	.72	...do.....	2.75
2.00	3.00	1.00	24.31	31.73	.85	...do.....	1.99
3.00	4.00	1.00	43.42	25.15	.95	...do.....	1.06
4.00	5.00	1.00	44.44	21.70	.48	...do.....	3.34
5.00	6.00	1.00	44.18	22.01	.68	...do.....	3.82
6.00	7.00	1.00	46.90	18.04	.70	...do.....	3.82
7.00	8.00	1.00	46.86	19.38	.80	...do.....	3.82
8.00	9.60	1.60	44.82	24.46	.58	...do.....	2.77
9.60	11.00	1.40	45.00	22.76	.80	...do.....	2.07
11.00	11.75	.75	41.17	27.61	.84	...do.....	2.22
*4.00	11.00	7.00	45.30	21.73	.65	...do.....	3.02
*1.00	11.75	10.75	42.70	24.05	.73	...do.....	2.52

TABLE 3.—*Analyses of core samples and grade of ores, Shati Valley iron deposits*—Continued

Depth (meters) From	Depth (meters) To	Thickness (meters)	Fe	SiO_2	P_2O_5	S	Al
Drill hole 11							
1.16	2.00	0.82	45.33	19.30	0.78	None	3.30
2.00	3.00	1.00	47.60	15.15	.85	...do.....	3.39
3.00	4.00	1.00	47.60	14.53	.77	...do.....	2.61
4.00	4.48	.48	12.57	72.81	.19	.04	1.80
4.48	5.00	.52	43.77	22.61	.70	None	2.56
*1.16	4.00	2.82	45.20	16.12	.80	...do.....	3.16
*1.16	5.00	3.82	40.90	24.20	.71	...do.....	3.10
Drill hole 12							
2.20	2.60	0.40	6.76	88.48	0.29	Tr.	0.14
Drill hole 13							
1.50	1.63	0.13	48.13	19.42	2.34	0.92	0.50
1.63	2.00	.37	2.14	84.53	.98	.25	.16
2.00	4.86	2.86	31.24	36.98	2.16	1.85	1.81
4.86	5.00	.14	5.78	81.16	.10	.13	3.10
5.00	8.16	3.16	20.20	51.77	1.88	1.01	3.59
8.16	9.57	1.41	33.84	33.33	3.06	.41	4.20
9.57	10.00	.43	8.66	82.78	.43	.21	.73
10.00	12.88	2.88	26.33	50.07	1.70	.58	1.82
*2.00	4.86	2.86	31.24	36.98	2.16	1.85	1.81
*1.50	9.57	8.07	26.80	46.30	3.04	1.13	2.93
Drill hole 14							
2.50	3.00	0.50	10.18	74.25	0.21	Tr.	1.99
3.00	3.20	.20	7.22	78.53	.14	.50	5.84
3.20	4.10	.90	9.54	71.42	.28	2.35	5.12
4.10	5.95	1.85	2.14	90.39	.09	.46	3.26
5.95	6.90	.90	4.29	85.73	.11	.40	3.62
6.90	14.50	7.60	----------	----------	----------	----------	----------
14.50	15.00	.50	.92	88.78	.06	Tr.	2.91
15.00	16.00	1.00	7.22	82.17	.27	1.29	1.20
16.00	17.00	1.00	14.94	71.92	.23	Tr.	1.00
17.00	18.00	1.00	31.73	46.31	.20	Tr.	.11
18.00	19.00	1.00	44.65	34.16	.19	Tr.	.54
*17.00	19.00	2.00	38.19	40.24	.30	Tr.	.32
Drill hole 15							
14.65	16.70	2.05	24.03	55.77	0.77	0.25	2.41
16.70	18.75	2.05	2.74	86.25	.12	.13	2.97
18.75	20.55	1.80	13.35	67.83	.09	.16	3.20
20.55	21.55	1.00	4.12	85.32	.24	.08	1.57
21.55	28.00	6.45	20.06	62.37	.75	.30	1.77
28.00	29.85	1.85	9.81	81.55	.48	.39	.50
*14.65	16.70	2.05	24.03	53.77	.77	.25	2.41
Drill hole 16							
2.00	2.95	0.95	13.69	72.04	0.48	0.24	1.93
2.95	4.65	1.70	3.35	88.72	.06	.08	1.51
4.65	5.00	.35	21.53	64.11	.77	None	.55
5.00	5.20	.20	1.82	86.47	.13	.06	5.06
Drill hole 18							
0.00	0.70	0.70	8.80	82.44	0.25	Tr.	1.26
0.70	2.30	1.60	44.07	20.28	.62	Tr.	4.97
2.30	3.00	.70	52.21	9.89	.40	Tr.	3.10
3.00	3.70	.70	49.14	26.53	.45	Tr.	1.67
3.70	71.0	----------	----------	----------	----------	----------	----------
*.70	3.70	3.00	45.41	18.95	.53	Tr.	3.76
Drill hole 19							
6.04	6.32	0.28	36.23	23.17	0.53	0.48	6.94
6.32	7.60	1.28	11.51	72.56	.46	.69	2.34
7.60	7.84	.24	44.24	12.40	.89	.34	7.41
7.84	8.72	.88	10.17	77.70	.41	.28	.94
8.72	9.45	.73	37.22	39.25	.44	.28	.59
9.45	10.75	1.30	23.53	57.50	.45	.23	1.68
10.75	11.75	1.00	6.62	76.88	.20	.04	3.65
11.75	25.00	----------	----------	----------	----------	----------	----------
*6.04	10.75	4.71	21.75	58.30	.20	.41	2.34

TABLE 3.—*Analyses of core samples and grade of ores, Shati Valley iron deposits*—Continued

Depth (meters) From	Depth (meters) To	Thickness (meters)	Fe	SiO_2	P_2O_5	S	Al
Drill hole 20							
0.11	1.35	1.24	25.15	33.48	0.31	0.55	4.43
1.35	1.63	.28	34.71	28.56	.58	.16	6.93
1.63	2.40	.77	4.19	85.89	.20	.13	2.02
2.40	2.98	.58	24.14	50.65	.72	.46	2.64
2.98	4.00	1.02	2.96	88.05	.10	.13	1.76
4.00	4.37	.37	37.61	26.77	.19	.12	5.52
4.37	5.00	.63	25.65	47.95	.68	.46	3.49
5.00	5.22	.22	48.62	20.20	.19	.14	1.53
5.22	6.80	1.58	31.46	40.71	.20	.04	3.53
6.80	7.35	.55	36.21	38.64	.20	.15	2.68
7.35	8.00	.65	16.21	64.72	.87	.64	2.64
8.00	10.80	2.80	34.76	42.75	1.21	.32	.40
10.80	23.00	.....	.....	.....	.....	.....	.....
*4.00	10.80	6.80	32.10	43.00	.72	.27	1.85
*1.35	10.80	9.45	26.30	49.60	.62	.25	2.25
Drill hole 21							
0.60	1.00	0.40	32.23	27.06	2.60	3.47	2.61
1.00	3.50	2.50	24.07	46.15	1.37	2.37	1.28
3.50	4.00	.50	22.53	41.57	1.13	.24	9.02
*.60	4.00	3.40	24.80	43.20	1.41	2.20	2.56
Drill hole 23							
0.00	1.60	1.60	15.76	70.39	0.08	None	1.14
1.60	2.75	1.15	38.07	30.79	.25	0.13	8.69
2.75	5.15	2.40	10.41	82.07	Tr.	.15	.34
5.15	7.50	2.35	13.68	68.63	.35	.25	1.58
7.50	8.40	.90	36.54	35.87	.18	None	.83
8.40	10.00	1.60	40.70	20.36	1.35	.06	2.53
10.00	13.00	3.00	39.75	21.92	1.60	.05	2.48
13.00	16.00	3.00	44.33	16.20	1.88	.03	1.91
16.00	19.00	3.00	47.52	4.80	2.18	.13	3.62
*13.00	19.00	6.00	45.92	10.50	2.03	.08	2.75
*8.40	19.00	10.60	43.40	15.22	1.80	.07	2.65
*1.60	8.40	6.80	19.70	62.60	.18	.16	1.40
Drill hole 24							
1.00	1.52	0.52	8.06	80.94	0.27	0.28	1.70
1.52	2.00	.48	36.62	41.01	.95	.29	.90
2.00	2.34	.34	10.44	77.18	.24	.26	1.74
2.34	2.55	.21	29.68	53.18	.14	.13	.04
2.55	3.70	1.15	4.58	91.35	.10	.03	.07
3.70	4.00	.30	38.52	36.99	.47	None	.36
4.00	5.20	1.20	7.31	82.43	.29	...do.....	1.07
5.20	6.40	1.20	6.51	83.03	.08	...do.....	.81
6.40	10.00	3.60	14.70	74.85	.37	...do.....	.26
10.00	12.45	2.45	51.85	12.29	1.29	...do.....	1.84
12.45	20.00	.....	.....	.....	.....	.....	.....
*10.00	12.45	2.45	51.85	12.29	1.29	None	1.84
*6.40	12.45	6.05	30.00	49.55	.74	...do.....	.90
Drill hole 25							
0.44	1.00	0.56	27.54	42.99	0.39	2.81	1.10
1.00	2.00	1.00	21.57	59.40	.29	1.08	.63
2.00	5.55	3.55	9.67	82.38	.27	.17	2.50
5.55	6.12	.57	5.25	91.16	.02	.10	.13
6.12	6.36	.24	31.58	51.29	.16	.07	.56
6.36	8.35	1.19	10.93	74.93	.06	.04	.44
8.35	11.00	2.65	46.79	14.90	.75	.18	2.93
11.00	12.30	2.30	36.97	23.52	.50	.11	2.24
12.30	25.00	.....	.....	.....	.....	.....	.....
*8.35	11.00	2.65	46.79	14.90	.75	.19	2.92
*8.35	12.30	4.95	42.25	18.92	.63	.15	2.65
Drill hole 26							
0.12	1.00	0.82	39.46	17.34	0.35	2.59	5.70
1.00	2.00	1.00	34.59	29.47	.36	1.79	4.52
2.00	4.00	2.00	45.58	15.79	.18	.23	5.05
4.00	6.38	2.38	30.79	43.49	.33	.26	2.94
6.38	10.00	3.62	12.16	78.35	.15	3.15	.36
*2.00	4.00	2.00	45.58	15.79	.18	.23	5.05
*.12	4.00	3.82	41.40	19.75	.26	1.14	5.13
*.12	6.38	6.20	37.30	23.82	.28	.80	4.29

TABLE 3.—*Analyses of core samples and grade of ores, Shati Valley iron deposits*—Continued

Depth (meters) From	Depth (meters) To	Thickness (meters)	Fe	SiO_2	P_2O_5	S	Al
Drill hole 27							
0.00	2.00	2.00	9.71	68.93	0.48	2.99	0.88
2.00	4.55	2.55	9.60	76.07	.19	1.64	1.42
4.55	5.00	.45	28.43	48.82	.93	.05	.78
5.00	8.00	3.00	34.68	38.70	1.12	.39	1.53
8.00	10.00	2.00	38.05	38.49	1.26	.68	.92
10.00	15.65	5.65	17.86	67.97	.48	.37	1.01
15.65	16.55	.90	2.96	94.03	.02	.27	.02
16.55	20.00	3.45	41.10	25.22	2.53	.14	2.93
20.00	25.00	5.00	51.32	14.54	1.67	.35	.78
25.00	25.50	.50	14.73	68.29	.68	.64	1.12
25.50	26.50	1.00	53.27	5.27	3.13	.08	2.05
*16.55	26.50	9.95	48.10	20.00	2.10	.27	1.76
*4.55	26.50	21.95	34.20	40.20	1.40	.35	1.40
Drill hole 28							
0.00	0.80	.....	.....	.....	.....	.....	.....
.80	5.00	4.20	52.53	5.59	.44	.10	4.99
5.00	11.50	6.50	55.53	6.98	.38	.08	3.05
11.50	15.00	3.50	3.44	92.74	.04	.04	.24
15.00	17.60	2.60	13.92	74.16	.04	.07	1.73
*.80	11.50	10.70	54.20	6.44	.40	.09	3.62
Drill hole 29							
0.00	2.64	.....	.....	.....	.....	.....	.....
2.64	5.00	2.36	10.58	78.03	.08	1.26	0.12
5.00	10.00	5.00	12.70	77.22	.12	.22	.91
10.00	15.00	5.00	29.88	51.52	.75	.21	1.07
15.00	17.30	2.30	3.72	93.48	.06	.12	.24
17.30	20.00	2.70	4.22	91.48	.07	.30	.16
*10.00	15.00	5.00	29.86	51.52	.75	.21	1.07
Drill hole 30							
0.00	1.00	1.00	.....	.....	.....	.....	.....
1.00	2.00	1.00	37.95	32.20	0.05	0.35	1.77
2.00	3.00	1.00	38.51	33.63	.12	.48	1.40
3.00	4.00	1.00	22.80	58.34	.07	.45	1.28
4.00	5.00	1.00	33.08	40.58	.08	.35	1.68
5.00	7.00	2.00	19.90	61.53	.06	.39	1.83
7.00	10.10	3.10	25.09	56.31	.60	.76	.02
10.10	13.20	3.10	24.66	51.61	.78	.57	.88
13.20	14.95	1.75	44.68	19.71	1.14	.59	2.48
14.95	15.70	.75	8.38	88.21	.11	.42	.04
15.70	17.75	2.05	36.34	33.53	.90	.19	.96
17.75	19.60	1.85	6.93	81.20	.07	.13	.25
*13.20	14.95	1.75	44.68	19.71	1.14	.59	2.48
*1.00	3.00	2.00	38.23	32.92	.08	.41	1.59
*1.00	5.00	4.00	33.08	41.19	.08	.40	1.53
*1.00	17.75	16.75	29.00	44.30	.51	.51	1.16
Drill hole 31							
0.11	2.00	1.89	48.00	17.21	0.47	1.71	4.92
2.00	4.00	2.00	47.90	21.58	.30	.65	3.79
4.00	5.79	1.79	53.48	9.57	.24	.45	2.96
5.79	6.70	.91	8.13	85.32	.11	.65	.82
6.70	10.00	3.30	11.98	78.76	.19	.65	.90
10.00	12.80	2.80	8.58	85.11	.23	.41	.39
*.11	5.79	5.68	49.60	16.62	.84	.92	3.90
Drill hole 32							
0.00	0.30	0.30	40.38	31.23	0.08	1.01	1.95
0.30	5.00	4.70	14.56	71.98	.24	.40	1.29
5.00	6.00	1.00	24.15	58.49	.29	.09	1.01
6.00	9.68	3.68	4.58	89.78	.48	.13	.01
9.68	13.00	3.32	49.60	17.22	.28	.13	1.56
13.00	17.40	4.40	37.61	34.35	.38	.14	2.90
*9.68	13.00	3.32	49.60	17.22	.28	.13	1.56
*13.00	17.40	4.40	37.61	34.35	.38	.14	2.90
*9.68	17.40	7.72	42.75	27.00	.33	.13	2.38
Drill hole 33							
0.00	0.30	0.30	.....	.....	.....	.....	.....
.30	3.70	3.40	45.55	20.04	.43	.16	3.47
3.70	4.30	.60	1.52	92.44	.14	.08	.88
4.30	4.53	.23	43.26	21.93	1.36	.12	5.29
4.53	11.00	6.47	15.12	66.91	.35	.19	2.87
11.00	14.58	3.58	17.32	64.48	.36	.26	2.54
14.58	20.00	5.42	6.59	86.98	.15	.15	.63
*.30	3.70	3.40	45.54	20.04	.43	.16	3.47
*.30	4.53	4.23	38.96	30.45	.40	.12	3.48

In computing the reserves of a certain grade in an ore block, the area is measured taking into account the eroded sections in the block.

The tonnage of a certain grade of ore is determined by the thickness of that interval multiplied by the area and the average specific gravity of the ore. For example, A_Y being the area of the block Y with the thicknesses and grades of the intervals of T, t_1, and t_2, and G, g_1, and g_2 computed above from core X in the block, it contains.

$$A_Y \times \text{sp gr} \times T = \text{tonnage of } G \text{ grade ore}$$
$$A_Y \times \text{sp gr} \times t_1 = \text{tonnage of } g_1 \text{ grade ore}$$
$$A_Y \times \text{sp gr} \times t_2 = \text{tonnage of } g_2 \text{ grade ore}$$

The ores are classified in four grades as shown in the table on plate 9, and data on the ores are given in table 4 in round numbers. These figures are the original estimates (Goudarzi, 1962a, p. 31) and represent only about 67 percent of the initially computed reserve figures. Therefore, in this report the inferred reserves (see below) include that part of the indicated reserves that is not reported in table 4.

INFERRED ORE

The inferred-ore estimates are made only for ore blocks that contain more than 40 percent iron. These estimates are based on the following:

1. The iron-bearing beds continue farther south under the younger sediments. Data from a water well a short distance (1 to 2 km) south of the blocked-out ore body indicate the presence of these iron-bearing beds at depth.
2. The outcrops of the iron-bearing beds continue more than 5 km east of the explored area. In computing the tonnage and grade of the inferred ore:
   (*a*) The inferred-ore limits are placed 1 km south of the indicated ore boundaries (pl. 9). This would necessitate the removal of an average of about 20 m of overburden.
   (*b*) The eastern limit of the inferred ore is placed 5 km beyond the indicated ore.
   (*c*) The grades and thickness of the indicated ore are assumed to persist at depth.
   (*d*) The inferred ore estimated here also includes ore that was arbitrarily deducted from the previous estimates made by the writer (Goudarzi, 1962a, p. 31).
   (*e*) The inferred-ore blocks are numbered 2A, 3A, 6A, 9A, 10A, 12A, and 12B, and the reserves are shown in table 5.

OVERBURDEN

In general, the thickness of the overburden, in the indicated-ore-reserve area outlined in plate 9, is about 10 m. No attempt is made to calculate the volume of overburden that needs to be stripped in the course of mining operations. Economic factors such as the mining practices, equipment, labor, supply, and the grade of ore to be mined by bulk or selective mining and treatment of the ore will be studied in detail by the future mine management. Consequently, any such data that are related to future mining and treating the ore would be meaningless and beyond the scope of the present paper.

ECONOMIC CONSIDERATIONS

The drilling and sampling carried out during this investigation can only be regarded as exploratory (Goudarzi, 1962a, p. 35). Much additional exploration by drilling and other methods is needed in order to

TABLE 4.—*Indicated reserves and composition of ore blocks, Shati Valley iron deposits*

[Where tonnage is given in more than one column for an ore block, column 2 includes column 1 and column 3 includes column 2]

Ore blocks	Millions of metric tons containing 45–50 percent Fe (1)	Millions of metric tons containing 40–45 percent Fe (2)	Millions of metric tons containing 30–40 percent Fe (3)	Millions of metric tons containing 25–30 percent Fe (4)	Thickness (meters)	Fe (percent)	SiO_2 (percent)	S (percent)	P_2O_5 (percent)	Al (percent)
1				34.7	4.8	27.9	40.9	0.5	1.8	5.3
2	112.2				3.3	47.5	14.0	.3	.5	3.4
2		321.4	321.4		9.0	40.4	22.2	.4	.6	3.9
3	139.6				7.0	45.3	21.7	Tr.	.6	3.0
3		211.9	211.9		10.8	42.7	24.0	Tr.	.7	2.5
4			169.2		2.9	31.2	37.0	1.8	2.2	3.5
5				21.0	2.2	27.6	51.5	.2	.4	3.0
6	61.4	61.4	61.4		3.2	45.9	23.2	.2	.5	3.6
7										
8				92.9	5.1	29.6	43.0	.4	.9	2.1
9	61.5				4.3	47.6	11.0	.1	.7	2.5
9		94.5			6.5	45.0	14.7	.1	.8	2.5
9			120.0		8.3	38.5	27.6	.1	.6	2.6
10	266.0	266.0	266.0		5.3	49.6	13.4	.2	.4	3.3
11				78.0	5.0	29.8	51.5	.2	.3	1.1
12	81.2				3.6	49.0	17.2	.2	.6	3.5
12		131.5			5.8	42.8	28.8	.1	.4	3.0
12			227.8		10.1	36.5	34.6	.2	4.8	2.5
Total	721.9	1,066.7	1,377.7	226.6						

TABLE 5.—*Inferred reserves and composition of ore blocks, Shati Valley iron deposits*

[For each ore block, column 2 includes column 1]

Ore blocks	Millions of metric tons containing 45–50 percent Fe (1)	Millions of metric tons containing 40–50 percent Fe (2)	Thickness (meters)	Fe (percent)	SiO_2 (percent)	S (percent)	P_2O_5 (percent)	Al (percent)
2A	116		8.3	47.5	14.0	0.4	0.5	3.4
2A		332	9.0	40.4	22.2	.4	.6	3.9
3A	246		7.0	45.3	21.7	Tr.	.6	3.0
3A		370	10.8	42.7	24.0	Tr.	.7	2.5
6A	93	93	8.2	45.9	28.0	.2	.5	3.6
9A	70		4.3	47.6	11.0	.1	.7	2.5
9A		109	6.5	45.0	14.7	.1	.7	2.5
10A	404	404	6.3	49.6	13.4	.2	.4	3.3
12A	55		3.6	48.9	17.2	.2	.6	3.5
12A		80	5.8	42.8	26.8	.1	.4	3.6
12B	49		3.6	48.9	17.2	.2	.6	3.5
12B		79	5.8	42.8	26.8	.1	.4	3.6
Total	1,033	1,467						

obtain satisfactory knowledge of the grade, size, and other characteristics of the deposit. The limited resources available during the study permitted the accumulation of only a fraction of the data needed for a complete appraisal of the iron deposit in the Shati Valley area.

The costs and difficulties of mining, processing, and transporting the material and of supporting the necessary population in the inhospitable desert environment of the region must be given careful consideration in planning exploitation of this huge resource. Furthermore, the costs of local beneficiation of iron ore by any of the available processes must be compared with the costs of shipping of the raw ore.

The iron deposit of the Shati Valley is comparable to other north African deposits. The reserves reported are based on the ore within limits of economic recovery by strip-mining methods. Field observations indicate that the rich zone of minable thickness extends about 15 km beyond the easternmost drill hole; this area should also be tested. Northeast of Guira an area where manganiferous veinlets cut the iron-bearing beds in a zone about 1 km long should be tested.

Western Europe imports iron ore from north and west Africa and high-grade ore from as far as Brazil, a distance of about 10,200 km. This indicates that the European iron and steel industry is highly dependent on foreign sources of iron ore. After beneficiation, the Libyan ore might well be marketed in Europe at some future date.

Because of the long haulage, it is the opinion of the present writer that the ore must be beneficiated to be considered for export within the foreseeable future. The efforts to upgrade similar ores in Europe and the United States have to date met with little success. However, nearby sources of cheap fuel, such as crude oil and natural gas, are available; and efforts to solve the technical and economic problems might be worthwhile, owing to the size of the resource, one of the larger in the world.

Limestone is available in the area, and the groundwater supply is adequate for industrial use in the region.

NORTHERN TRIPOLITANIA IRON-BEARING ROCKS

Iron-bearing beds in northwestern Tripolitania are in the Kikla Sandstone of Early Cretaceous age. Ferruginous sandstone beds 0.3 to 1.5 m thick are exposed in the Jabal escarpment from a few kilometers west of Yafran for a distance of about 70 km west toward Nālūt.

These ferruginous sandstone beds are locally quartzitic and average less than 25 percent iron. Locally, highly ferruginized hematitic material is found in small folds and other places as replacement in the overlying Ain Tobi Limestone (Cretaceous).

In the eastern flanks of Wādī Lumi, these ferruginous beds are locally 1 to 4 m thick and are underlain by a brown-stained crossbedded medium-grained conglomeratic Kikla Sandstone.

In Khasim Said Mountain on the western flank of Wādī Lumi, some siderite nodules and cavity fillings are at the base of the Ain Tobi Limestone, which overlies the Kikla Sandstone. The siderite and limonite ore minerals are in a dolomitic limestone host rock.

Brichant (1952) reported an occurrence of hematite near km 127 on the Yafran road and gave the following chemical analyses, in percent:

Sample	*Iron*	*Sample*	*Iron*
1	56.0	4	52.1
2	25.9	5	22.7
3	51.1	6	43.0

He noted that the occurrence is the filling of a local fault in contact with a sandstone of Albian Age and

has no significant lateral extent. This locality is probably similar to the highly ferruginized areas noted by the present writer in the Kikla Sandstone. These iron-rich zones are less than 2 m wide and not more than 50 m long.

Other iron-bearing beds, grading from a ferruginous sandstone to almost pure hematite, occur in the Cambrian and Ordovician sandstones in Dor el Goussa area, in central Fezzan. These beds, although noted in several areas, do not extend for appreciable distances, and they seem to be generally in form of lenses. In one place a hand specimen analyzed 67 percent iron. Similar lenses are noted in the Devonian sandstones in the same area (pl. 1).

The only other known iron-bearing beds in Libya are some hematitic beds west of Jabal Al Harūj al Aswad at about lat 26°30′ N. and long 17°10′ E. These beds are in Eocene strata that are overlain by the volcanic flows of Jabal Al Harūj al Aswad (fig. 42). They appear to have been formed as a result of downward percolation from the lava and replacement of a calcareous sandstone within a restricted area. The hematitic zones are in vertical tubular forms, and grab samples were found to contain about 45 percent iron. The entire thickness of the affected zone is about 8 m, consisting of three main beds, 1 to 2 m thick, separated by minor beds of sandstone. The mineralized area does not extend laterally for any appreciable distance.

MANGANESE OCCURRENCES

Manganese minerals are known in northwestern Libya near Nālūt and Wādī Urari and in the Shati Valley area of the Fezzan. In the Nālūt area, at Ulad Mahmud (Awlād Mahmūd), 5 km southeast of Nālūt, the manganese is in lenses about 3 or 4 m long and less than 1 m thick in the Ain Tobi Limestone. At Wādī Urari, near kilometer post 320 on the Tripoli-Nālūt road above the Jabal escarpment, the manganese is in a small zone about 75 m long and 60 m wide, almost parallel to the bedding in the Ain Tobi Limestone. The thickness of the mineralized zone is about 30 m. The manganese occurs as replacement or staining in the limestone as pyrolusite-bearing bands 3 to 30 cm thick. Some vugs in the limestone have been filled with pyrolusite (fig. 43).

In the Shati Valley area about 10 km east of Brach, north of Guira, manganiferous veinlets 5 to 15 cm thick, in the form of fracture fillings, cut across the iron-bearing beds in an area of about 1 sq km (fig. 44). North of Brach and near Sheb, thin beds of manganiferous material, less than 2 cm thick, occur within the iron-bearing formations as already described. The manganese in the area is associated with fault fracture and is probably related to the volcanic activities of Jabal as Sawdā'. The association of the manganiferous veinlets and beds with the iron deposit might permit their exploitation along with the iron deposit.

NONMETALLIC MINERAL RESOURCES

In addition to the large quantities of iron ore, Libya possesses appreciable amounts of nonmetallic mineral resources—notably gypsum, common salt, potash, building and ornamental stone, and limestone and other raw materials for portland cement. With the exception of petroleum and the aforementioned deposits, the country is poorly endowed with mineral resources. Libya has some trona, silica sand, sulfur, alum, very

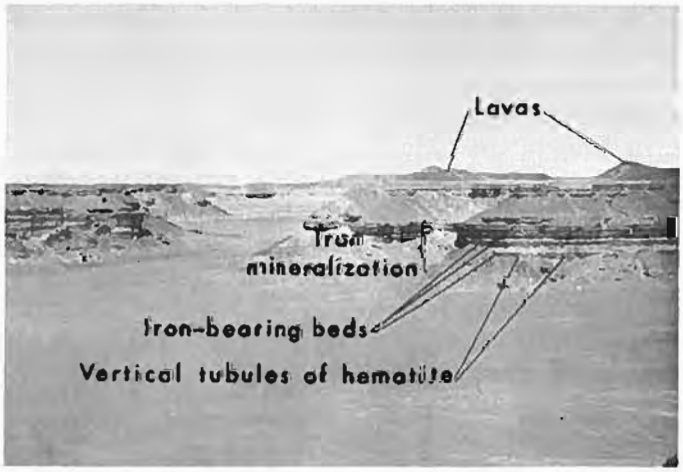

FIGURE 42.—Iron-bearing beds west of Jabal Al Harūj al Aswad in an Eocene calcareous sandstone. The lava flows are in the distant background.

FIGURE 43.—Manganese occurrences in the Ain Tobi Limestone at Wādī Urari in Jabal Nefusa. The black band is manganese mineral (pyrolusite) associated with a crystalline calcite band in the limestone host rock.

FIGURE 44.—Closeup view of manganiferous veinlets north of Guira about 14 km northeast of Brach. These veinlets cut across the iron-bearing beds in a fault-fracture zone.

low grade phosphate rock, carbonaceous or lignitic clays, barite-celestite, and kaolinite (pl. 1). There are some slight possibilities of discovering additional sources of raw materials for portland cement and commercial phosphate rock. Further study may also reveal suitable sources of silica sand for glass manufacture. By additional study and experimentation, a process may be developed for commercial recovery of potassium and magnesium salts from the brines of some of the saline deposits.

No waterpower exists in the country, for there are no perennial streams. Also, with the exception of a few oasis areas, the ground-water supply is limited even for agricultural use; and in most of the country, water is scarce for even human consumption. As a result of the recent petroleum exploration and development in the country since 1955, a plentiful source of cheap fuel, both in natural gas and in crude oil, for power generation is available. Available facts on all the known mineral resources are briefly given in this section of the report, as well as suggestions and recommendations for future exploration and development.

Detailed discussions of the potentially commercial mineral deposits by the present writer (Goudarzi, 1959, 1962a, b, c, d) are available at the Geological Department of the Ministry of Industry of the Government of Libya, the Agency for International Development in Libya, and the U.S. Geological Survey in Washington, D.C.

ALUM

Small alum (soda alum) deposits occur near Serdeles, in southwestern Libya, in evaporite basins which cover an area of less than 5 sq km. The basins are discontinuous and contain individual pools that are only 20 to 30 m in diameter. The salts are dissolved out of the surrounding Devonian sandstones and accumulate in small depressions where a crust of alum is formed by evaporation (fig. 45). The crust is harvested and used locally in the tanning of hides; some is shipped to Ghāt, Sebha, and other areas.

The analyses of the crust and the bittern, in percent are as follows:

	Na	Al	SO_4
Alum (crust)		9.2	45.3
Bittern	4.2	8.7	9.6

No production figures are available; however, probably less than 10 tons of alum is recovered annually from these basins.

BARITE AND CELESTITE

Barite and celestite occur in several localities in Tripolitania and Cyrenaica. No commercial deposits, however, are known in Libya. In Tripolitania, barite has been reported in several places in the Sirte area (oil-company geologists, oral commun.) associated with marl beds of middle Eocene age.

In the Wādī Soffegin area, celestite occurs in thin beds and lenses as much as 10 cm thick in shale and

FIGURE 45.—Alum recovered from evaporite basins near Serdeles. The pools are in the background.

marl beds in the Upper Cretaceous (Maestrichtian) sedimentary rocks.

Large amounts of float material consisting essentially of celestite are noted near Beni Ulíd in Wādī Umm El Lebd, but the actual celestite beds cannot be traced for any appreciable distance. The mineral is heavy and has a bluish tinge and an acicular structure. Locally it might be pseudomorphous after gypsum. Gypsum is present in the same beds in Garat El Gola' area in Wādī Soffegin about 10 km to the south. The proximity of the volcanic flows to the west suggests that celestite may be associated with the mineralizing solutions associated with volcanic activity.

In Cyrenaica, celestite has been reported by F. W. Kelly (Oasis Oil Co., written commun., 1958) from the El Haderiat area, about lat 28° N. and long 18°30′ E. The celestite lines or fills cavities in a 3-m thick yellow marl bed of Eocene age. The marl bed is exposed over much of the area, and celestite-filled cavities can be found at most outcrops. At about lat 28°10′ N. and long 18°37′ E., where the marl bed trends northwest, an area 3 to 4 km long and 500 m wide has abundant celestite-filled cavities. These cavities are irregularly distributed in the marl bed, are spherical in shape, and are from 20 to 60 cm in diameter. Most of the smaller cavities are completely filled with celestite, whereas the larger cavities have a central open space or "vug." The cavities have inward-pointing needle-shaped crystals (fig. 46) that are transparent and are colorless or have a blue tint.

FIGURE 46.—Celestite crystals found in vugs and cavities in Eocene marls. These crystals are as much as 5 cm long and 1 cm in diameter.

Kelly also reported that in several localities, in the same marl bed, the cavities are filled with gypsum rather than celestite. He suggested that possibly the mineralizing solutions which formed the celestite were associated with the igneous activity of Jabal Al Harūj al Aswad to the west and southwest.

BUILDING STONE

The most widely used building stone in the Tripoli area is the Gargaresh stone, a calcarenite, which is easily quarried and shaped. The Azizia limestone, long quarried for building stone, also provides a good source of ornamental stone, road ballast, and concrete aggregate. In Cyrenaica the Bengasi limestone is extensively used for building stone; the Cirene limestone provided material for the monuments and buildings of the ancient Greek city of Cirene.

In the Fezzan, red clay is utilized for sun-dried bricks in construction of buildings.

In 1962 a gypsum and plaster-board fabrication plant was established near Tripoli. The large gypsum and anhydrite deposit (p. 76) in the Bi'r al Ghanam area provides raw material for this plant as well as other plants supplying the building industry.

CEMENT RAW MATERIALS

Suitable limestone and clay deposits are probably available in sufficient quantities to support a cement industry in Tripolitania. Necessary cheap fuel is available and adequate amounts of water can probably be found at favorable sites near Homs, Azizia, and Tripoli. These areas are also close to good transportation and fairly close to the market. Suitable raw material for manufacture of cement has also been reported east of Bengasi, near the Benina (Banīnah) Airport (Geol. Dept., Ministry of Industry, Libya, oral commun.). However, the present writer did not visit the area, and no data on the extent and composition of these deposits are available.

Of major concern to a cement industry in Libya would be the continued high demand for cement for various kinds of construction and the encouragement of the use of concrete in place of scarcer and more expensive material. Furthermore, cement is such a low-price commodity that it is imperative that every economy of quarrying, rock crushing, transportation, and processing be carefully studied.

The requirements with respect to the chemical quality of rocks used for the manufacture of cement

are rigid, and the selection of raw materials in correct proportions is essential. Limestone low in magnesia composes about 75 percent of the raw material going into a kiln, and the remainder is alumina and silica. These materials must be in deposits near the plant. The size and quality of the limestone and clay deposits are major factors with respect to the most appropriate location for a cement plant.

The first search in Libya for suitable raw material for cement manufacture was made by Italian geologists under Desio, and the results were reported by Mancuso (in Desio, 1943, p. 287–297).

The writer, at the request of the Libyan Government, investigated areas near Tripoli and Azizia. The following discussions incorporate the work of the Italian geologists with information from more recent investigations.

HOMS AREA

About 110 km east of Tripoli, near Homs, are large deposits of limestone and clay, practically free of magnesia, that may provide raw materials for cement manufacture. These deposits occur in two hills, locally known as Ras El Margeb and Ras El Manubia, which are 4 and 8 km west of Homs (fig. 47) respectively. Mancuso (in Desio, 1943, p. 295) reported a marly limestone about 60 m thick, underlain by a clay bed of unknown thickness, exposed for a distance of about 2 km between Ras El Margeb and Ras El Manubia. He gave the following average chemical compositions, in percent:

	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na	Cl	TiO_2	Loss on ignition
Limestone	5.10	0.40	0.65	51.75	1.16				40.94
Clay	54.16	21.48	7.92	1.42	2.09	0.63	0.98	1.02	10.32
Clay	54.19	21.64	7.74	1.53	2.14	.57	.89	1.38	10.04

In 1958, at the suggestion of the present writer, Mr. Christensen, an independent geologist, collected several clay and limestone samples at Ras El Margeb and Ras El Manubia (fig. 58) and kindly made the analyses available (table 6).

From the foregoing it appears that the limestone and clay deposits of the Homs area may meet the raw-material requirements for the manufacture of cement. Surface geology and the topographic features of the

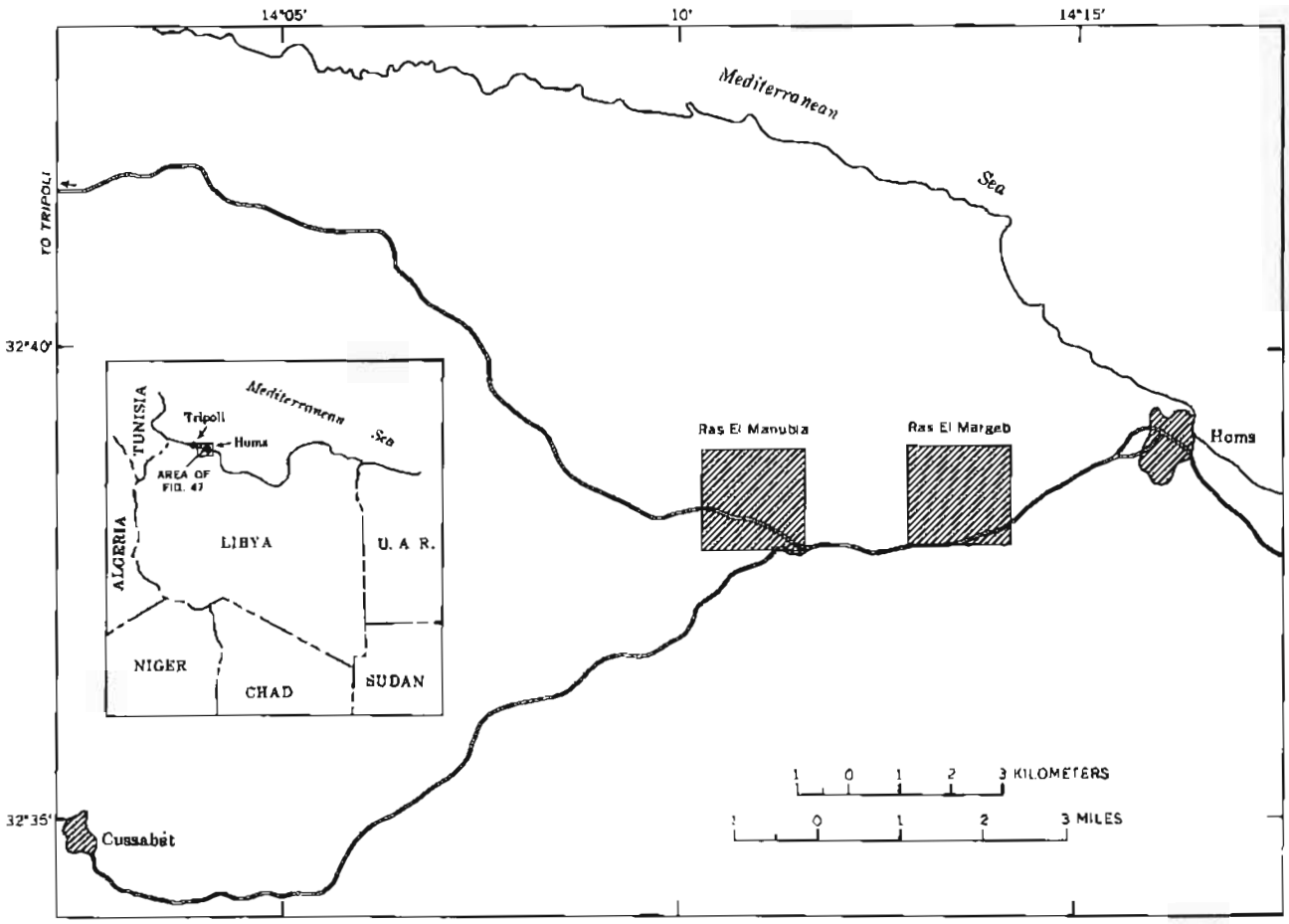

FIGURE 47.—Location of raw material for cement near Homs.

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TABLE 6.—*Analyses of limestone and clay samples, in percent*

[Samples were dried at 105°C. Loss on ignition not determined. Analyses made by Libyan-American Joint Services Chem. Lab., under supervision of Pierro Grossi]

SiO_2	CaO	Fe_2O_3	$Al_2O_3+P_2O_5$	MgO
Limestone samples:				
13.2	20.6	1.2	5.8	11.1
37.0	30.3	2.2	2.7	1.8
9.3	42.2	1.6	.8	.5
22.9	48.8	.6	1.2	.8
2.0	33.6	1.2	1.3	17.6
14.4	45.8	.9	.2	.6
.2	55.2	.1	.4	.3
15.7	37.0	2.1	5.1	3.7
Clay samples:				
70.3	6.4	5.4	8.3	.0
55.9	19.1	3.0	4.0	.7
46.3	20.0	1.4	6.8	6.5
41.3	3.7	3.7	8.5	8.5
19.5	19.6	2.4	4.5	18.2
88.1	1.2	4.8	6.8	.4
66.3	19.1	.4	.1	.1

area are also favorable for quarry operations. However, detailed study and sampling by core drilling or other methods are needed to determine the extent and composition of all the deposits.

AZIZIA AREA

Limestone and interbedded clay are exposed for about 10 km in a series of hills along the Azizia-Yafran highway between kilometers 50 and 60 from Tripoli. Most of the exposed rocks lie virtually flat or have low dips and belong to the Azizia Formation of Triassic age. The maximum exposed section is about 50 m thick in a quarry south of the main highway near kilometer 54. The stratigraphic section and sample analyses are shown on plate 10*A*.

The stratigraphic section and sample analyses of another quarry site at kilometer 59 are shown on plate 10*B*.

TRIPOLI AREA

The Gargaresh stone (Qarqarish Sandstone on fig. 3), long quarried at Gargaresh near Tripoli for building stone, composes Quaternary deposits which are present along most of the Mediterranean coast from Zuara to Gharabulli. These deposits, which extend to about 40 m above the present sea level, consist of shell fragments and quartz sand that have been blown up into dunes and later have been cemented.

Several of the quarry sites were studied, and no obvious variations of physical appearance or texture were apparent in the field. The rock appears to be composed entirely of carbonates, quartz, and a small amount of clayey material. This type of mixture has been used in some parts of the world as a natural cement rock for direct kiln feed, sometimes with addition of minor amounts of other materials to meet the requirements.

Two grab samples from quarries west of Tripoli at kilometer 7 (sample 1) and near kilometer 20 (sample 2) showed the following chemical compositions, in percent:

	Sample 1	*Sample 2*
Moisture	0.4	4.4
SiO_2	17.3	12.3 (insoluble in HCl)
Fe_2O_3	.2	.3
Al_2O_3	1.5	1.0
CaO	43.3	42.2
MgO	1.6	1.0
Loss on ignition	35.7	36.1 (CO_2)
SO_4	Positive reaction	2.8 (SO_3)

NOTE.—Analyses were made at the Libyan-American Joint Services Chem. Lab., Tripoli, under the supervision of Atom Pietri.

At the request of the writer, Dr. Robert van Everdingen (written commun., 1962), geologist for the Libya Ministry of Industry, sampled three quarries west of Tripoli designated as A, B, and C (fig. 48).

Table 7 shows the analyses of samples from each quarry, from top to bottom, taken at about 1-m intervals.

Dr. Robert van Everdingen (written commun., 1962) reported that the rock is similar in physical character from one quarry to another and from top to bottom in the section. The only apparent differences are the amount of small fossil fragments, which are more abundant in some places, and the firmness of the rock, which differs somewhat vertically and laterally from place to place. The firmer or more fossiliferous horizons are not easy to trace, even in a single quarry.

Quarry A is at the south side of the highway at kilometer 5. Quarrying is done by pickax and the workings are scattered over a large area. The highest recent working face is about 6 m, and total exposed thickness of the white to yellow rock, as calculated from three separate measurements, is approximately 13 m.

Thickness of overburden ranges from 0 to 2 m. Samples A–1 to A–15 (table 7) were taken at about 1-m intervals from top to bottom.

Quarry B is at the north side of the highway at kilometer 8. Quarrying here is done by rotary saws. The highest face measures 17 m, constituting most of the exposed thickness of the Gargaresh rock in this locality. The thickness of the overburden ranges from 0 to about 4 m. Samples B–1 to B–15 (table 7) were taken from bottom to top at about 1-m intervals. (See table for locations of sample intervals; samples B–11 and B–15 were taken close to overburden.)

Quarry C is at the south side of the same highway just west of kilometer 7. Rotary saws are also used here for quarrying. The fresh face, on the south side of the quarry, is about 11.5 m high. Older workings on the north side extend about 15 m below the top of the fresh face. Thickness of overburden ranges from 2 to about

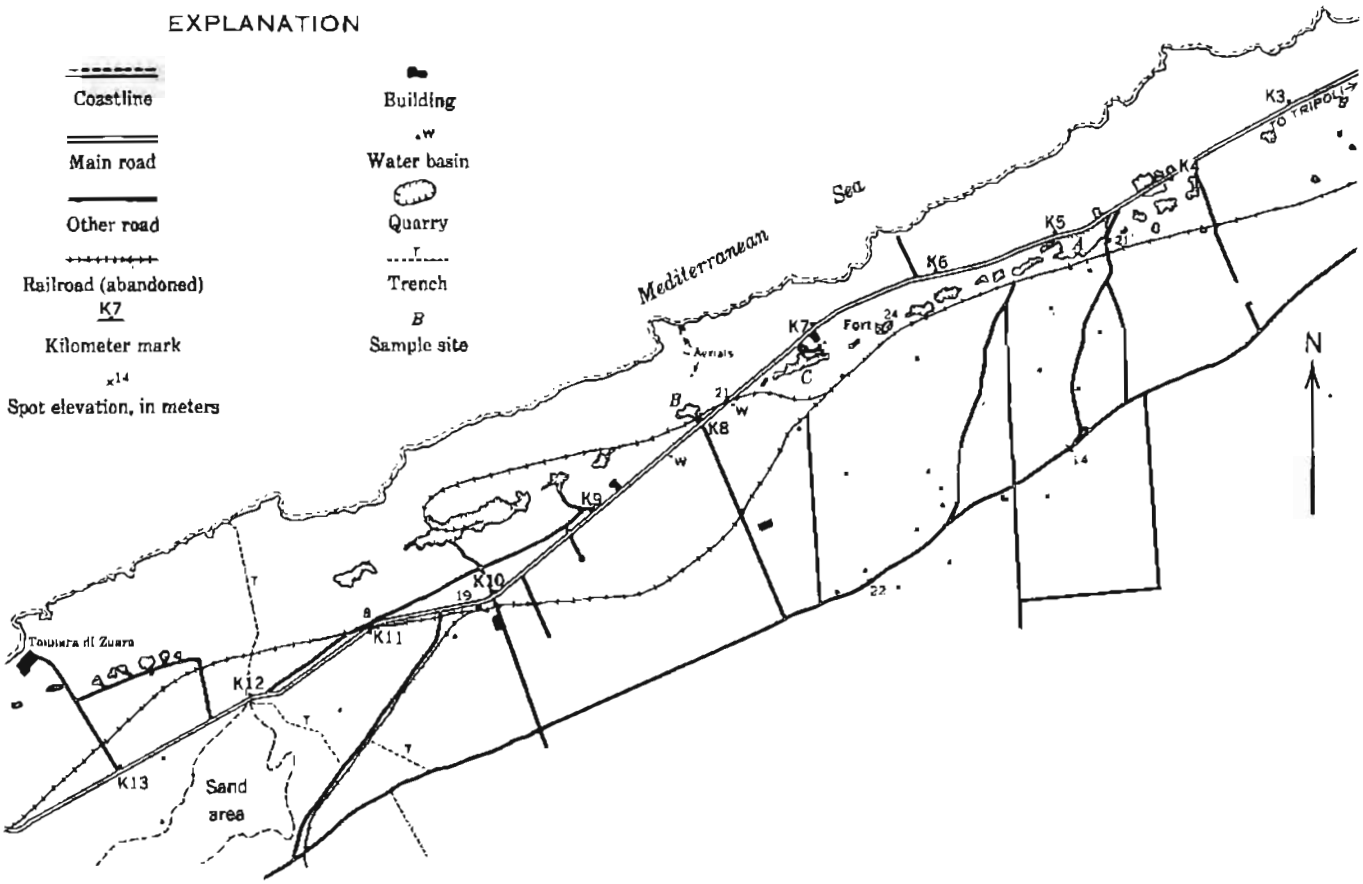


FIGURE 48.—Sketch map of the Gargaresh quarry area near Tripoli showing locations of quarries sampled for cement material.

4 m. Samples were taken from top to bottom: C–1 to C–5 (table 7) from the fresh south face, C–6 to C–9 from the older workings on the north side.

The Gargaresh rock, which extends for long distances along the Mediterranean coast, thickens to the west toward the Tunisian border. It shows little variation in physical appearance or texture.

The initial sample analyses of the Gargaresh rock indicate that it may be a suitable source of limestone and silica for the manufacture of cement. However, the rock contains only 1 to 1½ percent alumina, and bauxite or some other high-alumina material would have to be added to arrive at the necessary proportion for kiln feed. The analyses should be studied by a cement chemist to determine the type and required amount of materials needed to make it suitable for a kiln feed for portland cement.

If it is found that the Gargaresh rock is suitable as a source of raw material for cement manufacture, then the areas west of Tripoli, where the Gargaresh rock is as much as 40 m thick, should be examined, and quarry sites covering a total area of at least 1 sq km should be selected. An area of this size should furnish enough raw material for at least 50 years at an annual production rate of 100,000 tons of cement.

Initially, numerous holes should be drilled, cores collected, samples analyzed, and the results again studied by a cement chemist.

CLAYS

Bentonitic clays are exposed in the Jabal escarpment of Tripolitania and in the Fezzan, near Sebha.

Christie (1955) reported bentonitic clays underlying the Jurassic Bu Ghaylan Limestone in the Jabal escarpment and stated: "At Bu Ghaylan there is evidence that earth movements occurred while this limestone series was being deposited. The bentonitic clays that underlie the limestone series, and the rarer similar bands within it, suggest that volcanic action may have accompanied these earth movements." No data on the extent and composition of these bentonitic clays were given.

TABLE 7.—*Analyses of raw material for cement manufacture, Tripoli area*

[Analyses, in percent, made by U.S. Geol. Survey]

Sample intervals (meters)	Sample No.	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Loss on ignition	SO_3	H_2O^-	H_2O^+
Samples from Quarry A:										
0- 1	A-1	17.6	0.31	0.14	0.88	44.5	36.0	0.07	0.16	0.79
1- 2	A-2	19.4	.47	.20	.76	43.1	34.9	.07	.16	.85
3- 4	A-3	19.0	.76	.26	.88	42.7	35.0	.10	.15	.91
4- 5	A-4	14.5	.49	.26	.75	45.4	37.2	.09	.17	.79
6- 7	A-5	17.0	.51	.82	.47	44.0	35.8	.09	.20	1.0
7- 8	A-6	19.3	.83	.26	.57	42.6	34.8	.06	.21	1.0
8- 9	A-7	16.6	.64	.24	.70	44.6	36.3	.10	.18	.92
9-10	A-8	16.6	.68	.32	.68	44.2	36.1	.08	.15	1.0
10-11	A-9	16.0	.70	.30	.84	44.8	36.3	.08	.16	.93
5- 6	A-10	19.0	.80	.36	.76	42.7	35.0	.08	.20	.84
6- 7	A-11	20.2	.59	.29	.78	42.3	34.6	<.05	.16	1.0
7- 8	A-12	20.4	.70	.26	.82	42.1	34.3	<.05	.27	1.2
8- 9	A-13	18.1	.50	.20	.62	44.7	36.2	.12	.17	.92
9-10	A-14	13.4	.77	.20	.98	45.6	37.7	.07	.24	1.2
11-12	A-15	9.8	.40	.12	.88	48.0	39.2	.11	.21	1.2
Samples from Quarry B:										
0- 1	B-15	19.6	1.2	0.42	0.58	41.8	34.8	0.13	0.26	1.1
1- 2	B-14	20.8	1.2	.34	1.0	38.6	30.2	.12	.17	.71
2- 3	B-13	20.7	.95	.28	.91	41.5	34.4	.08	.17	1.1
3- 4	B-12	12.6	.49	.23	.94	45.8	38.0	.08	.16	1.2
5- 6	B-11	8.4	.36	.13	.90	49.1	40.2	.05	.09	.70
7- 8	B-10	6.3	.35	.13	.76	50.2	41.0	<.05	.10	.80
9-10	B-9	6.4	.35	.12	.61	50.8	40.9	.05	.09	.82
10-11	B-8	4.5	.30	.13	.76	51.7	41.6	.17	.10	.78
10-11	B-7	6.7	.29	.16	.98	49.8	40.8	.10	.13	.88
11-12	B-5	9.3	.36	.13	1.0	48.4	39.7	.05	.12	.82
12-13	B-4	9.1	.43	.12	.77	48.6	39.8	.10	.12	.80
14-15	B-3	6.3	.41	.12	1.1	49.9	40.8	.06	.08	.74
15-16	B-2	6.7	.35	.12	.96	49.7	40.5	.11	.16	.98
16-17	B-1	7.0	.37	.12	.62	50.3	40.5	.07	.16	.96
Samples from Quarry C:										
0- 1	C-1	40.1	2.0	0.78	0.67	30.0	25.0	0.05	0.46	1.2
2- 3	C-2	19.4	.68	.46	.58	42.8	34.8	.05	.24	.94
7- 8	C-3	6.8	.44	.14	.77	50.2	40.8	.05	.17	.82
9-10	C-4	8.9	.34	.08	.83	48.9	39.9	.05	.16	.68
10-11	C-5	9.8	.45	.12	.68	48.8	39.5	.05	.18	.87
11-12	C-6	6.6	.46	.12	.50	49.5	40.8	.06	~.15	.97
12-13	C-7	6.8	.46	.12	.80	50.3	41.0	.05	.13	.96
13-14	C-8	5.2	.30	.08	.64	51.5	41.2	.17	.16	.98
14-15	C-9	6.0	.28	.12	.94	50.1	40.8	.13	.33	.98

The known bentonitic clays in the Fezzan cover about 10 sq km. They are in playalike depressions in a region where the Nubian Sandstone crops out. The largest exposure of clay is south of Sebha in an area of about 2 sq km where the surface soils, about 20 cm thick, have been removed. Drill holes in this area penetrated several meters of the clay, but the actual thickness of the deposit is not known. The chemical analyses of one sample shows that it is mostly kaolinite.

The following analysis was reported by the U.S. Geological Survey X-ray laboratory in Denver:

An X-ray diffractometer and electron microscope examination shows the rock to be composed of the following minerals listed with a very approximate estimate of abundance. The estimates are plus or minus 20 percent of the amount shown.

	Percent		*Percent*
Kaolinite	60	Halloysite	5
Quartz	30	Mica	5

The origin of clays in this area is difficult to explain. Bentonites are generally regarded as an alteration product of volcanic ash, the alteration having taken place during or shortly after the deposition in water. The writer has suggested earlier (p. 50) that brackish lakes covered this area during late Eocene or early Oligocene time and during Quaternary time, and (p. 42) that the volcanic activities in Libya were post-Eocene, possibly during Oligocene and Quaternary times. Therefore, the occurrence of the bentonitic clays in Fezzan may be related to the volcanic activity of Jabal as Sawdā' and Jabal Al Harūj al Aswad. However, since the only available samples consisted mainly of kaolinite and halloysite, the clays may have formed as a result of the washing and reworking of the kaolinitic cement from the adjoining sandstones to the playa lake depressions.

Not enough is known about the nature and the extent of the clays in the Fezzan for an economic appraisal of the deposits.

GYPSUM

Gypsum occurs in several areas in northwestern Libya, near Yafran, Nālūt, Mizda, and Bu Ngem. Only the first of these deposits was investigated in any detail and is reported here.

BI'R AL GHANAM-YAFRAN DEPOSIT

A large deposit of gypsum and anhydrite occurs in the Bi'r al Ghanam–Yafran area of northwestern Libya. The area is connected by about 90 km of paved road to Tripoli on the Mediterranean coast.

The occurrence of gypsum was known to the Italian geologists who mapped the beds as part of the Jurassic System. Christie (1955, p. 14–15) mapped the gypsum

beds as part of the Bir al Ghanam Group. Brichant (1952) reported unlimited quantities of gypsum in Tripolitania but made no specific mention of the Yafran deposit.

The present writer made a brief study of the Yafran gypsum deposit in 1954 and recommended its exploitation as a source of building material to the Libyan Government. In 1957, because of the increased interest in low-cost housing by the U.N. experts and the Libyan Government, a detailed study of the gypsum deposit was made by James L. Gualtieri, of the U.S. Geological Survey.

Several holes were drilled at potential quarry sites; in Bi'r al Ghanam–Yafran area cores were collected, sampled, and analyzed. Logs of the drill holes, sample analyses, and a detailed account of the investigations were reported (Gualtieri, 1959).

The Bi'r al Ghanam–Yafran gypsum deposit is in the Bir al Ghanam Group (p. 29), which is divided into two laterally equivalent units—Bu Ghaylan Limestone and a gypsum-anhydrite unit. The gypsum-anhydrite unit consists of a white and gray massive gypsum interbedded with oolitic dolomite and dolomitic limestone and minor beds of clay. The following account of the nature and extent of the deposit is based on Gualtieri's (1959) report.

The gypsum and anhydrite deposit is exposed almost continuously along the Jabal escarpment from about 4 km west of Garian to about 14 km west of Yafran, a distance of about 60 km. The maximum exposed width of the deposit is about 25 km.

In exposures the deposit appears to be composed of gypsum interbedded with dolomitic limestone and some claystone, but considerable thicknesses of anhydrite were discovered in the drill holes.

In the Yafran area the deposit exceeds 400 m in thickness, but 40 km eastward, in the area of Caf el Caldia, it measures only 32 m, and about 2 km farther east it pinches away to nothing. The individual beds are lenticular, and only a few may be traced for more than a kilometer.

The deposit is flat lying to low dipping, but locally, at its eastern extremity the beds have been disturbed by intrusive igneous rocks.

The nature of the occurrence of gypsum and anhydrite revealed in some of the core samples strongly indicates that possibly much of the gypsum has been formed by the hydration of anhydrite. The anhydrite contains sparse selenite crystals which are rounded or roughly tabular, have a smooth outline, and are generally dark brown or brownish gray. They range from less than a millimeter to more than 2 cm in diameter, and some are zoned or contain clay laminae. Lesser amounts of selenite occur in the anhydrite as irregular seams or very thin undulating stringers which roughly parallel the bedding. These features are thought to represent an incipient stage of the conversion of anhydrite to gypsum. Where abundant crystalline selenite occurs in the gypsum, the host beds probably were originally anhydrite. As these selenite crystals occur in many of the gypsum beds, the deposit probably has undergone large-scale conversion. Contorted bedding, evident in the gypsum units as well as in the associated thin claystone seams and dolomitic limestone laminae, is believed to have resulted from the increase in volume of the rock upon the hydration of anhydrite (fig. 49).

Chemical analyses indicate small quantities of anhydrite in the gypsum which are thought to be residual, representing the last stage of the conversion process. The anhydrite in the deeper drill holes is considered to represent the unconverted parts of the deposit. It is therefore concluded that conversion has taken place only within a limited vertical zone that extends some distance beneath the present surface. This view is further substantiated by several surface exposures of gypsum units which, where intersected at depth in a drill hole, are found to be anhydrite.

Conversion probably affected the beds to a greater depth in the areas more distant from the main escarpment than in the nearer areas. The conversion process, resulting from the penetration of the beds by meteoric water, has likely been in effect longest in those places where the overlying beds were first removed. Based

FIGURE 49.—Contorted gypsum beds near kilometer 95, Azizia-Yafran highway. Dark bands in center of photograph are about 4 cm thick. Photograph by J. L. Gualtieri.

mainly on drill-hole information and also on the topography of the area, 30 m is estimated as the overall average thickness of the affected zone.

Because of their chemical similarity, the methods of quantitative determination of gypsum and anhydrite are much the same. The amount of sulfate as a weight percentage of the sample is determined, and from this figure the weight percentage of gypsum or anhydrite is calculated. Since the samples were thought to contain both minerals, calculations were made to ascertain the theoretical maximum percentage of each; the difference represented the theoretical weight-percentage of water of crystallization.

Plate 11 shows the log of a typical drill hole and chemical analyses of the samples.

RESERVES

Indicated and inferred reserves of gypsum were computed by Gualtieri (1962, p. 7). The location and extent of the reserves, by blocks, are shown in figure 50. Gualtieri stated the following:

The indicated reserves were computed from drill-hole data that were projected on 500-meter radii from the respective drill holes. Where two or more holes were drilled in an area to obtain a more complete section, the radius was projected from a point central to the holes. The computations were based on area, thickness, and specific gravity, and the results given in metric tons (1000 kgs). Topography of the areas included in the reserve blocks was taken into account in calculating the tonnages. The grades of the respective blocks were computed by combining and averaging the analyzed units. Only material averaging 64.5 percent or more $CaSO_4 \cdot 2H_2O$ is considered economically exploitable.

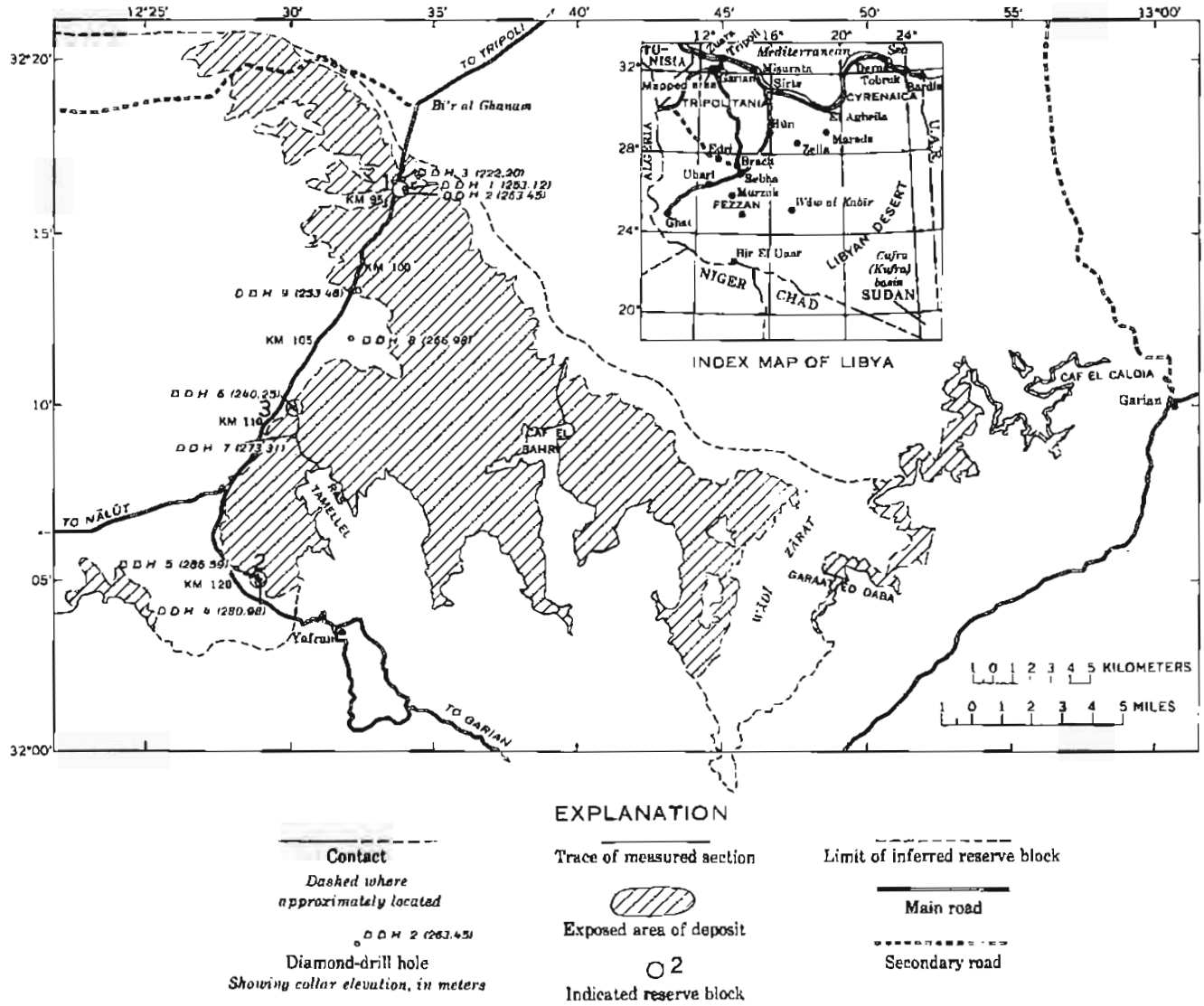


FIGURE 50.—Yafran gypsum-anhydrite deposits and reserve areas.

The indicated reserves are shown by blocks. The quantity is given to the nearest million tons and the grade to the nearest percent.

The figures are based on the assumption that all rock in the reserve blocks will be mined to the depths shown. The figures are as follows:

Block	Thousand of metric tons	$CaSO_4 \cdot 2H_2O$ (percent)	$CaSO_4$ (percent)	Overburden (m)	Thickness (m)
1 [1]	63,000	83	<1	0.07	53.82
2 [2]	31,000	75	(3)	1.00	34.61
3	91,000	80	<4	.55	50.20

[1] Based on combined data from diamond-drill holes 1, 2, and 3.
[2] Based on combined data from diamond-drill holes 4 and 5.
[3] Anhydrite may be present in very small quantities.

By mining all rock in the reserve blocks to the shallower depths, it is possible to obtain higher grade material in reduced quantities as indicated in the following table:

Block	Thousand of metric tons	$CaSO_4 \cdot 2H_2O$ (percent)	$CaSO_4$ (percent)	Overburden (m)	Thickness (m)
1 [1]	21,000	94	<1	0.07	23.11
2 [2]	10,000	91	(3)	1.00	26.31
3	67,000	85	<2	.55	37.29

[1] Based on combined data from diamond-drill holes 1 and 2.
[2] Based on combined data from diamond-drill holes 4 and 5.
[3] Anhydrite may be present in very small quantities.

Gualtieri (1959, p.9) further stated:

The inferred reserves are based on knowledge gained from examining and mapping the deposit and especially from the information obtained from the measured sections and drill holes. The reserves are estimated only for the exposed areas of the deposit and the adjoining alluvium-covered areas. The alluvium-covered areas include the broad valley of Wādī Zārat, the fringe area along the line of hills that trend northwest from Wādī Zārat to a point beyond Bi'r al Ghanam, and the large area west of the Azizia-Yafran highway from about km 90 to km 120. The extension of the deposit west of the highway to the limits shown on the reserve map is assumed because just east of the highway in the area of Ras el Tamellel and D.D.H. 6 it measures over 400 meters in thickness.

The indication that anhydrite predominates at depth, at least in the area immediately in front of the Jabal escarpment, has serious implications for it necessarily limits the volume of rock that can be assumed to be gypsum. Where the deposit is overlain by Cretaceous claystone beds, it must be assumed that little or no conversion has taken place and that the sulfate rock beds are predominantly anhydrite. Consequently this area is not considered as part of the deposit. As already indicated in the section on geology the zone of conversion is estimated to be no more than 30 meters thick, as an overall average.

The area of the inferred reserves was found by using a planimeter on a 1:100,000-scale map. The grade of the inferred reserve is considered to be equal to the weighed average of the three blocks of indicated reserves. This consideration is based on the field observation that generally the quality of the beds appear to vary but little from place to place.

On the basis of the concepts and procedures outlined above the inferred reserves are calculated to total 79,700,000,000 metric tons of material that is 80 percent $CaSO_4 \cdot 2H_2O$. The figure for tonnage is given to the nearest 100 million tons and that of grade to the nearest 10 percent as being more significant of the accuracy of the estimate.

OTHER OCCURRENCES

Occurrences of crystalline barite, selenite, and occasionally celestite have been found in the vicinity of Hūn and Socna, near Derj (Daraj), and at Ghadames. These minerals are on or near the surface in low sandy areas, and are commonly associated with gypsum or gypsiferous beds. They were probably formed through capillary migration and evaporation of the groundwater solutions in an arid desert environment.

The chemical analyses of some of these crystals indicate that some contain selenite, and others contain barite and, more rarely, celestite. The crystals contain large amounts of silica sand that is bound together by the sulfate.

In most localities these tabular crystals are less than 1 cm in diameter and are commonly intergrown as rosette-like aggregates. At Ghadamēs, near the Tunisian border, are unusually large and well-formed crystals as much as 25 cm in diameter grouped in clusters, some of which are at least 50 cm across (fig. 51). These clusters of large crystals, often called desert roses, are also abundant just northwest of Ghadamēs in Tunisia, where they are reported to occur in low dunes.

Microscopic study of one of these tabular crystals, by Charles Milton, U.S. Geological Survey, indicated that

FIGURE 51.—"Desert rose" from southern Tunisia at Fort Sainte close to Ghadamēs, Libya. Specimen, about 20 cm across, was supplied by Harry F. Thomas. The largest "petal" in this specimen is about 8 cm in diameter.

"It is a sand cemented by gypsum, with a very little carbonate. It resembles the well known 'sand-calcites' from South Dakota, only in this case the cement is gypsum. Possibly the concretions were originally cemented by calcite, which has been replaced by gypsum."

Gypsum replaces fossils in the Miocene and Oligocene rocks in the eastern Sirte area and in north-central Cyrenaica south of the Jabal area. In the Sirte area near Marada, north of Jabal Zaltan and northeast of Gialo, the middle Miocene coralline limestones are exposed in scattered butte-type outcrops. In some areas, fossil hexacoralla have been entirely replaced by gypsum (fig. 52).

This unusual replacement of carbonate by sulfate is probably a surface phenomena that may be attributed to the capillary migration of sulfate waters under arid desert environment. However, it is possible that gypsum may have been formed by hydration of anhydrite.

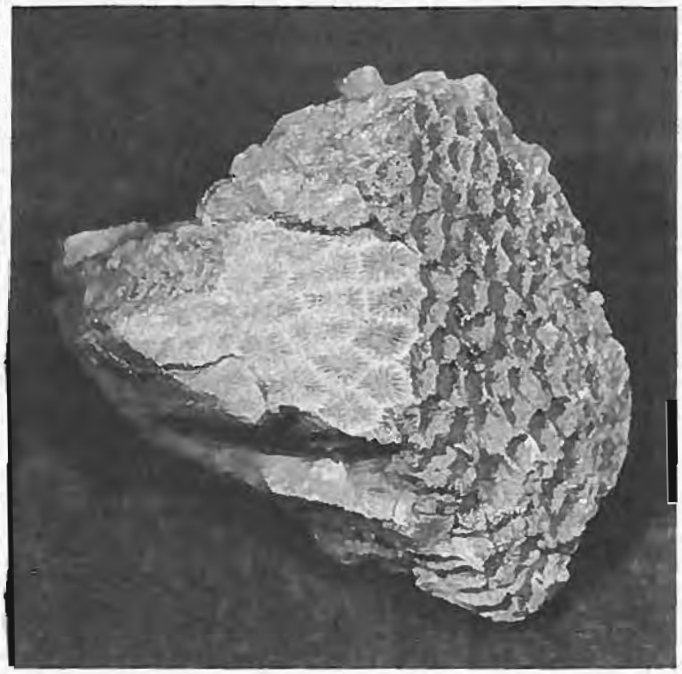


FIGURE 52.—Hexacoralla entirely replaced by gypsum in outcrops west of Marada. Note the perfect radial symmetry in the flat unweathered surface in front and the conspicuous weathered surface on top.

LIGNITE OR LIGNITIC CLAYS

Lignite has been reported in northern Tripolitania in the Lower Cretaceous Kikla Sandstone in Jabal Nefusa–Jabal Garian escarpment and in the Upper Cretaceous beds in the Al Kussabat region. Other occurrences of lignitic clays were noted by the writer in Wādī Ajal near Ubari and in the Ghāt area of southwestern Libya.

Italian geologists, notably Viezzer, Zaccagna, Principi, and Sassi, made a study of the lignite in the Jabal escarpment of Tripolitania at Kikla, Shecshuk, Giosc, Tijī, Nālūt, and other areas. Their work has been discussed in detail by Desio (1943, p. 266–285). According to Zaccagna, as described by Desio, the lignite is found between the sandy marls and sandstones of Wealden Age in the Jabal escarpment. The combustible material is impure and irregularly interbedded with carbonaceous marl. The present writer noted this lignitic zone at several places in the Kikla Sandstone but did not consider it of any commercial value.

Study of the so-called lignites in the Al Kussabat area, reported by Viezzer (1929), indicate that they are merely a carbonaceous (or organic) clay. Two samples collected from a dug well near Al Kussabat had the following chemical compositions in percent:

	1	2
Organic matter	1.4	1.1
Carbon	.4	.3
P_2O_5	.4	.5
$CaCO_3$	78.0	82.6
Other (by difference)	19.8	15.5

NOTE.—Samples were analyzed at the Libyan-American Joint Services Chem. Lab., Tripoli, under the supervision of Pierro Grossi.

Brichant (1952) also made a study of the reported lignites in Tripolitania and with Dr. Chiesa examined those reported by Viezzer in the Al Kussabat region. Brichant noted the occurrence of a lignitic layer near Shecshuk at the base of the Jabal escarpment but found no evidence of a potentially commercial deposit. Citing an unpublished report by Chiesa, he also noted the existence of a lignite bed about 8 cm thick near Al Kussabat. This lignite bed is within a series of lignitic clays that represent a lacustrine swampy facies that is characterized by the presence of fungi.

In the Ubari area in Wādī Ajal, an organic bed 15 to 30 cm thick occurs at several places between Al Qurayfah and Ubari. It was noted in many dug wells and can be traced for several kilometers along the valley. Samples collected from the beds had the following chemical compositions in percent:

	1	2	3	4
Carbon	10.6	9.5	21.9	10.5
Organic matter	3.5	2.6	3.6	2.5

NOTE.—Samples were analyzed at the Libyan-American Joint Services Chem. Lab., Tripoli, under the supervision of Pierro Grossi.

In the Ghāt region, carbonaceous or lignitic beds average about 90 cm in thickness. These beds seem to have been formed under lagoonal conditions restricted to small areas. They can be traced for several kilometers southwest of Ghāt where they are exposed in irrigation

canals, but their areal extent is unknown. The analyses of this material, in percent, are as follows:

	1	2	3
Carbon	6.0	4.1	30.5
Organic matter	1.5	1.1	2.2

NOTE.—Analyses were made at the Libyan-American Joint Services Chem. Lab., Tripoli, under the supervision of Pierro Grossi.

PHOSPHATE

Major phosphate deposits of north Africa in Morocco, Algeria, Tunisia, and Egypt are in lower Eocene and Upper Cretaceous rocks, which also crop out in some areas in northern Libya. A careful exploration by the Italian geologists from 1934 to 1940, however, failed to prove the existence of commercial phosphate deposits in Libya. Desio concluded that further search is needed to complete the investigations (Desio, 1943, p. 299).

The present writer made a reconnaissance study of the lower Tertiary and Upper Cretaceous rocks of Tripolitania and Cyrenaica. Several areas were studied and the rocks were tested in many places, but no phosphate of commercial value was found.

BENI ULID-WĀDI SOFFEGIN PHOSPHATE DEPOSITS

The existence of phosphate rocks in the Beni Ulid-Wādi Soffegin area was known to the Italian geologists, and Lipparini (1940, p. 249) pointed out that the phosphate beds are exposed in a narrow arcuate belt about 60 km long on the nose of a broad anticlinal structure. In this area the phosphate nodules are in a light-gray chalky marl (fig. 53) overlying a glauconitic limestone, below which is a thin phosphate-rich layer about 20 cm thick. The beds are exposed in patches, and the eroded surface is marked by a glauconitic bed that can be traced for several kilometers. Where now exposed the bed shows evidence of having been partially eroded during Late Cretaceous or early Tertiary time. It was thought that by drilling far enough down the flank or nose of the anticline, in an area where the beds were not eroded during and after movement, an appreciable thickness of phosphate rock might be found. The area was tested by 12 drill holes, but no commercial phosphate rock was found. A typical log of the drill holes follows, and the locations of the drill holes are shown in figure 54.

FIGURE 53.—Phosphatic nodules in the form of black concretions in a light-gray to white marl at about 40 km southeast of Beni Ulid in Wādi Soffegin area. The dark-gray nodules can be seen in the center of the photograph just above the pick.

Phosphate in Wādi Soffegin area—drill hole 9

From (m)	To (m)	Interval thickness (m)	P_2O_5 (percent)	Description
0.00	1.00	1.00		Surficial cover; soft, calcareous material, broken-up core.
1.00	2.20	1.20		Limestone or marl, soft, calcareous, white to pale-orange.
2.20	2.50	.30		Limestone, white, finely granular.
2.50	2.65	.15		Limestone or marl, soft, calcareous, white to pale-orange.
2.65	3.50	.85	0.1	Limestone or marl, yellowish-orange, soft, partly limonitic. Tubule structure in sections filled with gypsum; some fine sand grains and calcareous material.
3.50	4.55	1.05	.1	Limestone, very light orange to yellow, soft, slightly glauconitic.
4.55	5.00	.45	1.0	Limestone or marl, very pale orange to pale-yellowish-orange, soft; more glauconitic than unit above.
5.00	5.80	.80	1.0	Limestone, greenish-gray; contains abundant glauconite grains, about 20–30 percent of the material is glauconite; contains small sand grains, core broken up.
5.80	7.00	1.20	2.8	Limestone, pale-orange to greenish-gray; core partly broken up; contains abundant glauconite particles which increase toward the base of the unit.
7.00	9.75	2.75	3.0	Limestone, greenish-gray to green; about 40 percent of the material is glauconite; contains sparse sand grains, more abundant glauconite near the base of the unit (from 8.35 to 9.75, core broken up).
9.75	10.40	.65	2.0	Limestone, greenish-gray; contains glauconite particles, sparse sand grains, and thin calcite bands; limonitic in parts.
10.40	11.00	.60	.8	Limestone or marl, light-gray to buff; with sparse shale partings near the base.
11.00	13.50	2.50	1.9	Limestone, greenish-gray to green; contains abundant glauconite grains, core broken up.
13.50	13.70	.20	.6	Limestone or marl, greenish-gray; shale or clay bands as much as 5 cm thick.
13.70	15.00	1.30	1.5	Limestone or marl, pale-orange to yellowish-orange; contains sparse sand grains and calcite nodules; in parts limonitic.
15.00	16.00	1.00	.01	Limestone or marl, greenish-yellow; contains nodules of calcite crystals, sparse shale or clay partings, and sparse sand grains; limonitic in parts.
16.00	17.00	1.00	2.4	Limestone, greenish-gray to green; contains a moderate amount of glauconite particles and sparse sand grains; core broken up.
17.00	18.00	1.00	Tr.	Limestone or marl, light-gray to yellowish-pink, hard; contains sparse fossil fragments, some calcite grains and gypsum particles.
18.00	19.40	1.40	2.5	Limestone, greenish-gray to green; contains abundant fine glauconite grains.
19.40	20.00	.60	Tr.	Limestone or marl, grayish-green to buff; in parts limonitic.
20.00	20.55	.55	2.7	Limestone, grayish-green to green, contains fine glauconite grains and sparse sand particles; core broken up.
20.55	21.00	.45	Tr.	Limestone, yellowish-gray, hard; vuggy near base, in parts limonitic.

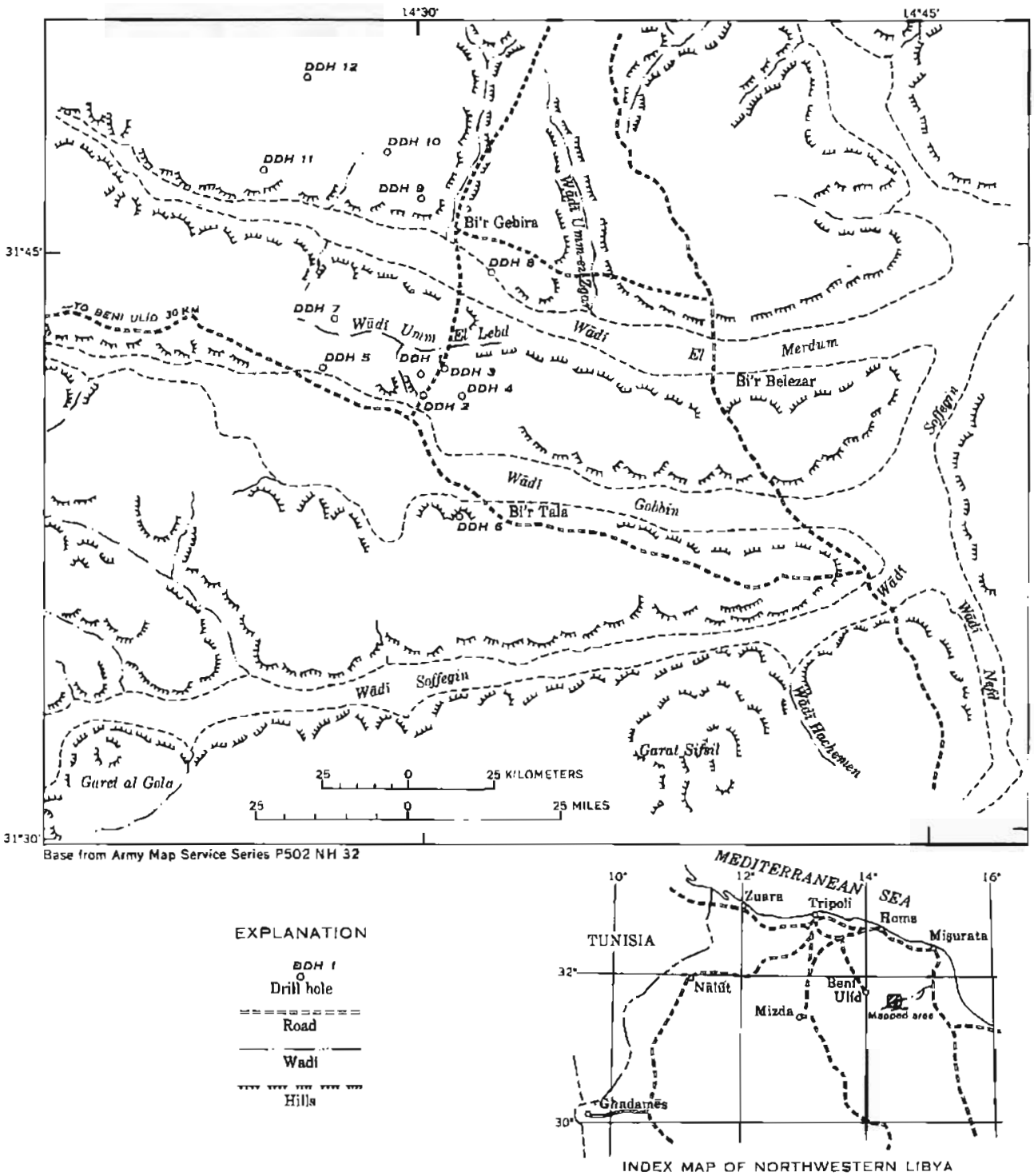


FIGURE 54.—Locations of drill holes in Wādī Soffegin area.

Field identification of phosphate rock is difficult; so even though investigations thus far have not been fruitful, the absence of commercial phosphate in Libya is not proven. Information obtained through the courtesy of some of the oil companies confirms the belief that a phosphatic zone occurs at the contact of the Tertiary and Cretaceous rocks. This phosphatic bed, as much as 10 m thick, has been found at depths greater than 1,300 m in several drill holes, but its phosphate content has not been determined. Exploration or exploitation of the phosphate beds at such depths is not economical, but it is recommended that the outcrops of lower Eocene and Paleocene beds and other outcrops near the Tertiary-Cretaceous boundary be thoroughly examined and studied. The areas east and west of Bu Ngem along the Hun graben and in Wādī Zamzam, Wādī Ruu's, and Wādī Zmam (Wādī az Zimām), where the Tertiary-Cretaceous contact can be traced for several kilometers, warrant further investigation (fig. 55).

SALINE DEPOSITS

The sebchas (sabkhah),[9] or salt flats, are formed as lagoonal deposits near the coast and as playas in closed depressions in the desert interior. The deposits along the coast are generally formed by infiltration of sea water through or over sandy barriers into coastal depressions. In the desert interior, the salts dissolved out of the rocks find their way into depressions where, by processes of capillary migration and evaporation, a crust of salt is formed on the surface. These deposits generally consist of a mixture of sand and clay containing variable amounts of sodium, potassium, and magnesium salts. They are superficial and of present-day formation.

Saline deposits in northern Cyrenaica occur near Bengasi, At Tamimi, and along the coast of the Gulf of Sirte where they cover vast areas and are separated from the sea by a coastal ridge. In the Cyrenaica desert they are present in several depressions, notably at Marada, Giarabub, Augila, Gialo, and Cufra. In the Fezzan, many salt flats are present in Wādī ash Shāṭi' and Wādī Ajal, at Edri, Ghāt, Trāghan, Umm al Arānib, Tmassah, Gatrun, and Wāw al Kabīr. In Tripolitania these salt flats occupy large areas along the Mediterranean coast at Pisida, near Tripoli at Mellaha (Mallāḥah), and on the west side of the Gulf of Sirte at Tauorga.

[9] The Arabic plural for sabkhah is sib'akh, but sebcha (or sebchas, plural) has been used in recent literature and is used in this report.

The first studies of saline deposits of Libya were made, beginning in 1926, by Italian geologists under Desio, and detailed study of the Marada deposit was begun in 1937. The results of their work were described by Desio (1943, p. 153–263).

In the present study several saline deposits in Libya—notably Marada, Edri, Ghāt, Pisida, and Tauorga—were investigated as possible sources of potash and other valuable salts and are discussed in the following pages.

MARADA

The Marada saline deposits are about 125 km south of El Agheila on the Gulf of Sirte and cover an area of approximately 150 sq km. The deposits occur in the lowest areas of an erosional depression approximately at the level of contact of the lower Miocene and Oligocene formations.

North of the sebcha, a high escarpment consists of a lacustrine or continental sequence of gray and green clay, sandy clay, marl, gypsum, and sandstone of Miocene age (fig. 56). To the southwest, the sebchas are bounded by Oligocene rocks consisting of dolomitic limestone having intercalations of gypsiferous green clays. The residual matter at the bottom of the sebcha consists of alternate beds of clay and sandstone interbedded with salt rock. These beds contain a rich fauna of lagoonal mollusks, indicating a transition from marine Miocene to a lagoonal facies (T. Lipparini, written commun., 1955).

Remnants of the Miocene formations in the form of buttes in the middle of the salt flats and the escarpment directly north of them suggest that part of the Miocene formations containing the salts was destroyed by erosion, probably by gradual dissolution, and was deposited at the bottom of the sebcha.

GENESIS

The Marada sebcha is thought to be a concentration of saline residues left by the receding Miocene seas, a concept also held by T. Lipparinii (oral commun.). Rainwater dissolves the residual salts from surrounding rocks and transports them to the low parts of this completely closed basin. These solutions supplement the already concentrated brine of the sebcha.

The salts carried out in solution are deposited in inverse order of their solubility. Therefore, the less soluble salts of gypsum and halite are deposited on the shallow western part of the area and the more soluble salts, largely KCl and $MgCl_2$, accumulate in the lower parts of the depression.

The Marada saline deposits consist of a crystalline salt about 50 cm thick above the brine. They are superficial and of recent origin and are being formed

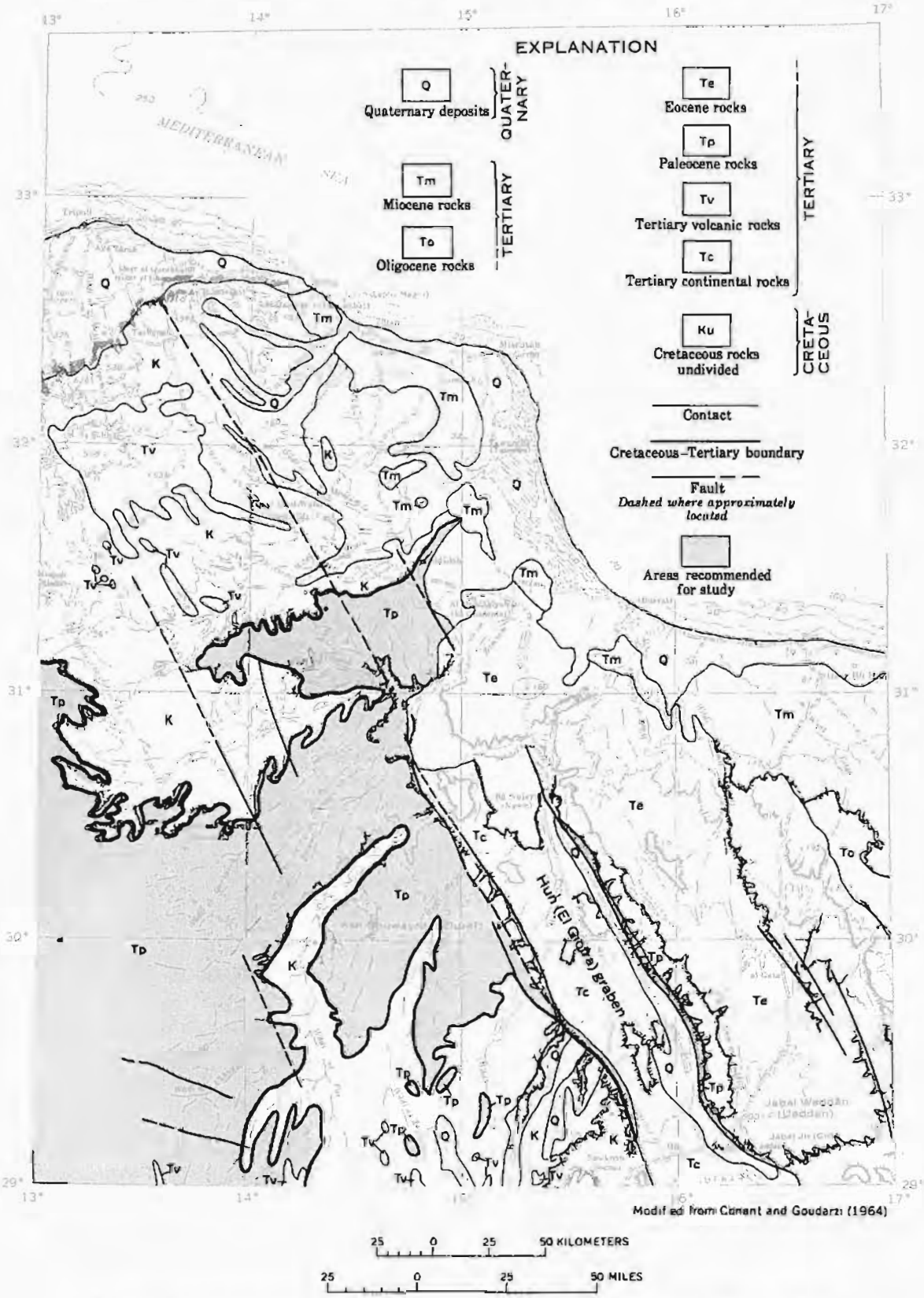


FIGURE 55.—Areas recommended for future exploration for phosphate in western Libya.

FIGURE 56.—Marada salt flats and Miocene escarpment north of the sebcha. The white material is carnallite deposited in experimental pits.

by processes of capillary migration and evaporation during the hot summer months.

The brines at Marada yield a mixture of $MgSO_4$, $MgCl_2$, NaCl, and KCl. The chief minerals are halite (NaCl) and carnallite ($KMgCl_3 \cdot 6H_2O$). Samples of the crystalline crust in the center of the area averaged 20.45 percent Na, 13.05 percent K, and 2.28 percent Mg. Samples from the crust in the higher areas, near the edges, averaged 4.46 percent Na, 1.88 percent K, and 5.13 percent Mg. The saturated brine in the pits averaged 18.6 percent Na, 15.3 percent K, and 20.3 percent Mg.

The deposits were worked in an experimental manner by the Italians in 1939. Several hundred pits 2 m square were dug to the water table into which percolated the brine. Within a week the pits would fill with an accumulation of salts, each pit netting about 80 kilograms of a mixture of $MgSO_4$, $MgCl_2$, NaCl, and KCl. These salts were redissolved and by fractional crystallization, a final product of potassic salt containing 40 to 50 percent K_2O equivalent was obtained.

During 1939 the Italian operators produced about 21,000 tons of potassic salts which were transported by truck from Marada to El Agheila and from there about 40 km west to the port of Ras el Ali for export.

Only 15 sq km of the entire area was considered to contain commercial quantities of potassic salts. Based on drill-hole information the reserves were estimated to be 1.6 million tons of potassic salts containing about 40 percent K_2O equivalent and 7.5 million tons of $MgCl_2$ (Desio, 1943, p. 153–263).

ECONOMIC CONSIDERATIONS

The present investigations indicate that the Marada deposits offer favorable opportunities for commercial exploitation (Goudarzi, 1962d, p. 7). Of 150 sq km of the sebcha, only 15 sq km has been developed. Larger areas of the Marada salt flats may contain salts in commercial quantities. The artesian water wells in the area may be of considerable value in local refining and concentration of the salts at low costs. A nearby source of fuel, such as natural gas and crude oil, is also available.

EDRI

The Edri saline deposit, about 135 km west of Brach, covers an area of about 35 sq km. The area is connected by about 250 km of secondary road to the hard-surface Fezzan road about 500 km south of the coast.

The Edri deposit lies in a closed depression in a region of Devonian rocks. Its origin is attributed to the percolating meteoric waters which dissolve the soluble constituents from the surrounding sandstone and siltstone and carry them into the Edri depression. The waters are concentrated to a brine which saturates the sand and which by capillary migration and evaporation causes salts to accumulate on the surface in the form of evaporites.

The deposit consists of a hard crust of fairly pure halite as much as 40 cm thick overlying an undercrust of mixed salts and wet sand 30 cm thick; below this undercrust at an average depth of about 60 cm is the brine level.

SAMPLING

The deposit was first investigated by analyzing samples of the salts and the brine from 25 test pits. Chemical analyses by the Libyan-American Joint Services Chemical Laboratory show that the crust is composed mostly of halite but that small quantities of potassium and magnesium chlorides are present. The undercrust is a mixture of wet sand and salts, and the brine contains even lesser amounts of the salts.

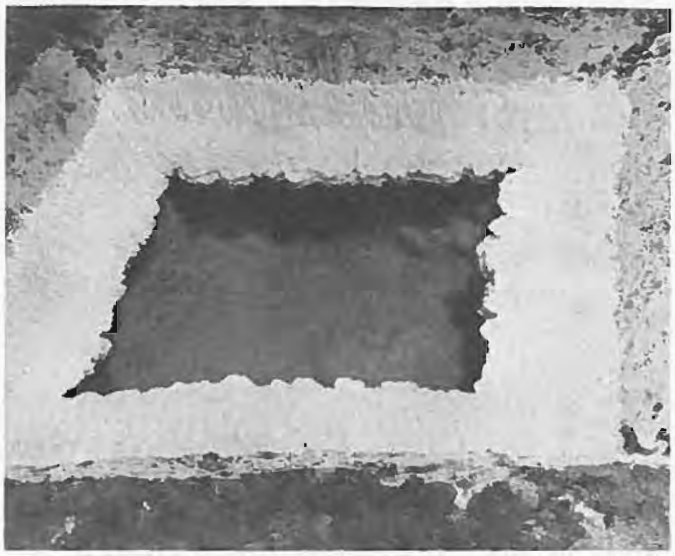
The average compositions of the 25 samples in percent, are as follows (water-insoluble components not determined):

	NaCl	K_2O equivalent	$MgCl_2$
Crust	69.9	3.4	1.6
Undercrust	13.5	.7	.4
Brine	11.2	.6	.6

SOLAR EVAPORATION

The Edri deposit was further investigated by selection of 14 areas, each 30 m square, for evaporation tests. As a first step the crust was removed, and samples of the crust, undercrust, and brine were collected. The locations of these areas and test pits, together with summaries of the sample analyses, are shown on plate 12.

A



B

D

E

FIGURE 57.—Sequence of crystallization of brines by solar evaporation at Edri, Fezzan. *A*, Experimental pits in test areas. The pits are about 3 m square and 60 cm deep. The test areas are 30 m square. Evaporation tanks are shown in the center. *B*, Supersaturated brines in the pit. *C* (facing page), Crystals formed at bottom of pits within 2 weeks. *D*, Salt crust formed on top of pits. *E*, Salts produced in evaporating vats.

C

In each area 25 pits, each about 3 m square, were dug to the water table, and the brines were allowed to accumulate and evaporate (fig. 57*A*). Brine samples were collected periodically from each area and, although a trend toward gradually higher concentration was noted, no appreciable increase in the total dissolved solids was observed. Several tables showing the analyses of the periodic samples of the brine have been reported (Goudarzi, 1962b, p. 10–23). Figures 57*B*–*E* show the different stages of evaporation in the pits.

FRACTIONAL CRYSTALLIZATION

As a third phase of the investigation, two tanks, A and B, were constructed in each area. In each area, brine was poured into tank A, sampled and allowed to evaporate. After several days the residual brine was transferred to tank B, sampled and allowed to evaporate to dryness. The crystallized salts from each tank were collected, weighed, and sampled. The initial volume and composition of the brine in each tank, the date sampled, the number of days in each tank, and the weight and composition of the crystallized salts, were recorded (Goudarzi, 1962b, p. 31).

Experiments on fractional crystallization of the salts by solar evaporation were inconclusive, but the tests for recovery of potash indicated that a fairly pure table salt of about 96 percent NaCl could be obtained from the Edri brines on the first stage of crystallization (fig. 58). Analyses of the residual brines and those of the salts collected in the second stage show that they contain an average of 4.7 percent K_2O equivalent. Laboratory experiments indicated that from 1 metric ton of the natural crude salt, 200 kg of a product containing 6 to 10 percent potash (K_2O equivalent) could be recovered. The experiments also indicated that generally in the east-central and lower parts of the Edri deposit area the potassium content is higher than at the edges.

ECONOMIC CONSIDERATIONS

The present naturally formed crust at the deposit is estimated to contain about 3 million tons of mixed salts, of which about 2 million tons is common salt (NaCl) and about 160,000 tons is potash (KCl). Because salt crusts continue to accumulate on the surface, it is estimated that within 5 to 10 years the harvested areas would be covered by a new salt crust. Therefore the deposit may be worked repeatedly if selective harvesting is practiced and only 10 to 20 percent of the area is mined in 1 year. However, marketing, transportation, operational expenses, and other economic factors will have to be considered before any development of the deposit is undertaken.

GHĀT

Salt flats cover a small area of about 1 to 2 sq km south of Ghāt. Salt from this deposit, mined in a primitive manner, is used locally as common table salt.

Analyses of several samples of the crust, about 20 cm thick, show the following average chemical composition, in percent: Na, 28.2; K, 1.6; Cl, 44.4; SO_4, 4.5; and CO_3, trace. (The water-insoluble components were not determined. Analyses were made at the Libyan-American Joint Services Chem. Lab., Tripoli, under supervision of Pierro Grossi.)

FIGURE 58.—A cluster of halite crystals formed in a pit at Edri. Note the perfect crystal cubes in the cluster. The crystals are about 1½ cubic centimeters.

This impure salt could be dissolved and recrystallized by solar evaporation to produce a better quality of table salt for local consumption.

PISIDA

The Pisida salt deposit is about 165 km west of Tripoli on the Mediterranean coast and covers an area of about 50 sq km in Libya. It parallels the coast westward from the village of Pisida and continues across the border into Tunisia.

The deposit is a natural salt flat in a depression separated from the Mediterranean Sea by a narrow sandy barrier. It is an ephemeral deposit of brine-impregnated salt, formed during the dry season by solar evaporation of sea water percolating through the sand barrier. Cores collected from drill holes show that the deposits are surficial and that there is no salt stratum at depth. The deposit consists of a crust of fairly pure salt (NaCl) 3 to 10 cm thick and an undercrust as much as 30 cm thick consisting of impure salt having a high brine content.

Chemical analyses of the crust show that potassium and magnesium chlorides are present in small quantities. That greater amounts are not present may be due to the relatively cool and humid climate of the area which prevents completion of the ideal cycle of evaporation. Halite and sylvite salts, less soluble than $MgCl_2$, crystallize out to form the surface and the subsurface crusts, resulting in a residual brine that is relatively high in $MgCl_2$ (Goudarzi, 1962c).

The deposit was investigated by collecting and analyzing salt and brine samples from 19 test pits and two drill holes (fig. 59 and accompanying table).

The log of drill hole 2 follows.

Log of diamond-drill hole 2, Pisida salt flat

From (m)	To (m)	Thickness (m)	Description
0.00	0.60	0.60	Quartz sand, reddish brown, fine, rounded, loosely cemented. Some larger round calcareous particles.
.60	1.68	1.08	Quartz sand, light-brown, coarse to medium, well-cemented; contains shell fragments.
1.68	2.88	1.20	Quartz sand, poorly cemented, white; abundant shell fragments, fine, angular to rounded.
2.88	4.33	1.45	Quartz sand, very light brown; rounded to angular grains, sparse shell fragments; very poorly cemented.
4.33	4.86	.53	Quartz sand, white, coarse; abundant rounded shell fragments and calcareous oolites; fairly well cemented.
4.86	6.04	1.18	Quartz sand, white, fine to medium; abundant shell fragments; well cemented.
6.04	6.55	.51	Quartz sand, white, coarse, rounded; abundant shell fragments; well cemented.
6.55	7.40	.85	Quartz sand, yellowish-brown, coarse; very poorly cemented; some macrofossils.
7.40	10.09	2.69	Calcarenite, white, very fine; abundant fine-grained quartz, macrofossils.
10.09	10.33	.24	Quartz sand, white, coarse, rounded; abundant shell fragments; well cemented.
10.33	11.48	1.15	Quartz sand, light-gray, fine; macrofossils.
11.48	12.33	.75	Quartz sand, light-brown, fine.
12.23	14.13	1.90	Quartz sand, light-brown, fine, argillaceous.
14.13	16.13	2.00	Quartz sand, light-gray, fine, calcareous; macrofossils; base coarser and well cemented.
16.13	18.33	2.20	Quartz sand, reddish-brown, medium to coarse, subangular to rounded grains; sparse shell fragments.

Analyses indicate that the surface evaporites contain about 6.2 percent potassic salts and that the brine contains an average of about 9.5 percent $MgCl_2$. The concentration of magnesium and potassium chlorides is greatest in the northwestern part of the area; there the KCl content of the crust and undercrust averages about 7 percent compared with an average of 5.5 percent at other localities. In the same part the $MgCl_2$ content of the brine ranges from 11 to 20.5 percent, averaging about 14 percent, in contrast with the other parts of the area where the average is about 7 percent $MgCl_2$ (fig. 60). The reason for the local concentration of these two salts is not known, but it may indicate a lateral migration of the brine.

ECONOMIC CONSIDERATIONS

In 1929 under the direction of Dr. Niccoli, an Italian chemist, extensive experiments were made to determine the economic recovery of potassium and magnesium salts from the Pisida brines. The Niccoli process was developed whereby the brine was concentrated by solar evaporation to produce bitterns relatively rich in potassium. The bitterns were treated in three stages to prepare a commercial grade product. During the present study, inconclusive laboratory experiments indicated that extraction of potassium and magnesium salts from the Pisida brines might be possible by fractional crystallization. However, much additional field and laboratory work is needed to determine the commercial feasibility of exploitation of the deposit.

TAUORGA

The Tauorga saline deposit or salt flat (sebcha) is due south of Misurata along the west coast of the Gulf of Sirte and has an area of about 1,000 sq km. It is a natural depression separated from the gulf by a small narrow sandy barrier.

The brines accumulating in the basin consist of sea water that has either flowed over the sand barrier at high tide or percolated through it, plus brines concentrated by evaporation from stream discharge.

During the hot summer months, a crust forms at the surface by capillary migration and evaporation. Analyses of grab samples of the surface crust at Sabkhat al Hescia (Sabkhat Heshia) averaged 23.16 percent Na, 4.35 percent K, and 0.83 percent Mg; about 3 km farther south the samples averaged 36.35 percent Na, 0.19 percent K, and 0.18 percent Mg.

Various thicknesses of gypsum and halite have been deposited around the edges of the sebcha. Several hundred samples of the crust and the brine were collected in July and August of 1957 (fig. 61). A few samples of the surface crust, in localized areas, contained

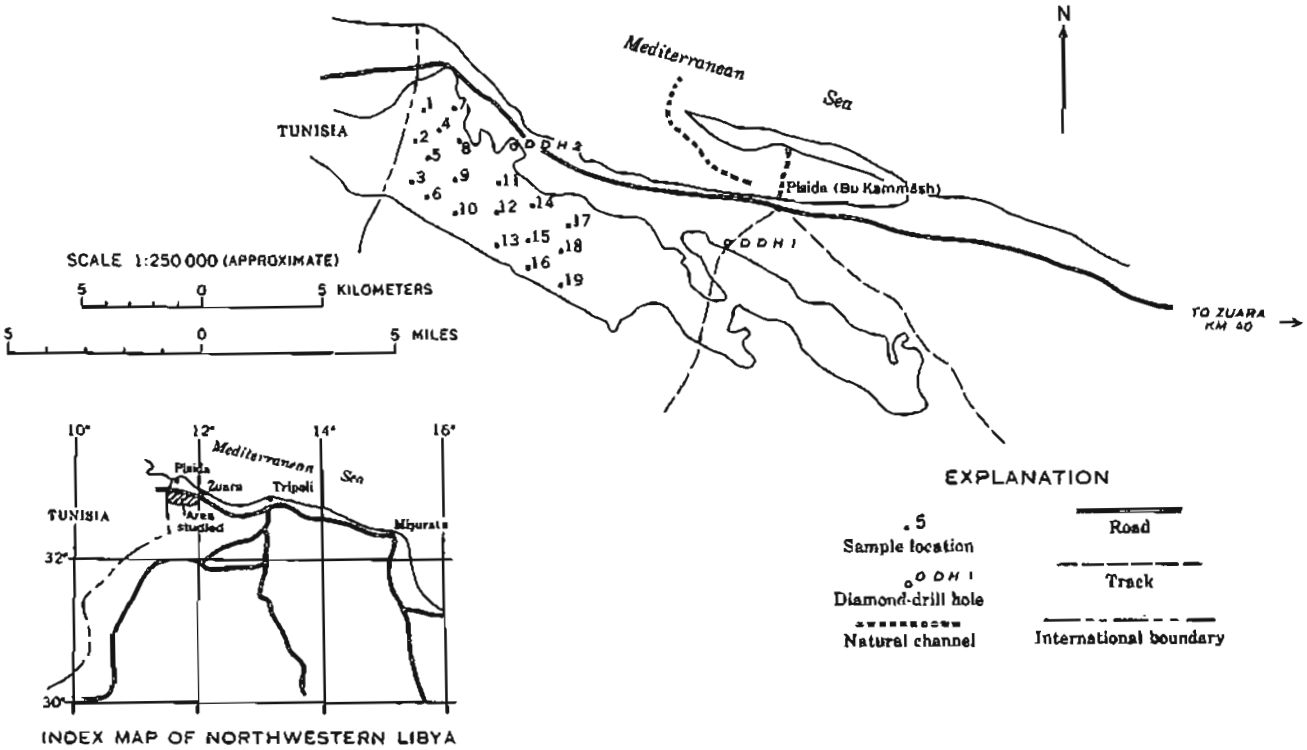


FIGURE 59.—Locations of sample pits and drill holes at Pisida. See also accompanying table.

Analyses of samples from Pisida whose locations are shown in figure 59

[Type: a, crust or surface composite; b, subsurface or undercrust; c, subsurface or undercrust (muddy); d, brine]

Sample No.	Type	NaCl	KCl	$MgCl_2$
1	a	85.2	4.9	0.8
	b	87.7	4.9	0.8
	c			
	d			
2	a	89.1	5.4	1.1
	b	6.9	.9	2.4
	c			
	d	13.8	1.1	8.9
3	a	86.1	7.8	.9
	b	71.8	4.9	1.2
	c			
	d	15.1	1.1	8.4
4	a	89.3	5.4	.8
	b	10.3	.7	3.7
	c	89.8	5.9	.5
	d	17.1	.8	6.2
5	a	94.7	6.1	1.0
	b	47.5	6.2	1.6
	c	86.2	9.6	.4
	d	14.1	1.3	20.5
6	a	88.3	6.3	.9
	b	53.8	6.5	1.1
	c	90.5	7.5	.3
	d	14.3	1.0	8.5
7	a	85.8	8.6	1.1
	b	3.3	.4	1.5
	c	89.1	5.3	.5
	d	15.0	1.2	8.7
8	a	85.8	9.2	.7
	b	12.0	1.5	2.4
	c	83.9	10.2	.6
	d	14.1	1.5	11.2
9	a	90.8	6.6	1.0
	b	81.8	8.0	.7
	c	85.2	9.8	.5
	d	10.2	1.7	16.6
10	a	85.2	7.4	1.0
	b	70.0	6.8	1.1
	c	92.9	6.5	.5
	d	14.2	1.3	11.0
11	a	92.2	4.7	1.0
	b	67.3	7.4	1.3
	c	93.7	6.2	.4
	d	11.9	1.5	11.8
12	a	91.7	6.8	.9
	b	70.9	5.8	1.0
	c	93.2	6.1	
	d	14.9	1.0	8.2
13	a	90.8	7.8	1.5
	b	7.8	3.2	2.7
	c	92.6	5.5	.8
	d	22.8	1.0	7.5
14	a	90.0	8.4	1.0
	b	8.4	.8	1.8
	c	93.8	5.9	.3
	d	18.5	.9	7.8
15	a	88.4	8.2	.8
	b	11.8	1.9	1.7
	c	89.9	6.2	.3
	d	23.2	.9	7.1
16	a	51.7	9.0	1.7
	b	10.4	3.1	3.5
	c	73.8	17.4	.3
	d	19.0	.7	7.0
17	a	45.8	7.1	1.4
	b	10.0	1.8	1.5
	c	89.0	7.3	.2
	d	10.6	.2	2.7
18	a	53.4	7.0	1.0
	b	8.4	1.9	1.4
	c	89.2	10.3	.5
	d	29.1	.5	5.1
19	a	12.0	.5	.9
	b	11.9	.7	1.5
	c			
	d	25.7	.4	6.5

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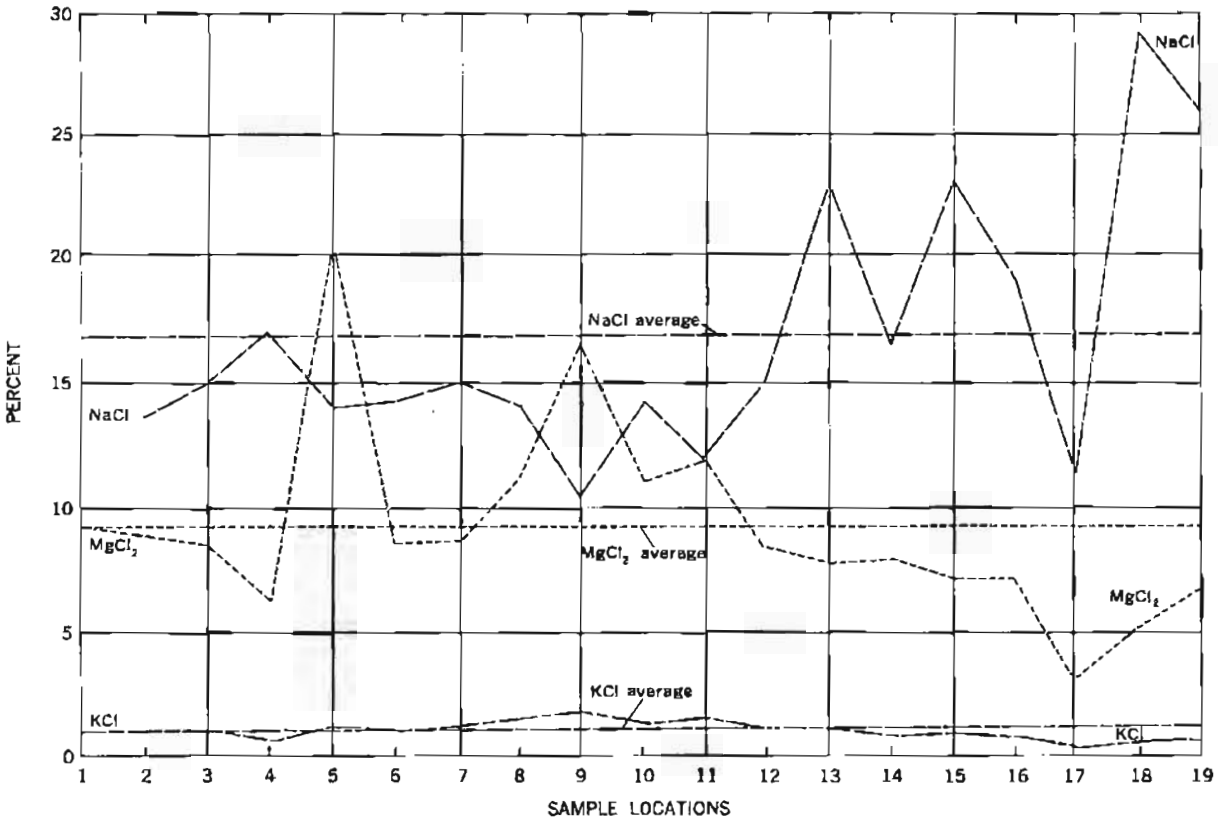

FIGURE 60.—Variation in salt contents at Pisida.

as much as 3 percent K, but the average potassium content of the crust and the brine is less than 0.5 percent.

MELLAHA (MALLĀḤAH) SALT WORKS

Mellaha (Arabic word for salt) deposits are east of Tripoli and cover an area of about 12 hectares (30 acres) along the Mediterranean coast. They occur in a depression slightly below sea level and are utilized as a salt plant or salt works consisting of several manmade evaporating pans in a depression or basin fed directly from the sea by a canal. The brines are allowed to evaporate and the crystallized salts are harvested, piled up in heaps, and transported to market. No accurate production figures are available, but it is estimated that about 30,000 tons of table salt is produced annually. Similar saltpans are also worked in the Bengasi area.

OTHER OCCURRENCES

Several other saline deposits are present in Libya and are shown on plate 1. Some of these deposits were studied by Italian geologists and described by Desio (1943). (See p. 83.) Owing to remoteness of the area, time, inaccessibility, and other factors, these deposits were not investigated.

SILICA SAND

Silica sand derived from sandstone exists in large quantities in Tripolitania at the base of the Jabal escarpment. The sandstones belong to the Tījī Group of Jurassic age and are well exposed between Giado and Giosc where they are several tens of meters thick. The rock is light gray and loosely cemented, and locally near Giosc sand has been piled up in heaps. This area is close to some newly discovered gas wells and would provide a good source of raw material for a glass industry.

The Gargaresh stone near Tripoli and the "Panchina" near Bengasi, and in general the Quaternary deposits of the coastal area, may also furnish raw material for glass industry.

SULFUR

Sulfur has been reported in the Sirte area about 35 km west southwest of El Agheila, and southwest of Marada; in the Jabal Al Harūj al Aswad and Wāw an Nāmūs areas of the Fezzan (pl. 1); and at Edri.

In the Sirte area the sulfur is associated with sulfur springs in the salt flats of Sebcha Kebirah (As Sabkhah al Kabīrah), west southwest of El Agheila. These de-

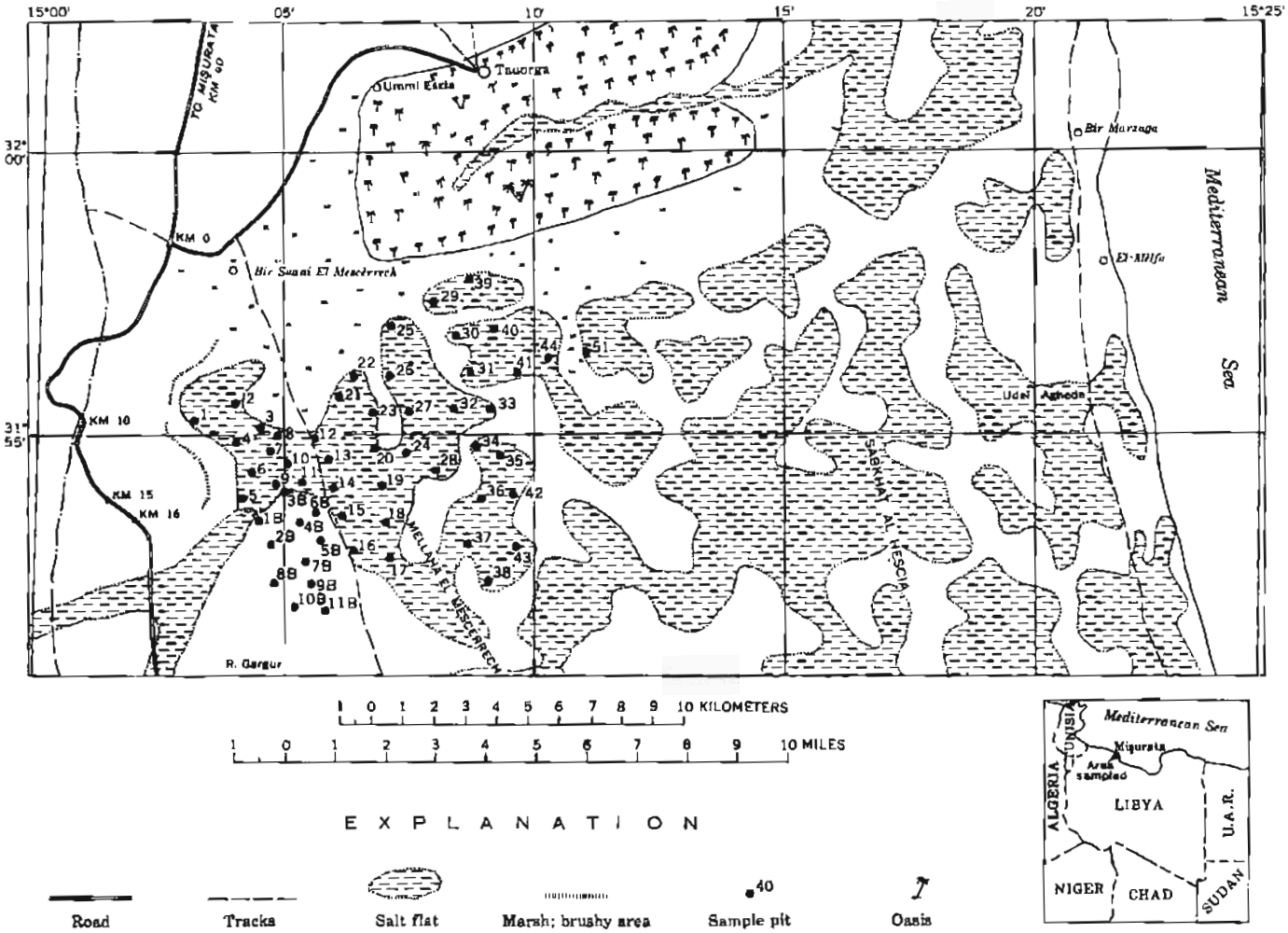

FIGURE 61.—Location of sample pits at Tauorga salt flats.

posits are of organic and biochemical origin (Brichant, 1952), and colloidal sulfur has been precipitated from spring waters by bacterial action. Brichant stated that British scientists K. A. Butlin and J. R. Postagate, of the Chemical Research Laboratory of the U.K. Department of Scientific and Industrial Research, reported a deposit of colloidal sulfur about 15 to 30 cm thick.

The lakes have been exploited by the native population for many years for medicinal purposes; 200 tons of 50 percent S probably could be recovered annually from the lakes (Brichant, 1952). The British scientists made laboratory experiments in an attempt to accelerate the rate of precipitation of sulfur and thus increase the productivity of the lakes. The results of this work are not known to the writer.

Brichant (1952) also reported sulfur associated with gypsum beds in the Miocene rocks north of Sebcha Kebirah. He reported that fragments of sulfur are sparsely scattered in the vicinity of gypsum outcrops and gave the following analyses, in percent:

	Sulfur
Choice sample (specimen)	51.83
Average sample more than 60 cm	16.4
Sulfurous soil	1.52

The writer examined the same areas and, like Brichant, considers them noncommercial. However, economic recovery of sulfur from the lakes mentioned earlier cannot be entirely precluded.

Other scattered sulfur occurrences are reported in the Sirte area between Marada and Zella (oil-company geologists, oral commun.; pl. 2).

Sulfur was noted by the writer in the Fezzan at Wāw an Nāmūs, where it has been deposited around the lakes on a sandy clay surface, or in cavities or vugs in the central cone, and on the walls of the central crater (see p. 46). Grab samples of the material analyzed

14.6 and 5.7 percent S, and a choice hand specimen analyzed 73.7 percent S.

Sulfur has also been reported (H. A. Claridge, written commun., 1951) at Jabal Al Harūj al Aswad and about 250 km south of Zella at Jabal Kebrit (sulfur mountains), where it is found in several volcanic cones that rise about 60 to 90 m above the surrounding area. These deposits have been worked by the bedouins (nomads) for many years for treatment of camels, and according to Claridge, appreciable amounts of pure sulfur exist in the general area.

Sulfurous rocks are also associated with gypsum at Edri, but several test pits and a search of the area failed to reveal any appreciable quantities of the material. (See pl. 12.)

Anhydrite and gypsum are large potential sources of sulfur, and a few plants for the extraction of sulfur from such sources are now in operation in Europe. The use of anhydrite as a source of sulfur has increased sharply in Great Britain in recent years. The large petroleum and gas reserves in Libya as a source of fuel, together with the possible high demand for sulfuric acid by the oil industry, provide good reason for investigating the extensive reserves of gypsum and anhydrite in the Bi'r al Ghanam area.

TRONA

Sodium carbonate, also called trona, exists in different areas of the Fezzan. It is formed as crusts around the edges and particularly in bottoms of the lakes at Maatan, Nashnusha, and Fredga about 60 km northwest of Umm Al Abyaḍ in the Ubari Sand Sea. Trona has also been reported at Chugraya and Tmassah lakes and in lakes near Gatrun (Muller-Feuga, 1954). It is also present in small quantities near Wāw al Kabīr and at Wāw an Nāmūs in the south-central part of the country. So far as the writer knows, only the lakes that were visited in the Ubari Sand Sea are or have been actually exploited and are economic sources of trona (pl. 1).

One form of sodium carbonate, natron, $Na_2CO_3 \cdot 10H_2O$, a decahydrated sodium carbonate, is transparent and colorless and occurs as prismatic monoclinic crystal. According to Thorpe (1912, p. 662), natron crystallizes only at temperatures below 20°C, and only under exceptional conditions is it likely to be found in the soda lakes of the desert regions. Where natron is formed, it quickly effloresces upon exposure into monohydrate $Na_2CO_3 \cdot H_2O$, known as thermonatrite. Because of this efflorescence in air, it does not occur naturally in crystal form except when immersed in a saturated solution.

The trona deposits in Libya are lake-bottom deposits which accumulate in crystalline form (fig. 62) and consist almost entirely of trona ($Na_3H(CO_3)_2 \cdot H_2O$) and rock salt (NaCl). The mineralogical analyses of the natural rock show cubical halite crystals on top, trigonal tabular rhombs of aphthitalite, and fine-grained crystalline trona at the bottom (fig. 62).

The temperature of the waters of the lake at Maatan at the time of the present writer's visit was about 20°C (67°F). The average composition of the lake water was 7.0 percent Na, 4.4 percent K, 5.9 percent CO_3, 3.4 percent SO_4, and 6.4 percent Cl. The analyses of the natural salts, in percent, that had been harvested from the lake were (insoluble constituents not determined):

	Na	K	CO_3	SO_4	Cl
1. Bulk sample from harvested material from the lake	36.7	9.1	14.6	4.9	24.8
2. Grab sample	21.8	4.8	17.7	15.9	12.9
3. Surface evaporite (around edges of the lake)	28.4	2.3	16.8	19.9	4.6

About 10 liters of the lake water was allowed to evaporate in the laboratory at room temperature of 20° to 23°C (65° to 70°F). Sodium carbonate and other salts crystallized out. The crystals had the following chemical composition, in percent: Na, 31.5; K, 3.2; CO_3, 18.0; SO_4, 13.8; and Cl, 33.3.

Muller-Feuga (1954, p. 304) reported the following minerals from the lakes in the Ubari Sand Sea:

1. Natron ($Na_2CO_3 \cdot 10H_2O$), a monoclinic crystal form which has theoretical existence in a warm country and is stable only below 29°C. He considered the existence of the mineral to be due to the low temperature of less than 29°C at the time the samples were collected.
2. Thermonatrite ($Na_2CO_3 \cdot H_2O$), an orthorhombic crystal formed by transformation of natron.
3. Trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). He also reported (p. 305, tables 65, 67, 68) the following compositions (table 8, this rept.) from the various deposits in the Fezzan:

TABLE 8.—*Analyses, in percent, of trona, composition of trona salts, and mineral constituents of trona deposits in different areas in Fezzan*

[Adapted from Muller-Feuga (1954)]

	Nashnusha	Trona	Fredga	Tmassah	Gatrun
Ions:					
CO_3 (carbonate)	18.90	12.70	27.70	19.80	18.00
CO_3 (bicarbonate)	12.30	8.00	12.50	8.40	8.40
Ca	.03	.03	.03	.03	.05
Mg	.09	.03	.10	.03	.02
Na	30.60	29.10	25.60	21.90	29.20
K	.04	.16	.....	.10	.20
Cl	21.30	23.40	1.40	3.50	21.30
SO	.....	8.14	.30	9.37	3.30
Insolubles	2.30	6.00	9.80	24.40	4.20
Loss at 100°C	18.00	12.00	18.00	15.50	15.50
Salts:					
Na_2SO_4	.....	11.9	.....	13.7	4.8
NaCl	34.9	38.3	2.2	5.7	34.9
KCl	.07	.40	.....	.19	.38
Na_2CO_3	33.4	22.8	48.8	35.0	31.8
$NaHCO_3$	17.2	11.3	17.7	11.8	11.8
Mineral Constituent:					
Trona	46.0	30.1	47.6	37.7	31.70
Natron	15.3	10.2	6.5	12.1	13.15
Thermonatrite	7.3	5.6	28.4	18.5	14.25
Insoluble	31.4	54.1	17.5	37.7	40.90

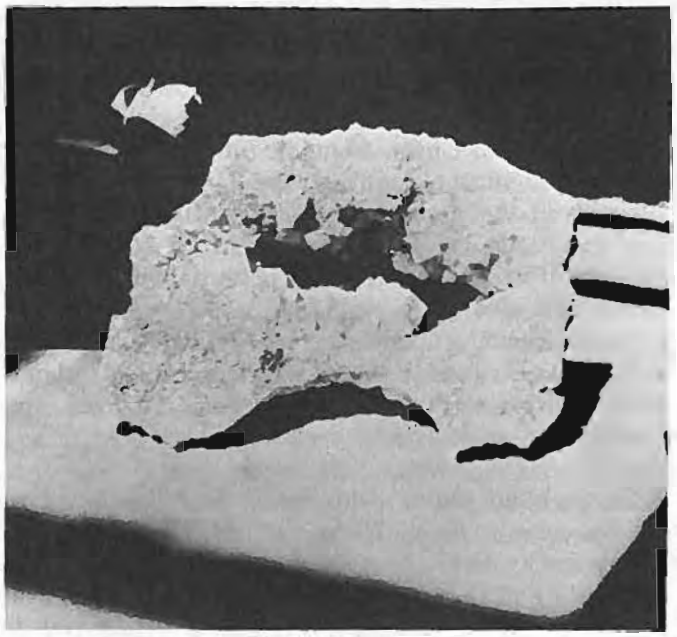

FIGURE 62.—Specimen of natural lake-bottom deposit of trona. The cubic crystals in the innermost layer are halite; the finer smaller crystals in the outermost layer are trona.

The origin of the constituents in these salts is unknown. Muller-Feuga considers that they may be related to the volcanic eruptions of the Jabal as Sawdā' 250 km to the northeast, which may also be the source of the hot water in some radioactive hot springs at Socna. Wherever may be the source of the original solutions, the accumulation of the salts is directly attributed to the waters that migrate through the nearby rocks and accumulate in the depressions. During the hot, dry summer months, saturation of the lake waters by evaporation takes place, resulting in deposition of the crystalline salts at the bottoms of the lakes.

The lakes dry up completely, and each year the salts are harvested and stockpiled and taken by camel to Sebha for marketing. The average production from the lakes is estimated at about 100 metric tons annually. Although limited amounts of trona may be produced from the lakes and the transportation factors present economic problems, the deposits were worked until 1955 by the local population under the supervision of the provincial administration. The use of trona, notably in petroleum refining, soap, and water softening, may encourage further development of these deposits which would become a source of income for the local population.

The lakes at Gatrun and Tmassah and the deposits at Wāw al Kabīr, although in remote areas, warrant additional study and investigation to determine their extent and the possibility of their commercial exploitation. The only sample collected from Wāw Al Kabīr and studied by Jewel J. Glass (written commun., 1956) is almost entirely leonite, a potassium magnesium sulfate.

PETROLEUM RESOURCES

An outline of the petroleum exploration and development in Libya is published annually by the Petroleum Commission of the Ministry of Petroleum Affairs of the Government of Libya. In the first issue (Petroleum Commission, 1959), "Petroleum Development in Libya—1954 through mid-1958," the Petroleum Law of 1955 is discussed; amendments introduced into the law by royal decree in July 1961 are contained in the issues of 1962 and 1963. These booklets also contain valuable statistical data such as aerial photography coverage, aeromagnetic surveys, and the estimated amount of annual expenditures by the oil industry in Libya. Further information is given on the number of wells drilled, the depths, and the rates of flow, as well as the status of the oil fields, pipeline capacities, and oil exports. Concession maps and surrendered areas have also been included; thus the booklets give an excellent overall account of the petroleum development and exploration activities in the country. The following is a brief summary of oil development in Libya, based on 8 years of observations encompassing almost the entire exploration and oil development in the country to 1963. (See pl. 1.) Some technical aspects of the industry are also discussed briefly.

Several oil companies began geologic reconnaissance in Libya in 1953, about 2 years prior to the enactment of the Petroleum Law, and by early 1956 concessions had been granted covering over half the country.

Although hydrocarbons in the form of gas had been noted for several years in many of the water wells drilled in northwestern Libya, the showings had been considered unimportant. The first surface indication of petroliferous material in Libya was noted by the writer early in 1956 in Fezzan, and a summary report was presented to the Libyan Government. Later, this information was made available to the oil companies in an effort to assist them in their search for oil in the country.

The presence of the petroliferous material in outcrops in the Devonian and Tournaisian sandstones and siltstones in the Shati Valley was noted by the writer. Later, occurrences of petroliferous material (asphalt or tar) were noted in several drill holes and cores, indicating an intimate association of petroliferous material with the iron formation. In many cores, petroliferous material was noted around the grains

(oolites) and saturating many of the beds. In the Tārūt area about 20 km west of Brach, about 40 cm of asphalt was cored in one drill hole. The logs of the drill holes were made available to the oil companies.

The discovery of an oil seep, in the course of geological mapping in 1956–57 about 8 km southwest of Gotah, a small village about 50 km west of Brach, was of special interest and possibly a stimulus to the active search for oil and gas. The seep is on top of a sand dune about 10 m high. Tar and asphalt have seeped out of the ground, forming a dark brown and black deposit of iron oxide, asphalt, and tar. The top of the dune is generally saturated with moisture and, by digging to a depth of less than 1 m, a flow of water can be obtained that contains about 40 to 50 percent of petroliferous material.

In January 1958, soon after the discovery of this seep, the second Esso test well at Atshan (Ḥasy 'Aṭshān) along the Algerian border in southwestern Libya was brought in at a reported flow of about 1,500 barrels per day. This spurred hope for the discovery of major oil fields in Paleozoic rocks of the Murzuk basin, and exploration was greatly intensified. Subsequent discoveries by the Oasis Oil Co. in the Sirte area in February 1959 and by Compagnie des Petroles Total (Libya) in Fezzan gave additional encouragement. However, it was the Esso Libya strike at Bi'r Zelten (Zaltan) in Cyrenaica early in 1959 that gave proof of major oil potential in Libya. This strike in the Sirte basin was soon followed by several other discoveries, and Libya was established as an important oil province, soon to become one of the leading oil producers of the world.

The present writer stated in 1959 that "although it is early to predict, it is the writer's opinion that Libya will become a major oil producer in north Africa possibly only second to Algeria." He further stated that "the Zelten field and the adjoining concessions possibly hold large oil reservoirs, and in the Sirte area, the Oasis concession 32, Libyan American Concession 17, and Amoseas concession 47 will develop into several small and possibly some large oil fields."

Early in 1964, about 6 years after the initial noncommercial Atshan discovery, test-production capacity of the country's 300 or more producing wells was over 1 million barrels per day. At least half a dozen oil fields have been found (pl. 1), and more than 1 million barrels a day was exported through two 30-inch pipelines in March 1965.

Little subsurface information is available to the writer because of the highly competitive status of the industry. The following brief summary is based on the writer's personal observations during geological reconnaissance and on oral and written communications with colleagues in Libya.

It is noteworthy that about 43 percent of the oil wells drilled in Libya have been successful and that a show of oil has been found in more than half the wells drilled in the country. The largest commercial fields are in the Tertiary and Cretaceous reservoirs in the Sirte basin, but by reviewing the oil development in Libya, it is apparent that the potential oil-producing beds have a wide stratigraphic range. Oil has been found in the Miocene? (noncommercial?), Oligocene, upper and lower Eocene, Paleocene, Cretaceous, Carboniferous, Devonian, Silurian, Ordovician, Cambrian, and Precambrian rocks. See correlation chart (pl. 3) and plate 1.

Although no major fields have been developed in the Paleozoic rocks of Libya and no field production records are available, these rocks are highly productive in Algeria and may hold large oil reservoirs in Libya.

Sandstone comprises practically all the Paleozoic reservoirs in Cambrian, Ordovician, Silurian, Devonian, and Carboniferous Systems. Pay thickness, porosity, and permeability of the Paleozoic reservoirs vary. The reported production from individual test wells in these reservoirs ranges from 50 to 2,000 barrels per day. Paleozoic unconformities (pl. 3) probably have had an important effect in the migration and accumulation of oil. However, according to Colley (1963), the structural element of closure seems to have been most significant in the majority of the discoveries made so far.

The Mesozoic oil-producing zones in northwestern Libya are restricted to the Triassic rocks. No major production estimate has been established for these sandstone reservoirs, but the reported production from test wells averages about 2,000 barrels per day. It is the opinion of the writer that major oil and gas fields will soon be developed in these rocks. No data concerning the reservoir characteristics of the Triassic rocks are available; this writer believes that the lateral facies change and the stratigraphic traps are probably the major element in oil and gas accumulations and that structure plays only a secondary role in hydrocarbon accumulations within the individual reservoir.

The major Mesozoic oil-producing zones are the Upper Cretaceous strata and the basal sands in the Sirte basin. These strata are either limestone or sandstone, and the production figures from individual test wells are several thousand barrels per day. The pre-Cretaceous erosional surface exerted a profound effect on the accumulation of oil in Cretaceous rocks. Depositional environments were controlled by preexisting topography that became the initial sea floor. Basal sands

and organic shales of Cretaceous and Paleocene age initially filled the topographic and structural deeps. Although these depressions were soon filled, the early influence was preserved by differential compaction and renewed fault movements. According to Colley (1963), most of the oil found in the Cretaceous rocks is trapped in the carbonate or sand reservoirs, generally at either the crest or the flank of the above-mentioned large features.

Tertiary reservoirs yield the greater part of the oil found in Libya. Oil has been found in Paleocene, lower and upper Eocene, and Oligocene strata. Oil has been found in the middle Eocene and Miocene, but not in commercial quantities. The Tertiary reservoirs of Paleocene age are carbonates, and production records show as much as 17,500 barrels per day. The other Tertiary reservoirs are either carbonate or sand, and production figures range from 250 to several thousand barrels per day.

The depth of the productive horizons found in Libya thus far ranges from about 600 to 3,000 m (about 2,000 to 10,000 ft), and the gravity of the oil ranges from 33° to 46°API. High oil-gas ratios are found in a few wells, but only two wells may be considered true gas wells: one in the Devonian rocks in the Murzuk basin (Esso-Lybia concession 1) along the Algerian border and one in the Triassic sands in northwestern Libya in the Hamada basin (Compagnie Française de Pétrole-Libya in concession 23). Although no gas fields have been developed in these areas and the reserves are not established, an estimated production capacity of 10 million cubic feet per day was given by the Petroleum Commission in 1963.

WATER RESOURCES

It is beyond the scope of this report to discuss in detail the water resources of Libya, a country almost one-fourth the size of the conterminous United States. An attempt is made, however, to give a general picture of the ground-water conditions and some information on the deep water wells drilled by governmental agencies and private oil companies (pl. 13). Previous work in the field of hydrogeology is briefly discussed to establish a source of reference and some basis for future investigations.

Italian geologists prior to 1940 carried out extensive fieldwork on the geology and hydrology of northern Libya, and French geologists, notably Muller-Feuga (1954), did much work in Fezzan during the postwar period. Several agencies have also carried out hydrological investigations. Hill (1959) has referred to most of these works, and van Everdingen (1962) has referred to later studies.

U.S. Geological Survey geologists have made regional and local ground-water studies in Libya in addition to collecting basic data since 1952, in cooperation with the Nazirate of Agriculture and other Libyan Government agencies.

Water is Libya's most precious resource but is nowhere plentiful in the country. Generally, where an ample water supply exists, such as the Shati Valley area of Fezzan, much of it is wasted. The most heavily populated areas in the northwestern part of the country are also the most intensely cultivated. In these areas, overdraft pumping of ground-water reservoirs has caused the water level to decline at an alarming rate, as much as 13 m from 1930 to 1960 in Suani ben Adam area (Cederstrom and Bertaiola, 1960, p. 78).

With the exception of springs which flow for short distances from their sources, there are no perennial streams in Libya. There are more than 40 large springs and many other smaller ones in the Jabal area of Cyrenaica, but many of these are inaccessible for agricultural use.

Rainfall is the only source of surface-water runoff and of recharge of the ground-water reservoirs in Libya. Figure 4 shows the average annual precipitation from 1926 to 1950. The percentage of total recharge and the manner of its infiltration into the aquifers is generally unknown. Cederstrom and Bertaiola (1960, p. 33) gave a figure of 60 to 65 percent for recharge in the Suani ben Adam–Gar ben Gashir area of Tripolitania. However, not enough data are available for most of the country and the details of recharge have not been studied. Cederstrom and Bertaiola (1960, p. 87) stated, "In some areas geologic conditions may be such that some recharge may occur with an only moderate rainfall whereas elsewhere much higher rainfall may be necessary before the ground reservoir is affected."

The water for irrigation and domestic use in northwestern Tripolitania (Gefara) is supplied by wells at various depths. There are four different aquifers or water-bearing strata in the Gefara (Lipparini, 1940; Cederstrom and Bertaiola, 1960). Beneath the sandy cover of the Gefara is a phreatic zone, about 10 to 20 m deep, from which almost all the wells of the coastal plains obtain their water. Around these wells, gardens or oases are nourished by water from this shallow zone. The water level is subject to seasonal changes, and some wells dry up during the hot season. The origin of this water can be ascribed principally to winter rains, and the aquifers are recharged by percolation direct from rain and also from ephemeral stream while in spate.

The second aquifer ranges from 25 to 50 m in depth, depending on the local topography. This aquifer rests

on impermeable beds of clay (probably the top of the Miocene) and is a good source of water from drilled or dug tubular wells.

The third aquifer is about 400 m deep and is near the base of the Miocene. The recharge is probably caused by the precipitation on the Jabal Nefusa–Jabal Garian; rainwaters that are shed on the Jabal make their way seaward and percolate into permeable beds of the Miocene before reaching the coast. At some places, such as in the Gharabulli area, water in the aquifers has pressure head above the land surface, and flowing artesian wells are obtained by deep drilling.

Ogilbee in several papers (Ogilbee and Tarhuni, 1962; Ogilbee, Vorhis, and Deghaies, 1962; Ogilbee, Vorhis, and Russo, 1963; Ogilbee, Vorhis, and Tarhuni, 1963) has discussed the ground-water resources of Surman, Zawia, Gharabulli, and Al Mayah areas of the coastal zone of the Gefara.

Near Azizia, farther south in the Gefara, another aquifer occurs at a depth of about 60 m. The water-bearing bed is probably the Bu Sceba (Triassic) sandstone. This aquifer has not been studied sufficiently but a preliminary test at the rate of 60 cubic meters per hour indicated a highly productive aquifer, which contains water of good quality. Other drilled wells in the Bi'r al Ghanam area have also provided a good source of water for irrigation. Christie (1955) has described the lithology and the aquifer characteristics in several wells drilled in the Gefara, and Cederstrom and Bertaiola (1960) gave statistical data on the majority of the wells in the Tripoli quadrangle. In general, the farther south a well is in the Gefara the greater depth to water; thus, a limiting condition is imposed on development of water for irrigation.

Several springs occur at the base of and in the Jabal Nefusa–Jabal Garian escarpment of Tripolitania at Giosc and Tījī, and several water-table wells in the bottoms of wadis near Nālūt furnish water for domestic use. On the upland in the Garian and Yafran areas, water is derived from the Ain Tobi Limestone and Yafran Marl (Upper Cretaceous) and is collected and pumped to these communities.

Farther south at Mizda, wells 30 to 50 m deep tap the Upper Cretaceous beds, furnishing water for small garden plots and domestic use. In the Ghadamēs area, water of good quality from the Nubian Sandstone at depths of more than 350 m furnishes water for irrigation and domestic use. These drilled wells flow about 60 cubic meters per hour each. Also several springs in the area have good yields.

With the exception of the places mentioned, water is scarce in the entire hamada area of northwestern Libya. Exploratory drilling by the oil companies has proved the existence of water at various depths. (See pl. 13.) The water ranges from good to poor in chemical quality.

Along the coast between Tripoli and Miṣurata, almost all the water is obtained from shallow dug wells under water-table conditions and is of rather poor quality. Since 1957, the springs at Wādī Caam have provided water for an area of about 400 hectares of irrigated land. Shallow wells also yield water of good quality for human consumption in this area. In the Miṣurata area at Giado and Crispi (Al Kararim), deep wells, probably in Triassic rocks, yield water for irrigation (G. C. Tibbitts, 1957); and recently south of Miṣurata deep water wells, probably tapping Miocene rocks, yield good water for the Miṣurata city water supply. The springs at Tauorga yield large volumes of water not generally suitable for domestic use or for irrigating certain crops, but high-salt-tolerant crops can probably be cultivated in the area.

In the eastern part of the Jabal area, at Tarhuna and Beni Ulīd, a limited amount of good water exists for irrigation and domestic use. Farther east in the Al Kussabat area, water is obtained from a few shallow water-table wells. Several wells in sparsely scattered areas also furnish water to the nomadic tribes.

In the Sirte area of Tripolitania, fresh water is almost nonexistent except in the Qaṣr Bu Hadi area where water containing less than 400 parts per million total dissolved solids has been found (Ogilbee, 1964). Several wells drilled by the oil companies in the Sirte area failed to find water of quality suitable for irrigation or domestic use. (See pl. 13.) In the El Giofra (Al Jufrah) group of oases, artesian water flows from a deep well at Hūn and from a spring near Socna. Farther east at Waddān and Zella, very limited water of good quality is found at shallow depth (Tibbitts, 1957).

In Fezzan, in the Shati Valley area, water is relatively plentiful and generally under artesian head. The water is derived from the Devonian sandstones, but shallow water-table wells generally obtain their water from the sandstones and siltstones of Tournaisian Age (Carboniferous). This water has probably percolated from the Devonian sandstones into the overlying beds through faults and fractures.

In the Sebha and Bouanis areas, water is derived from the Nubian Sandstone (Lower Cretaceous) continental beds. Structure and topography in localized areas have resulted in flowing artesian conditions. The Nubian Sandstone of Early Cretaceous age also provides water to the Murzuk-Trāghan-Tmassah line of oases. In these oases, water exists under artesian head; and at Trāghan, wells drilled in some depressions flow. In Wādī Ajal area, water is found at various depths under water-table conditions and is extracted from the loosely

cemented Holocene deposits or the Nubian Sandstone, and the deeper wells near Ubari probably flow from post-Tassilian continental sandstone.

Farther west in Serdeles, water is derived from the Devonian sandstones. In this area most of the deeper wells tap flowing water of good quality. In the Ghāt–Al Barkat series of oases in the southwestern part of the country, the water is derived from lower Silurian sandstones or the sandstone of Ordovician and Cambrian age. Many springs occur within the area, and most of the drilled wells flow.

In eastern Fezzan, in the Majdūl and Gatrun areas, water exists under shallow water-table conditions, commonly in loosely consolidated Holocene sediments. Deep wells, however, may yield water of good quality from the Nubian or the Devonian sandstones.

In the coastal plains of northeastern Libya (Cyrenaica), water is generally obtained from shallow wells. The water is mostly of rather poor chemical quality in the vicinity of Agedabia and elsewhere in the coastal plain, and water levels fluctuate seasonally. Only a few springs occur in the Marada area. In the Bengasi area drilled wells near Benina yield water of fair to good quality (Doyel and Maguire, 1964, p. 14; Jones, 1960, p. 9).

In the Barce area some water is available for domestic use, but test drilling in the area has shown that water levels are too deep for irrigation (Jones, 1960, p. 11; Newport and Haddor, 1963, p. 23). In the Jabal area, at Beda and Cirene, several springs of moderate yield furnish water to these communities. In the Derna area, water of good chemical quality occurs in quantity sufficient both for irrigation and domestic use (Jones, 1960, p. 12). Several drilled test wells at Tobruk have failed to prove the existence of any water of good quality.

In southern Cyrenaica, ample water exists in the scattered oases of Tazerbo, Rebiana, Zighan, and Bzema for domestic use and limited irrigation. In the Cufra oasis, water is obtained from shallow water-table wells and from the few springs within the area. Water is obtained from the loosely cemented Holocene sediments and the sandstones of Early Cretaceous age (Nubian).

In southeastern Libya at Jabal Awenat, several small springs of low yield provide water to the nomadic local population.

With the industrial development in the country and the increased demand for water, particularly in the coastal areas, water supply presents a critical problem to the government and the people. Continued ground-water investigations in the country are extremely important (Cederstrom and Bertaiola, 1960), particularly in the coastal plains where decline of water levels and salt-water intrusion by overdraft may be disastrous for sustained agriculture. Studies are needed in other areas where a potential source of water may exist for irrigation; the enactment and enforcement of a water law is of prime importance.

A great deal of research has gone into development of inexpensive methods of salt-water conversion, and significant progress has been made in distillation and electrolytic methods. Water treatment and demineralization is possible at relatively low costs, and research to discover cheap and efficient techniques for a large quantity of water is being carried out in the United States and several other countries. At some future date the water supply of Libya, particularly in the heavily populated areas, may have to be supplemented by desalinization of salt water.

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