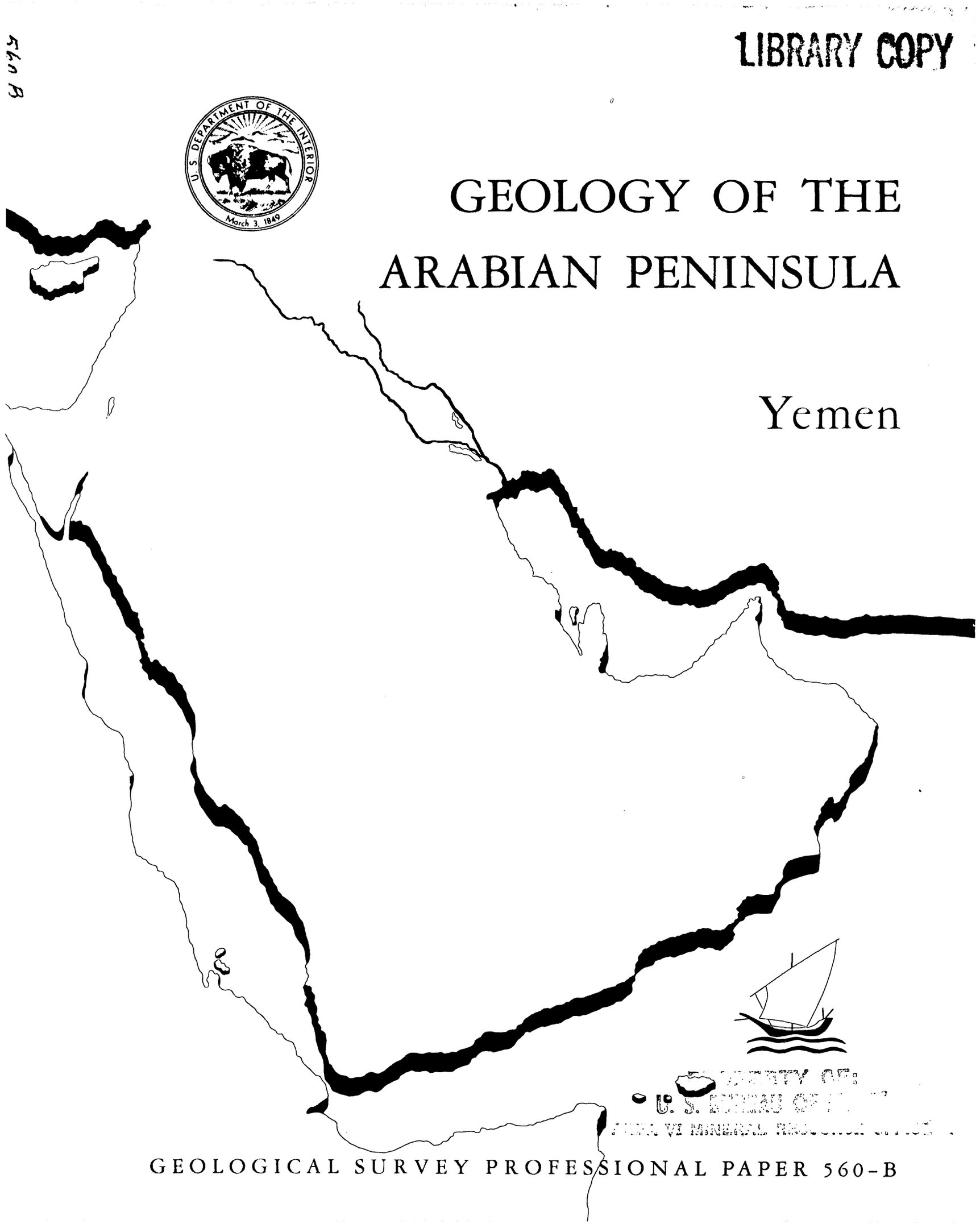
GEOLOGY OF THE ARABIAN PENINSULA

Yemen



GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-B

Geology of the Arabian Peninsula

Yemen

By F. GEUKENS

Translated from the French by S. D. BOWERS

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A review of the geology of Yemen as shown on USGS Miscellaneous Geologic Investigations Map I-270A, "Geologic Map of the Arabian Peninsula," 1963

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FOREWORD

This volume, "*The Geology of the Arabian Peninsula,*" is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1958. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I–270 A).

As work on the quadrangles progressed, geologists, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Aramco and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Aden Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Aramco geologists. Exploratory conversations were begun by Aramco with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed by the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.

O. A. Seager

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Arabian-American Oil Co. (Retired).

W. D. Johnston Jr.

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By F. GEUKENS [1]

English translation from the French by S. D. BOWERS [2]

ABSTRACT

After the leveling of the Precambrian metamorphic basement toward the end of the Paleozoic, sandy formations of continental facies were deposited mainly in the northern part of Yemen.

From the Liassic onward a zone of subsidence occurred in the central and northern areas. This zone was filled with fluviolacustrine sediments. It was only from the Late Jurassic on that a marine transgression covered the entire territory. The zone of subsidence remains, more accentuated toward the Red Sea.

During the Mesozoic, sandy conglomerates were deposited in the areas of subsidence.

The last marine transgression, of Paleocene age, involved the central part of the country.

INTRODUCTION

The southwestern part of the Arabian Peninsula, called "Arabia Felix" in the ancient literature, was long known as a mysterious and impenetrable country. Scientific exploration was limited to that done during a few journeys made by botanists, philologists, entomologists, and others.

Geological studies did not begin in Yemen until the 20th century, but geographical exploration dates from the 18th century with the travels (dearly paid for by his companions) of Niebuhr in 1763, who succeeded in crossing the area between Al Ḥudaydah, Ṣan'ā, Ta'izz, and Al Mukhā. Much geographical information was acquired during the 19th century. The travels of Botta (1841) in 1836 and Passama in 1843, and the well documented journeys of archeologists Halévy from 1872 to 1879 and Glaser (1913) from 1885 to 1899 provided the foundation for future exploration.

The first regional topographic mapping was done by Beneyton (1913) for the purpose of constructing a railroad and branch line from Al Ḥudaydah to Ṣan'ā. He mapped the borders of the triangular area between Ta'izz, Ṣan'ā, and Zabīd (Al Ḥudaydah). The first geological studies resulted from explorations by Botez (1912) along the Al Ḥudaydah-Ṣan'ā route during the Turkish occupation. Petrographic material which he brought back was studied by Roman (1925), who prepared an extensive report. Lamare (1923a) crossed the southwestern and central parts of Yemen, where he gathered considerable geographic and geologic data and established a preliminary stratigraphic column.

Some years later, Rathjens and Wissmann (1929) obtained permission to conduct scientific research in the Al Ḥudaydah-Ṣan'ā-Ta'izz area. They made four trips—in 1927–28, 1931, 1934, and 1937–38—and completed the studies started by Lamare.

Werdecker's (1939) geographical work and Scott's (1939) descriptions of his scientific journeys furnish supplementary information concerning the area traveled by their predecessors.

Geologists Fricke (1953), Lipparini (1954), and Karrenberg (1956) visited the country for economic geological study. The purpose of their investigations being limited, they deviated only slightly from the triangular route from Al Ḥudaydah to Ṣan'ā to Ta'izz. Karrenberg was the first geologist to cover the Ta 'izz-Ibb-Ṣan'ā route by automobile.

In two journeys, 1953-54 and 1954–55, the author, as an expert under the technical assistance program of the United Nations, was able to travel through the country on a geological survey and visit previously unexplored regions, thanks to the cooperation of the United Nations Organization and the Government of Yemen (Geukens, 1960).

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[2] Arabian American Oil Co., Dhahran, Saudi Arabia.

PHYSICAL GEOGRAPHY

MORPHOLOGY

Yemen can be divided into three physiographic provinces: a maritime plain called At Tihāmah bordering the Red Sea, a mountainous region drained by streams debouching into the Red Sea, and an interior undulating plateau in the east, between 1,500 and 2,500 meters in elevation, where drainage flows inland.

The maritime plain, 30 to 40 kilometers wide, is a sediment-filled part of the Red Sea graben. It consists of two parts, the limits of which are not precise and are, therefore, difficult to trace. One part, adjacent to the Red Sea, is composed of late Tertiary and Quarternary marine formations covered by Recent eolian deposits. The other part, toward the interior, consists of thick deltaic deposits related to numerous important wadis which disappear in the maritime plain. Numerous fresh-water springs are found near the border between the two parts.

The central mountain region occupies the west flank of a horst which lies between the Red Sea graben on the west and the Arabian desert on the east. The mountains are dissected by wadis characterized by strong headward erosion which is highly diversified depending on the composition of the bedrock. South of Wādī Lā'ah, from Jabal Shu'ayb through Jabal Ḍawrān and toward Ta'izz, the mountain region is incised by rivers (torrential during the rainy season) whose valleys progressively widen to the west. The many mountain massifs in this part are commonly secondary horsts. The terrain consists mostly of tuffs and compact lavas in horizontal attitude and explains the formation of steep ravines more than 1,500 to 2,000 m deep in several places. Near the outlets of the main wadis the valleys widen, and large stepped terraces alternate with moderately high hills. Near At Tihāmah the western limit of the mountainous area is difficult to define because isolated hills emerge through the fluviatile deposits.

North of Wādī Lā'ah fluviatile erosion is more advanced and has cut into basement rock and sedimentary formations. Thick calcareous strata form very steep cliffs, chiefly in the upper courses of these wadis (Ḥajjah and Kuḥlān areas).

In the interior, plateaus of various dimensions range from 1,500 to 2,500 m in elevation and are covered with either fluviatile, eolian, or volcanic deposits. They are separated only by low hills. The southern part of the Ṣan'ā plain became a terrace by capture of the Wādī Wa'lān tributaries. In other places, the plateaus are cut by faults which form depressed areas and appear as alluvium-filled valleys—notably the plains of Ṣan'ā 'Amrān, Al Ḥarf, Ṣa'dah, and others.

Generally, the interior plateaus grade without a sharp break into the more desert region to the east. This is illustrated in the northern part of the country where the Wādī al Jawf drops evenly to the desert. The area southeast of Jabal Mafluq is characterized by intrusive granitic mountains which rise above the calcareous plateau, and dense vegetation grows for some distance along the main wadis. Local silt and loam plains are commonly formed through deposition behind ancient artificial dams. The true desert region begins east of the horst formed by Jabal Haylān and Jabal Balaq. The transition in this area from plateau to desert is locally very abrupt. The upper channels of Wādī Adhanah and Wādī Raghwān show very active headward erosion by the sharp intensification of relief east of Jabal ash Sharafah (Ṭiyāl).

Contemporaneously with the subsidence of the Red Sea graben, young rivers brought large quantities of sediment. The subsurface of At Tihāmah plain on the eastern side is formed of thick conglomeratic and other terrigenous deposits; on the western side, of salt, sand, shale and limestone.

At the end of the Pleistocene, tributaries to the Red Sea captured many tributaries of the rivers flowing toward the interior of the country. The capture as well as the decrease of rainfall during the Holocene explains the presence of gravelly fluviatile deposits standing out in relief in the desert region to the east, the surrounding sand having been removed by the wind.

METEOROLOGY

Precipitation in Yemen is strongly influenced by relief and consequently varies considerably from place to place. Meteorological observations were made by J. E. Hansen, engineer, and Dr. Carlo Toffolon, then personal physician to the Imam, at Ṣan'ā and Ta'izz from 1942 to 1944. According to their observations at Ta'izz, the number of rains ranges from 90 to 160 per year, and annual precipitation ranges from 450 to 700 millimeters. Rainfall may exceed 50 mm in a single torrential shower. Two rainy periods are distinguished at Ta'izz: (1) the most important period, in which precipitation may exceed 600 mm, extends from April to May, or in some years to June, and (2) a shorter period in which rain falls mostly during August and September. West winds predominate during the rainy seasons.

At Ṣan'ā annual precipitation ranges from 200 to 500 mm (60 to 90 showers) and also falls largely within two periods: (1) April to May and (2), the most important, from the latter part of July through the first half of August. Clouds generally gather on the west slopes of the main massifs and cause very heavy rainfall which accounts for the erosive action of the

wadis, the fertility of the land, and the number of local springs.

GENERAL SKETCH OF GEOLOGIC HISTORY

Schistose formations cut by masses of Precambrian granite crop out mainly in the east, north, and northwest parts of the country as well as in some isolated horsts. Preliminary study of these areas did not lead to an adequate mappable subdivision.

The formations have undergone regional metamorphism and intense folding in a general north-south direction. During this period important granitic massifs were emplaced. Precambrian formations oriented east to west were observed only in isolated places, a condition which did not allow establishment of structurally differentiated units.

During a continental period of long duration, erosion converted the region to a Precambrian peneplain. Paleozoic transgression (Cambrian through Silurian?) probably extended over the area. Folding is indicated by a few remains of almost vertically inclined dark shales.

In another long continental period that followed, erosion almost completely removed the Paleozoic formations and created a perfect peneplain on which a very leached almost entirely quartz soil developed. At the end of the Paleozoic, or Permian, the peneplain was warped and the old surface was eroded in the south and redeposited as a delta or as dunes in the north (Wajid Sandstone). The beginning of the Mesozoic was characterized by a warm climate in which secondary basins formed in northeast Yemen. These basins were filled by continental red sandstones, indicating the nearness and influence of the landmass. Deposition of dark-green and gray-black shales of fluviolacustrine origin (Kohlan Series) followed. In isolated bays or near the coast short periods of emergence resulted in the formation of gypsum lenses.

During the Malm, the most important transgression extended over the entire country, and formed shallow-water calcareous deposits (Amran Series). Initially, the transgression followed along local depressions. An example of such a depression is northwest of Ṣan'ā where Bathonian to Callovian carbonate rests on the Kohlan Series. To the north where the limestone is more chalky, the transgression was a little later (Callovian to Oxfordian). This area corresponded to the neritic zone containing stromatoporoids, and was separated from the great basin which extends into Saudi Arabia.

Commencing with the Oxfordian, the transgression covered the whole eastern and southern parts of the country. During this period subsidence zones formed in the desert area of Ramlat as Sab'atayn and in southwest Yemen. In the central and southern parts of the country, Late Jurassic marine transgression took place directly on the Precambrian basement. (See fig. 1.)

A period of continental environment followed toward the end of the Late Jurassic. A lagoonal stage occurred in the center of the depressions, where gypsum and salt were deposited, while the margins of the basins emerged and were subjected to erosion. Continental sandy conglomerates of Cretaceous age (Tawilah Group) were laid down, probably over the entire area. The Tawilah Group is found wherever it is covered and protected by the overlying Trap Series. Tilting followed, along with greater deposition of sand in the flat-bottomed basins.

During the Paleocene a narrow sea spread over the center of the country; the neritic facies (Medj-zir Series) attests to the nearness of the landmass, where a tropical climate formed lateritic soil on its exposed surface.

Tectonic movements, resulting in faulted domes, affected especially the central part of the country, where Jurassic and Cretaceous beds were removed by erosion at the beginning of the Tertiary.

Intense volcanic and intrusive activity began locally at the end of the Cretaceous and became widespread during most of the Tertiary. Volcanism is especially evident in southwestern Yemen where flows and tuffs locally exceed 1,500 m thickness (Trap Series); silicic laccolith intrusions are more common to the north. Calm intervals during the Oligocene and Miocene produced fluviolacustrine deposits intercalated with the Trap Series. Very intense tectonic activity characterized by normal faulting continued to the end of the Tertiary. Recent granitic intrusions penetrate the Trap Series, especially in the western part.

In the Quaternary, volcanic materials were sporadically distributed over the whole country; large areas of basalt flows and many craters characterize the central part of Yemen near Ṣan'ā, Dhamār, and Ma'rib. Small basaltic craters are irregularly distributed over the entire territory.

Major loess deposits extend widely over the plateaus. Recent faults which facilitated erosion abruptly limit the areal extent of the loess fields.

Structural deformation has strongly modified the drainage pattern. Examples of very recent stream capture and indications of future capture are noted in the terrain, especially south of Maḥwad. Major terraces occur not only in the lower channels of the wadis but also in the upper channels of the Red Sea tributaries where the waters erode the old fluviatile deposits related to the wadis which flow eastward toward the interior of the country.

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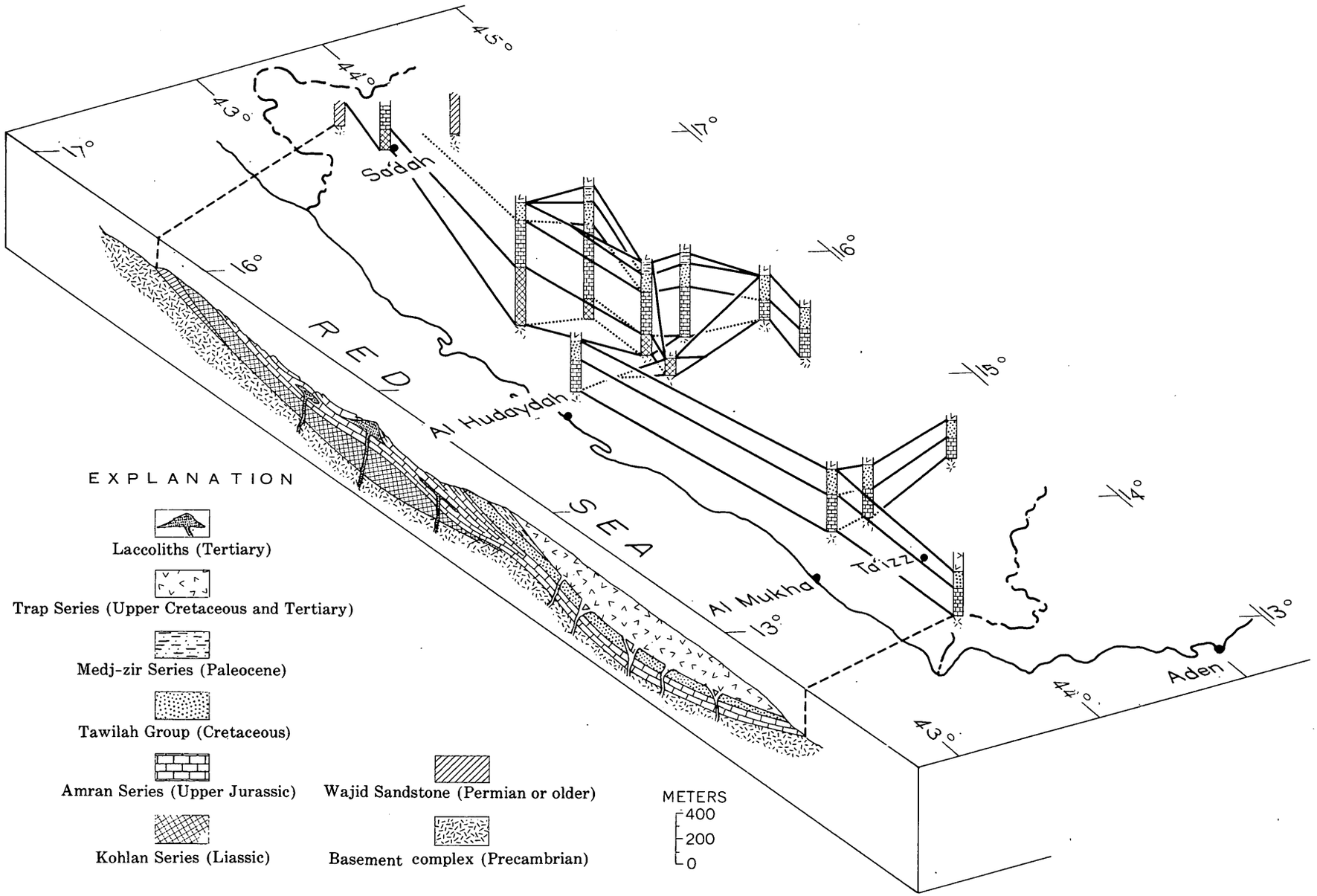

FIGURE 1.—Block diagram showing sedimentary units in Yemen and a schematic north-south section.

BASEMENT ROCKS

A complex, not yet subdivided, underlies all the subhorizontal sedimentary formations. It is composed of highly metamorphosed rocks enclosing large granitic massifs. The basement crops out mainly in the eastern and northern parts of Yemen, as well as in the bottoms of horsts which are uplifted through the Trap Series.

In the eastern part of the area of horsts north of Ta'izz, the basement consists mainly of mica schist (oriented generally north to south) and pink granite which has two micas and contains pegmatite and aplite veins. In the central part the granites contain large gneiss and mica-schist xenoliths, at places measuring several tens of meters in thickness.

The basement in the horst south of Bājil is likewise composed of gneiss and mica schist, as well as pink orthoclase granites.

The basement exposed south of Wādī Surdūd is composed of mica schists oriented east to west and dipping 45°S. In the Wādī Surdūd (fig. 2) farther north, granite exposures include large mica-schist xenoliths.

In the floor of Wādī Lā'ah north of Aṭ Ṭawīlah, the Precambrian is oriented N. 40° W. and dip is nearly vertical. It consists of chlorite schist, garnet schist, and gneissic quartzite. Several pegmatite veins, 20 to 50 centimeters thick, containing black tourmaline crystals as much as 14 cm long, cut the basement. Downstream, the metamorphic series includes three granite massifs.

The anticline uplifted between Radā' and Ṣirwāḥ in the southern part near the Aden Protectorate frontier is a highly folded complex oriented generally N. 10° E. The folds show very pronounced dip.

Farther north, in the upper channel of Wādī Adhanah, the basement is composed of gneiss, mica schist, and amphibolite. Nearly midway between Aḍ Ḍayq and Ṣirwāḥ, the basement includes a conglomerate layer which appears to separate two different tectonic complexes.

In the Ṣirwāḥ area the general orientation of the Precambrian is north to south. West of the town, gneiss and garnet schist crop out; to the east, gneiss and mica schist are exposed.

Toward Ma'rib, west of Jabal Balaq, mica schist, quartzite, and amphibolite (oriented north to south) are exposed. This great Precambrian dome plunges to the north near the upper channel of Wādī Raghwān.

Jabal Dakhan, 25 kilometers northwest of Ṣirwāḥ, is a granite dome more than 5 km long. On the east and west slopes, the granite is covered by a thin quartzitic bed overlain by green chlorite schist which grades into gneiss and amphibolite within several meters

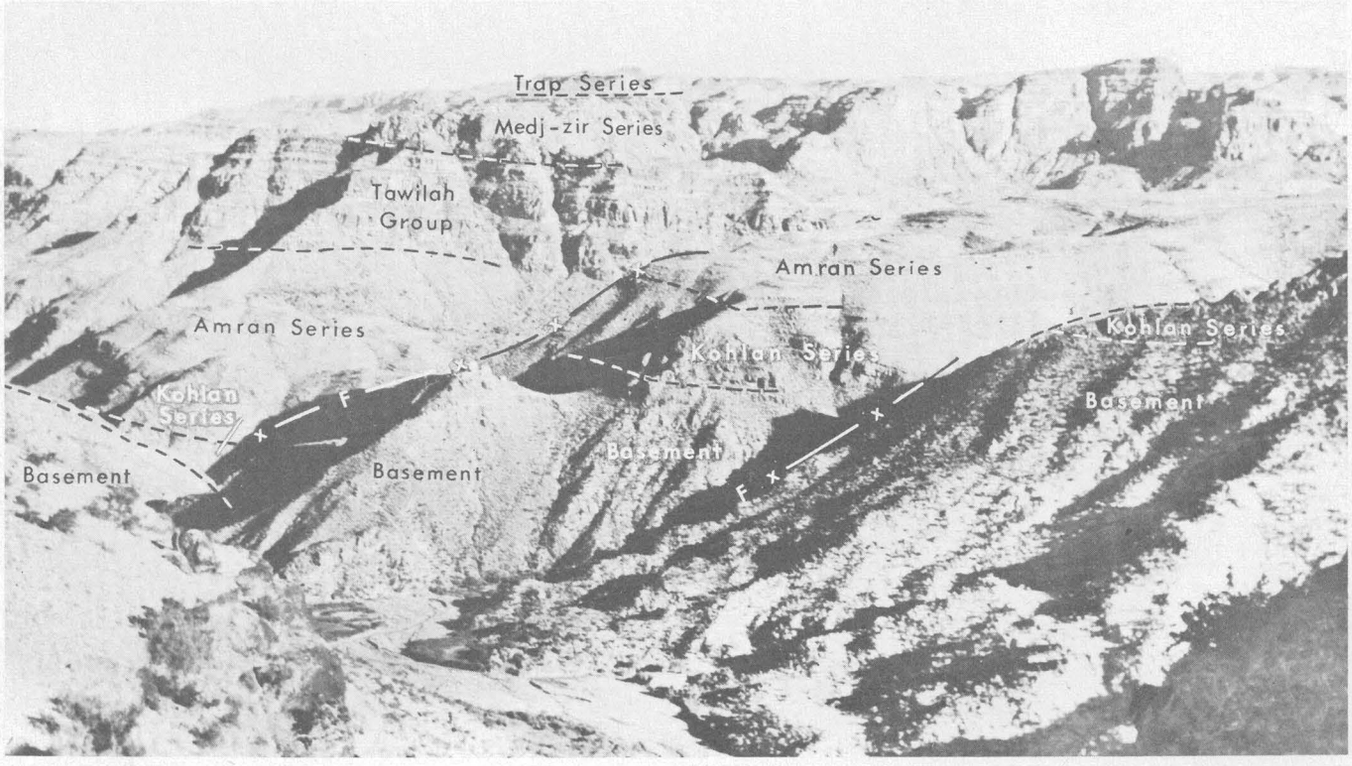

FIGURE 2.—Basement and sedimentary formations exposed in the upper course of Wādī Surdūd. F indicates fault.

East of Jabal Ṭiyāl, the basement consists of gneiss and garnet schist overlain by quartzite.

The Precambrian basement is exposed for a long distance in the horsts marking the limits of the two sides of the Ṣa'dah graben. The east horst is pink granite near Ṣa'dah, and gneiss and mica schist farther north. North of Wādī Akwām the basement includes white marble much deformed by tectonic movements. The marble is locally mineralized by ilmenite at the contact with gabbro intrusives. Farther north of Wādī Akwām (tributary of Wādī Najrān), the white marble crops out as lenses appearing as small white hillocks surrounded by fluviatile deposits.

Toward the Saudi Arabian frontier, the basement is composed of grayish-black mica schist and gneiss oriented north to south and includes some granitic massifs.

The west Ṣa'dah horst consists, from south to north, of mica schist, granite and pegmatite, biotite schist, and quartzite locally containing magnetite.

Compared lithologically with the Precambrian of Saudi Arabia, the basement would be the equivalent of the oldest formations grouped in the Hali Schist.

SEDIMENTARY ROCKS

WAJID SANDSTONE

A well-stratified sandy conglomeratic formation covers the Precambrian basement for a great distance east and north of the Jawf area and north of Ṣa'dah (fig. 3). The southern boundary east of Al Jawf is a fault. Some remnant hills (Jabal an Nu'aym) still exist in small isolated grabens west of the Ṣa'dah depression.

This formation is composed mainly of well-rounded white quartz sandstone and conglomeratic gravel lenses. In Jabal Dalhān, north of Ṣa'dah, it exceeds 200 m in thickness. Apparently, the Wajid Sandstone represents deltaic deposition by rivers flowing from the southeast. Toward Wādī Najrān, the sandstone forms a thin cover over the plateau, a cover partly removed by the wadis and their tributaries. To the north, the Wajid Sandstone is less coarse grained, possibly formed, in part, of eolian deposits.

The stratigraphic contact between the Wajid Sandstone and the Kohlan Series was not observed because a fault separates the Wajid and Kohlan where they approach each other. Sedimentary conditions for these two sequences are quite different. The percentage of quartz is very high in the Wajid and greatly exceeds that of the Kohlan. Owing to the complete lack of index fossils in Yemen, we must look for the stratigraphic evidence in Saudi Arabia. Near the frontier the Wajid Sandstone is mapped as being of Permian age or older (Brown and Jackson, 1959).

KOHLAN SERIES

Below the Upper Jurassic Amran Series in Jaba Muṣawwar, Lamare and Carpentier (1932) found sedi

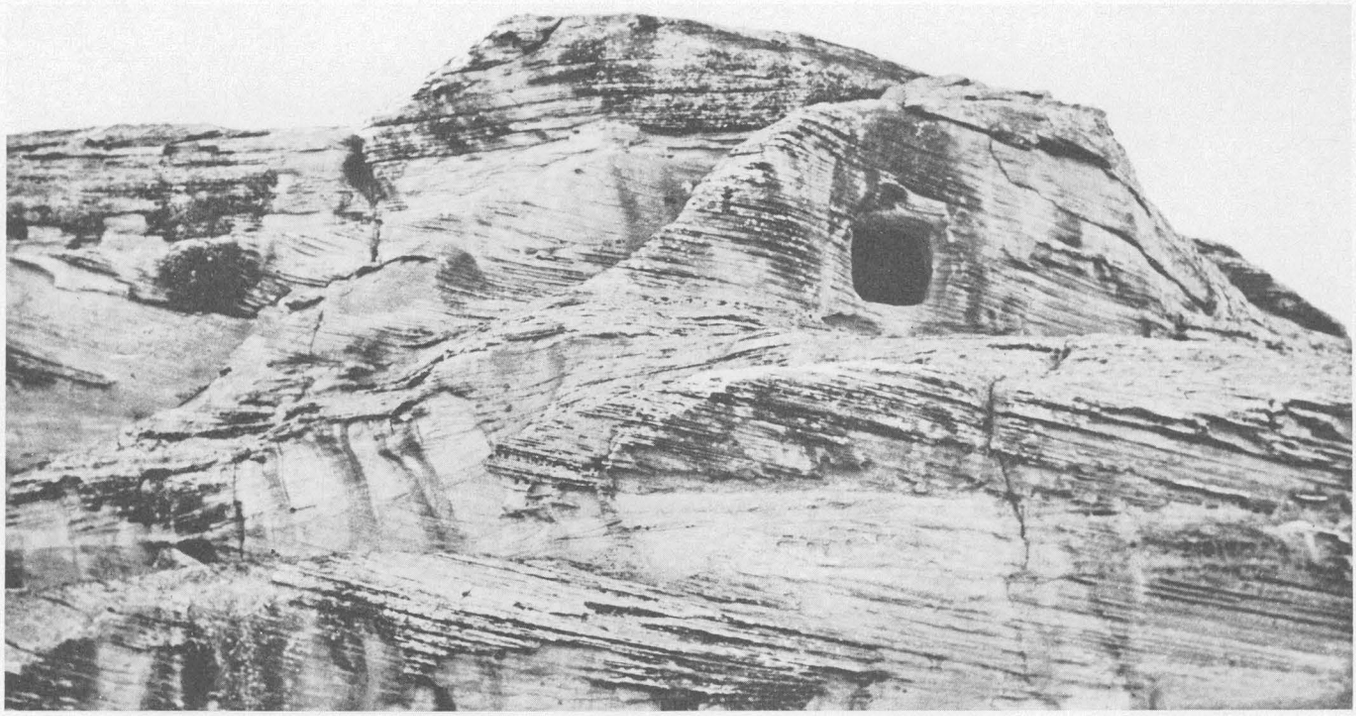

FIGURE 3.—Wajid Sandstone outcrop north of Ṣa'dah.

mentary rocks which they were able to date as Liassic from plant fossils found in the upper part. The beds were grouped by this author in the Kohlan Series, which is exposed mainly in the central and northern parts of Yemen. To the north the Kohlan Series does not go beyond the latitude of Ṣa'dah, and to the northeast it is bounded by the major horst which extends from Ṣa'dah-Jabal Baraṭ to Jabal al Lawdh. The southern extension includes a pre-Trap Series horst which bounds the Aṭ Ṭawīlah-Ṣan'ā Jurassic basin on the south (upper course of Wādī Surdūd). The series shows great facies variation from south to north and from east to west.

The series is highly arenaceous southward in the upper channels of Wādī Khawbah and Wādī al 'Urr, west of Jabal Shu'ayb, the highest mountain in Yemen. Resting on the basement and directly overlain by the Trap Series, the Kohlan in this area consists of yellowish-white sandstone with conglomerate lenses containing well-rounded quartz fragments. It is better exposed and thicker a little farther north in Wādī Nasīm (upper course of Wādī Surdūd). Here, the gneiss basement is overlain by about 150 m of white sandstone interbedded with many layers of conglomerate, violet fine-grained sandstone, and white crossbedded coarse-grained sandstone containing pseudonodules. There are also several zones of irregular accumulations of hematite. One hundred meters from the base, beds containing green-white, green, and red chert nodules are interbedded with conglomerate containing quartz fragments and green-gray shale debris. These are fluviolacustrine and neritic formations, and are probably equivalent to the green shale beds which crop out on the south side of Wādī Lā'ah where Lamare found a Jurassic flora. The neritic facies thins toward the north. The conglomerate beds, numerous north of Wādī al 'Urr, are almost completely absent in Wādī Surdūd, whereas shaly and tuffaceous beds are present to the north.

Section of Kohlan Series on south side of Wādī Lā'ah, north of Aṭ Ṭawīlah

(see fig.4)

Amran Series at top of section.

Kohlan Series:	Thickness (meters)
Sandstone and shale; violet-red sandstone, and slaty shale overlain by gray shale	50
Shale, sandstone, and gray shale overlain by conglomeratic sandstone and 3 m of red shale	18
Shale, gray-green; includes large rounded blocks of granite, pegmatite, and gneissic mica schist as much as 1 m in diameter	7
Shale and conglomerate, a few meters of basal conglomerate containing basement fragments; some very thin conglomeratic layers with very fine well-stratified fragments, overlain by slightly green-gray shale	25
Total	100

Basement at base of section.

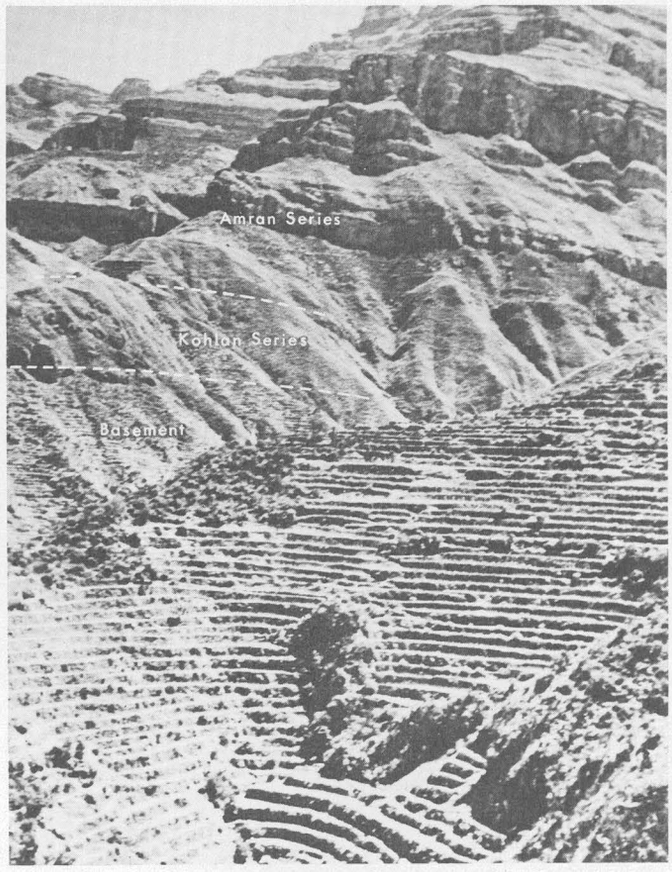

FIGURE 4.—*Wādī Lā'ah valley north of Aṭ Ṭawīlah.*

The upper calcareous gray shale contains the Amran Series fauna; thus the boundary between the Kohlan Series and the Amran Series is arbitrary because there was no break in sedimentation. From this section, it appears that the zone of large blocks about 7 meters thick separates an older complex about 25 m thick. Lamare without specifically stating so in his text, likewise depicted a conglomeratic bed with large fragments in his stratigraphic section.

The Kohlan Series may actually include two complexes of different age—the lower being more shaly. In any case, the sandstone facies thickens toward the west; in the lower course of Wādī Lā'ah, the Kohlan Series is several hundred meters thick (700 m according to O. Schmidt, oral commun., of C. Deilmann Bergbau). North of Jabal Muṣawwar, the series is about 300 m thick (Lamare, 1930b, and Wissmann and others, 1942). Thicknesses given by different authors do not compare closely because the upper boundary of the Kohlan Series is difficult to determine.

A complete section of the Kohlan Series is not exposed in any part of the Ṣa'dah area. Nevertheless, a part of this series about 125 m thick is exposed north of As Sinnārah (Jabal 'Ablah), the mountain on which the

fortress of Sa'dah is constructed (fig. 5). From observations made west and southwest of Sa'dah, it seems probable that a complete Kohlan section is exposed at Jabal 'Ablah.

Section of Kohlan Series at Jabal 'Ablah, north of As Sinnārah

Amran Series at top of section.

Kohlan Series:	Thickness (meters)
Sandstone, gray, hard, with worm tracks. Progressive transition to the overlying Amran Series	15
Sandstone, white, crossbedded	10
Sandstone, white, friable, crossbedded; red sand with ripple marks	26
Sandstone, calcareous and vuggy	14
Sandstone, gray, light-gray to yellow, friable	10
Sandstone, coarse-grained, red and yellow, crossbedded, and white poorly cemented sandstone	18
Shale, pebbly; conglomeratic layers with gray shaly cement and fragments as much as 10 cm in diameter	20
Clay shale, light-gray	2
Sandstone, coarse-grained, with a red crossbedded band and irregularly disseminated pebbles and gravelly layers	8
Conglomerate, coarse; fragments as large as 10 cm in diameter; contains pebbles of volcanic rocks	2
Total	125

Basement at base of section.

These observations show that at the time of Kohlan deposition a zone of subsidence, which is now more pronounced toward the Red Sea, existed in central Yemen.

AMRAN SERIES

TYPE LOCALITY

The calcareous formations which crop out over a large part of Yemen, especially in the north, were grouped by Lamare in the Amran Series. 'Amrān, a town about 40 km from Ṣan'ā, is in the bottom of a northeast-trending secondary graben. It has not been possible to locate precisely where Lamare established the type section, but he does show a figure in which he defines the Amran Series (Lamare, 1930b, p. 52).

The fossils of Jurassic age found in the lower part of the Tawilah Group, as defined by Lamare (beds 13 and 14), permit modification of the type section and the proposal of the outcrop in the south side of Wādī Lā'ah as type locality of the Amran Series. All the sedimentary sequences of Yemen except the Wajid Sandstone are exposed in this valley.

The Amran Series crops out mainly in the Ṣa'dah-Jabal Muṣawwar-Ma'rib area, although it formerly covered the entire country. In fact, traces of Amran rocks are found in the extreme eastern sector of the country, notably in the desert area of Ṣāfir, in the far south near the frontier along Wādī Banā, as well as in the west in an isolated horst which is uplifted through the Trap Series. The facies varies from place to place but is everywhere calcareous, a characteristic which

FIGURE 5.—Granitic basement and overlying Wajid Sandstone in fault contact with Jurassic sandstone and limestone. Walls of Sa'dah in the foreground.

easily distinguishes this series from the upper sandstones and from the lower shales and sandstones.

In the type area, Lamare (1930b) estimated the series to be 320 m thick; however, the thickness is highly variable from place to place in relation to local subsidence. Since the first exploration, the Amran Series has produced fossils which establish its age as a Malm equivalent.

PALEONTOLOGY

Fossils collected by Botez (1912) in the Bājil area:

Cidaris cenomanensis Cotteau
Exogyra africana Lamarck
Ostrea syphax Coquand
Ostrea ouremensis Choffat
Ostrea dieneri Blanckenhorn
Nerinea sp.
Natica sp.
Terebratula sp.
Rhynchonella sp.

Fossils collected by Lamare (1930b) in the 'Amrān-Kuḥlān area:

Cidaris glandarius Lang
Rhynchonella moravica Uhlig
Terebratula subsella Leymerie
Avicula cf. *A. gessneri* Thurmann and Etallon
Ostrea suborbicularis Roemer
Ostrea thurmanni Etallon
Alectryonia pulligera Goldfuss
Exogyra bruntrutana Thurmann
Modiola subangustissima Dacqué
Mytilus subpectinatus d'Orbigny
Arca sublata d'Orbigny
Isocardia (=*Ceromya*) *striata* d'Orbigny
Lucina substriata Roemer
Cardium banneanum Etallon
Pholadomya protei (Brongniart)
Anatina (=*Cercomya*) *striata* d'Orbigny
Anatina (=*Cercomya*) sp. indet.
Natica hemisphaerica Roemer
Natica sp.
Tylostoma sp. indet.
Perisphinctes cf. *P. virguloides* Waagen
Perisphinctes aff. *P. praestenococylus* Waagen
Perisphinctes (*Virgatites*) cf. *P. dorsoplanus* (Vishchniakoff Burckhardt

Fossils collected by Herbert Karrenberg (in Basse and others' 1954) north of Ṣan'ā:

Modiolus (*Pharomytilus*) cf. *M. perplicatus* Etallon
Exogyra nana (J. Sowerby)
Exogyra sp. indet.
Lopha karrenbergi Basse
Gryphaea balli (Stefanini)
Praeconia rhomboidalis (Phillips)
Protocardia somaliensis Cox
Cardium sp.
Pholadomya (*Homomya*) *inornata* J. de C. Sowerby
Nerinella retrogressa Etallon
Nerinea acreon d'Orbigny
Nerinea binodosa Etallon
Cryptoplocus subpyramidalis Munster
Cryptoplocus n. sp. Basse
Cryptoplocus yemenensis Basse
Globularia hemisphaerica Roemer
Spinigera sp. indet.
Pseudocidaris thurmanni Etallon
Terebratula subsella Leymerie
Comophyllia thamnastroides Gregory
Plesiophyllum harensis Basse

Fossils collected by Geukens are listed in table 1.

LITHOLOGY

The Amran Series may be differentiated by facies in four areas, as follows: (1) South of Bājil-Ṣan'ā; (2) Wādī Surdūd and Wādī La'ah basins; (3) 'Amrān-Ṣa'dah-Al Jawf, and (4) Ma'rib-Ṣāfir.

SOUTH OF BĀJIL-ṢAN'Ā

South of the Bājil-Ṣan'ā area the Amran Series is exposed in small horsts uplifted through the Trap Series. In the northern part of this area, the series begins with a 1- to 2-m thick basal conglomerate that contains basement fragments 2 to 3 cm in diameter. Above this are beds of blue-gray limestone with lumachelles. This unit is overlain by the dark-gray limestone which is predominant throughout the whole series. The thickness of the series does not exceed 250 m.

In the southern part of this area, the top of the Amran Series is marked by 2 to 3 m of dark-gray shale and calcareous shale characterized in the upper part by signs of emergence and slightly violet shale and limestone.

Toward the west, the Amran Series limestones are dark blue and contain Mytilidae and *Ostrea* which were transported a great distance. Near the longitude of Ta'izz, the base of the series rests on the Precambrian and is composed of a few meters of pink quartzite and conglomerate containing small fragments overlain by thick beds of dark-blue limestone. A shaly complex about 200 m thick overlies the blue-gray limestone extending westward toward At Tihāmah. This complex of green and violet shale with gypsum lenses is overlain by 100 m of dark shale, including beds of gray limestone, in turn overlain by calcareous sandstone (30 m thick) and a shaly complex with several thin lenses of marl and limestone. The contact with the Tawilah Group is very distinct.

To the south, the Amran Series consists of thick beds of dark-blue limestone, thinning to the east, which were deposited on the basement as a result of a marine transgression from the west. Many lumachelle beds show that the subsidence was slight and that the basin was progressively filled. After a period of emergence, a lacustrine period followed which was succeeded, in turn, by slight subsidence during which Upper Jurassic limy-marly and shaly deposits were laid down.

TABLE 1.—*Fossils collected by F. Geukens*

	NE of 'Amrān	Khawbat 'Alī	Jabal Ramid	Al Ḥarf	Wādi Wakhd	Khusrān	Aṣ Ṣafrā'	As Sinmārah	Jabal 'Ablah	Bab al Ahjar	N of Aṭ Ṭawīlah	E of Maḥwad	Al Bayaḍ	Aḍ Ḍayq	SW of Ṣa'dah	Ma'rib (Jabal Balaq)	Wādi Surbūd	Khamir
Bourguetia striata J. Sowerby								×										
Burmirhynchia?										×								
Camptonectes aff. *C. virdunensis* (Buvignier)									×									
Ceratomya cf. *C. plicata* Agassiz							×						×					
Ceratomya cf. *C. wimmisensis* (Gillieron)								×										
Ceratomyopsis cf. *C. kiliani* (Rollier)								×	×									
Chlamys (*Chlamys*) *curvivarians* Dietrich								×										
Chlamys sp		×																
Daghanirhynchia?										×								
Eligmus cf. *E. aualites* (Stefanini)								×										
Exogyra													×					
Eligmus cf. *E. rollandi* Douville									×									
Exogyra nana (J. Sowerby)	×	×																
Exogyra Fourtaui Stefanini									×									
Hemicidaris (*Hypodiadema*) *Macfadyeni* (Currie)																		×
Globularia sp		×																×
Homomya inornata (J. de C. Sowerby)									×									
Inoperna perplicata (Etallon)								×										
Lima (*Plagiostoma*) sp		×						×										
Lima (*Plagiostoma*) *harronis* Dacque										×	×							
Lopha solitaria (J. Sowerby)								×	×									
Mactromya sp								×										
Mactromya aequalis Agassiz									×									
Modiolus imbricatus J. Sowerby														×				
Modiolus jurensis (Roemer)				×			×							×				×
Brachidontes (*Arcomytilus*) *laitmairensis* (de Loriol)								×						×				
Nerinea	×								×					×		×		
Ostrea				×	×									×			×	
Pholadomya			×															
Pholadomya aubryi Douville														×				
Pinna cf. *P. stoliczkai* Cox									×									
Pseudocidaris thurmanni Etallon		×																
Somalirhynchia sp									×								×	
Somalirhynchia africana Weir						×												
Somalirhynchia africana var. *mesoloba* Muir-Wood									×									
Terebratula cf. *T. bicanaliculata* Schlotheim											×							
Terebratula aualites Stefanini											×							
Terebratula sp		×	×			×		×				×			×			×
Terebratula suprajurensis (Thurmann)									×					×				
Trochalia cf. *T. yemenensis* (Basse)			×									×						
Trochalia depressa (Voltz)			×															
corals						×			×									
echinoids						×					×							
gastropods				×							×			×				
pelecypods				×														
plant debris					×	×				×								
stromatopores						×			×						×			

WĀDĪ SURDŪD AND WĀDĪ LĀ'AH BASINS

In the Wādī Surdūd-Wādī Lā'ah basins, the upper and lower boundaries of the Amran Series are more difficult to determine. This is natural considering that in this area subsidence began before deposition of the Amran Series and continued into later epochs. For example, on the north side of the Wādī Surdūd valley near the junction with Wādī al Ahjar, the lower sandstone series (Kohlan Series) grades progressively upward into limy and marly beds of the Amran. In that area the series, at least 360 m thick, consists of about 300 m of pure limestone and shaly limestone. These calcareous rocks are overlain by light-green and light-yellow shale and some sandy beds that enclose alternating layers of black shale and marl. This sequence grades progressively upward into sandy conglomeratic beds of the Tawilah Group.

In the upper channel of Wādī al Ahjar, the shaly-marly part of the Amran becomes more continental, whereas the limestone becomes more marly.

Section of Amran Series in upper channel of Wādī al Ahjar

Conglomeratic sandstone of Tawilah Group at top of section.

Amran Series:	Thickness (meters)
Sandstone and violet shale	20
Sandstone, ribboned; includes plant remains and a few beds of nodular sandstone	20
Shale, violet and green	15
Total	55

Typical limestone and marl below.

In this upper part of the Amran Series, beds of gypsum and dark bituminous shale increase toward the east, as seen in the east side of Wādī al Ahjar, and have been recognized north of Ṣan'ā in wells drilled in 1953 by German engineers to study the bituminous shale.

In spite of the gradual transition to adjacent series, the most complete section and the easiest to study is in the south side of Wādī Lā'ah.

Section of Amran Series in south side of Wādī Lā'ah

Tawilah Group at top of section.

Amran Series:	Thickness (meters)
Limestone and shale: shaly limestone, interbedded gray shale, and a few limestone beds containing many large sea urchins are overlain by alternating marly limestone and light-yellow argillaceous shale, many spicules, and *Lima* (*Plagiostoma*) *harronis* Dacqué	140
Limestone, thick-bedded; large *Ostrea*	50
Limestone and shale: complex of thick beds of light-gray limestone separated by shale lenses; toward the top the limestone becomes more marly and yellow	170
Shale, calcareous, gray; *Terebratula* cf. *T. bicanaliculata* Schlotheim and *T. aualites* Stefanini	20
Total	380

Kohlan Series at base of section.

The Amran Series thus consists of 380 m of predominantly light-gray limestone, the upper part of which contains a shaly-marly-limy complex 90 m thick. This thick sequence occurs, however, in the axis of subsidence; toward the north and west the Amran Series is not as thick.

Just south of Ath Thillah, the top of the calcareous Jurassic rock is in direct contact with crossbedded gravelly and sandy beds; at the contact is a conglomeratic breccia having calcareous cement. This is the margin of the Jurassic basin which emerged prior to the Cretaceous.

Toward the west in the direction of Maḥwad, the upper part of the light-gray limestone containing *Trochalia yemenensis* is overlain by about 20 m of sandstone interbedded with generally violet shale and limestone overlain by red sandstone. The sharp thinning of the marly-limy beds seen at Aṭ Ṭawīlah, the arenaceous facies, and the violet coloring show that the Maḥwad area represents the western margin of the Late Jurassic basin.

The Jurassic reappears farther to the east on the west flank of a large anticline with a Precambrian core, where a sharp thinning of the Amran Series is also observed. The upper marly-limy part seems to be completely eroded here, and the base of the sandstone of the Tawilah is composed of conglomerate with limestone fragments.

'AMRĀN-ṢA'DAH-AL JAWF

In the 'Amrān-Ṣa'dah-Al Jawf area only rocks of the Amran Series crop out. Bounded on the northeast by faults and on the west by unexplored ravines, the area is not favorable for paleogeographical study. The region is characterized by predominantly light-yellow marly limestone, reminiscent of the upper part of the Amran Series in the Wādī Lā'ah valley. That these are shallow-water deposits is indicated by (1) many intercalated sandy layers and interstratified gypsum lenses, as for example, at Al Ḥarf southwest of Ṣa'dah, (2) claystone lenses and crossbedded sands with plant debris alternating with calcareous beds containing globular stromatoporoids and isolated corals, (3) beds filled with Cidaridae spicules, (4) beds showing traces of emergence and crossbedded sandy limestone.

The stratigraphy of the top and bottom of the series is more complex. Toward the base the Amran Series passes without interruption into the Kohlan, as demonstrated in the section near Jabal 'Ablah southeast of Ṣa 'dah.

The upper part is exposed in the synclinal axis in the 'Amāsīyah area and consists of a dark-yellow to buff sandy layer containing plant debris.

MA'RIB-ṢĀFIR

The Amran Series is exposed in the desert region of Ma'rib-Ṣāfir, but rare outcrops only give a general idea of the evolution of this part of Yemen.

The base of the series rests on the metamorphic basement exposed on the southwest side of Jabal Balaq, west of Ma'rib. The basal part consists of 1 to 2 m of coarse-grained quartzite overlain by oolitic limestone and calcareous and sandy shale. The series itself is composed of light-yellow marly limestone similar to that at Ṣa'dah, but containing, on the east side of the jabal, many beds of alabaster and white marble which were quarried in ancient time. Eastward near Ṣāfir, the Amran Series consists of major salt deposits overlain by bituminous shales, several meters of gypsum, and yellow-gray argillaceous and calcareous shale containing fish remains (fig. 6). The character of the rocks in the upper part of the Amran Series indicates a major isolated basin characterized by desiccating conditions.

TAWILAH GROUP

The Tawilah Group is composed mainly of white coarse-grained sandstone containing at irregular intervals conglomeratic layers of rounded or subangular quartz fragments; red sandstone is intercalated locally. In the upper part, generally immediately below the Trap Series, are beds containing globules or nodules of hematite. To date, no fossils have been collected from this group, which is considered to be of Cretaceous age by reason of geometric relationships.

Type section of the Tawilah Group at Jabal aṭ Ṭawīlah
(see fig. 7)

Medj-zir Series at top of section.

Tawilah Group:	*Thickness (meters)*
Sandstone, white, crossbedded; coarse conglomerate lenses	120
Sandstone and shale; violet shale in thin beds interstratified in white sandstone	20
Sandstone and shale; white sandstone with conglomerate layers alternating with red and green shale	40
Total	180

Amran Series at base of section.

The delineation of the upper boundary is rather arbitrary in the zones of subsidence, such as in the zone west-northwest of Ṣan'ā, although breaks in sedimentation occur elsewhere which allow more precise determinations of the boundaries of the group.

Because coarse-grained sandstones and gravelly layers everywhere characterize the Tawilah Group, the shaly-sandy transition beds (55 m thick) containing

FIGURE 6.—Salt dome at Ṣāfir.

FIGURE 7.—Tawilah Group exposures at the town of Aṭ Ṭawīlah.

plants were considered Jurassic. These beds crop out in the upper channel of Wādī al Ahjar above Jurassic limestone.

The group is less thick (150 to 200 m) in the area north of Ta'izz where it may be studied in isolated horsts. At the base is a gray brecciated bed, about 1 meter thick, containing limestone fragments and is overlain by numerous conglomerate beds interstratified in coarse-grained sandstone.

The upper part includes white sandstone with layers of irregular hematite nodules, crossbedded sandstone, conglomerate, and finally a few lava flows. This alternation, however, is only local and shows that volcanic activity began with local extrusions.

East of the Trap Series (Jabal Ṭiyāl), the Tawilah Group is no more than 150 m thick. There, the base is a conglomerate containing fragments from the Amran Series, which demonstrates active erosion at the time of the Cretaceous transgression.

Stratigraphic observations prove that post-Jurassic tectonic movements produced undulations with a large radius of curvature. The margins of the basin were elevated, eroded, and the sedimentary debris deposited conformably on the earlier beds in the center of the basin. Toward the margins the contact is slightly unconformable, and the basal beds of the Tawilah Group contain pebbles of the underlying Jurassic limestone.

The Tawilah Group extends slightly beyond the Trap Series to the north and east. The extent of the Tawilah Group corresponds very closely to that of the Trap Series, as if the Trap Series has protected the Tawilah from erosion.

MEDJ-ZIR SERIES

LITHOLOGY

The morphology between Aṭ Ṭawīlah Kawkabān Ṣan'ā and Wādī as Sirr is dominated by steep cliffs that are partly due to tropical erosion, which tends to form a peneplain and inselberg topography. These cliffs contain numerous caves (ancient Himyaritic tombs?) and consist of whitish-gray coarse-grained sandstone and conglomerate layers containing quartz fragments and ferruginous layers.

In the Al Gharās area, just north of Majzir, the cliffs expose Tertiary formations lithologically very similar to the underlying Cretaceous rocks.

Section of the Medj-zir Series in cliffs just north of Majzir (Al Gharās area)

[Total approximate thickness of Medj-zir Series, 120 m]

Trap Series at top of section.
Medj-zir Series:
- Sandstone with ferruginous, spherulitic concretions and nodules; appears to be a paleosol that covered the area before the extrusive phase.
- Sandstone, white, mottled red, becomes finer grained and more shaly.
- Sandstone, white.
- Clay, light-gray, slightly hardened.
- Sandstone, white.
- Shale, green-red, a few meters thick.
- Sandstone, white, fine, slightly calcareous (altered), fossiliferous; contains a 30-cm bed filled with worm tracks.
- Sandstone, white, coarse-grained, quartzitic, very compact; contains crossbedded layers altered to a darker color (these are displayed over a great distance).
- Conglomerate, 10 to 30 cm thick, of rounded quartz fragments 1 to 3 cm in diameter.

Tawilah Group sandstone at base of section.

The lowermost conglomerate layer is considered to be the base of the Medj-zir Series, and lies with apparent conformity on sandstone beds with very similar facies more than 200 m thick. At Majzir the thickness of Tertiary rocks is about 120 m. These form the upper part of the sandstone cliffs on two sides of the Rawḍah plain, north of Ṣan'ā; they are also seen on the summit of Kawkabān-Aṭ Ṭawīlah (fig. 8) where the fossiliferous layers are found in the fortress constructed on the south side of the cliff which dominates the town of Aṭ Ṭawīlah.

This series is no longer present east of the Trap Series and was not recognized in sections between Aṭ Ṭawīlah and Maḥwad, nor in strata exposed in horsts uplifted through the Trap Series.

The sedimentary sandy series which crops out in horizontal attitude east of the Trap Series dips under the Jabal Ash Sharafah (Ṭiyāl) massif, but the Medj-zir is not present there. On the other hand, it is apparent that the massif Ḥaḍūr ash Shaykh, in the Ath Thillah area, is a dome and that the sedimentary series dip toward the south.

Although the age of these tectonic deformations cannot be precisely determined, the Medj-zir Series appears to be deposited in a fairly well defined basin. It is difficult to establish the direction of the transgression, but the series is apparently thicker to the west and, therefore, the sea probably came from this direction. In fact, at Aṭ Ṭawīlah, where the Medj-zir Series is no longer protected by the Trap Series, it is the same thickness as at Majzir town and the rocks are finer grained and more calcareous (the calcium carbonate being in large part removed by solution).

FOSSILS AND AGE

The Aṭ Ṭawīlah area has furnished only internal molds of *Nerinea*, as much as 7 cm long, whereas

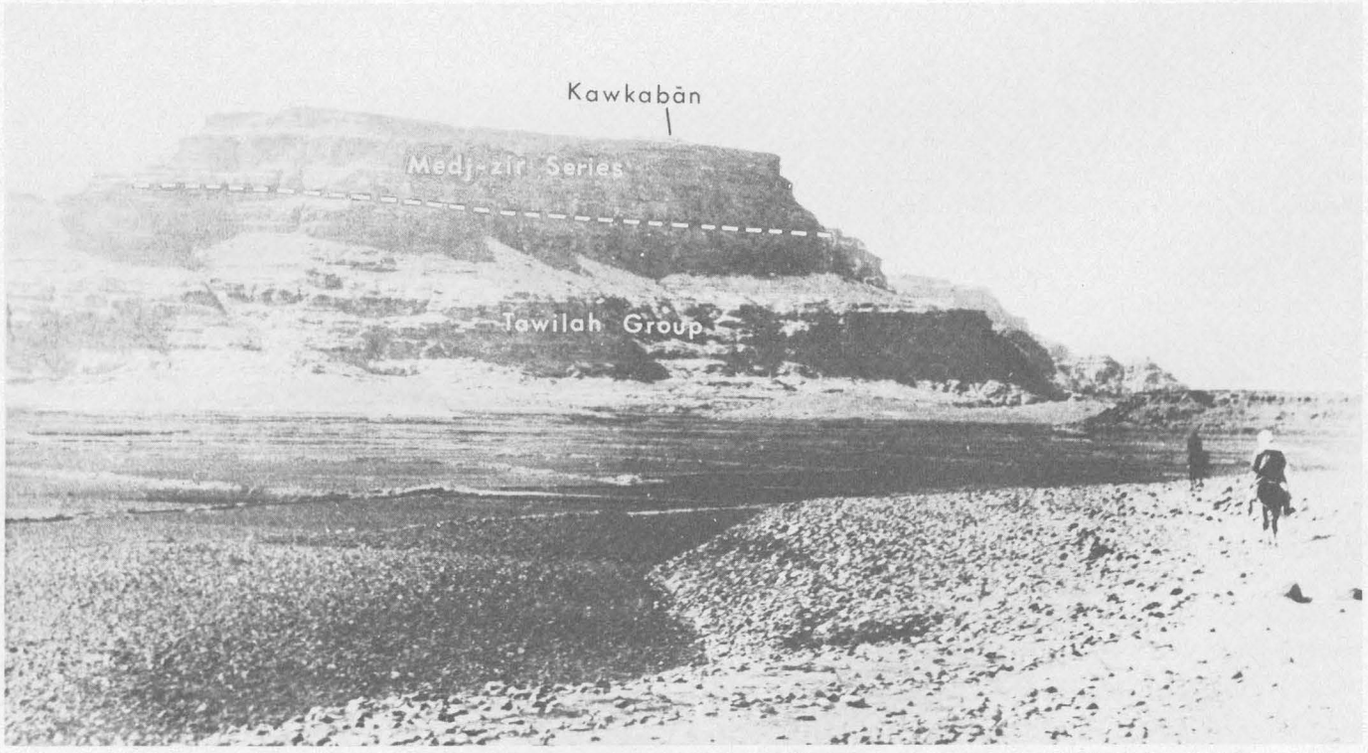

FIGURE 8.—Medj-zir Series above Tawilah Group in the cliffs at Kawkabān.

at the town of Majzir, northeast of Ṣan'ā, the fauna includes the following, which date the Medj-zir Series as Paleocene:

Myliobatus sp.
Campanile, internal molds
Calyptraea sp.
Architectonica sp.
brachiopods

The sequence at Majzir also includes slabs of irregular elliptical outline (from 3 to 20 cm long) filled with small triangular forms grouped into hexagons that are probably due to recrystallization of calcite.

IGNEOUS ROCKS

TRAP SERIES

VOLCANIC ROCKS

The southwest part of Yemen, almost one-quarter of the country, is covered by volcanic rocks grouped into the Trap Series. The Trap Series is made up mainly of alternating lava flows, basalts, andesite, or trachyte porphyries, and different types of varicolored tuffs (fig. 9). The maximum thickness is difficult to estimate because of faults but is locally in excess of 1,200 m.

Throughout the Trap Series are seen intrusive basaltic rocks irregularly distributed as dikes, sills, or laccoliths. The old major volcanic centers are rather rare. They are noted either by lava flows which thicken toward the centers or by the transition from tuffs to conglomerates. Volcanic centers are also marked by chimneys standing above the general ground level. Large dikes, some of which can be followed for several kilometers, are seen in numerous places.

INTER-TRAP DEPOSITS

During the period in which the Trap Series formed there were quiet intervals, some of long duration. During these quiescent periods four types of inter-Trap deposits accumulated:

1. Fresh-water deposits, probably lacustrine, which are fossiliferous: generally contain bituminous beds and plant and fish remains.
2. Typical alluvial deposits with fragments of partially carbonized wood.
3. Sandy deposits without fossils (fluvioeolian?).
4. Paleosol, generally lateritic, at some places developed along plane surfaces, and locally cutting different beds.

The fossiliferous beds include small gastropods, lamellibranchs, and ostracods. These are *Sphaerium* sp., *Amerianna* sp., *Melanoides* (*Tarebia*) cf. *M. acuta* (Sowerby). These fresh-water fossils, which suggest an Oligocene to Miocene age, occur from north of Ṣan'ā to south of Ta'izz. Mr. R. W. Morris, of the Arabian American Oil Co., recognized nonmarine ostracodes: *Candona* sp., *Cyprideis* sp., *Gomphocythere* sp., and *Cypridopsis*(?) sp.

FIGURE 9.—Trap Series near Zarājah.

AGE

Volcanism probably started in the south toward the end of the Cretaceous but became more intense and extensive during the Tertiary. It is characterized by extrusive and explosive periods related to tectonic deformation along faults. Volcanic activity continued into the Recent.

LACCOLITHS

GEOGRAPHIC DISTRIBUTION

The area between 'Amrān and Ṣa'dah, north of the extension of the Trap Series, has major laccolith massifs of granitic composition, some deeply breached by erosion (fig. 10). Such examples occur at Jabal Ramid south of Ḥūth and in the hills near Jabal Maflūq in the Jawf area (fig. 11). The granitic laccoliths are especially noticeable in the calcareous Amran Series.

In Jabal Ramid, the granite exposed in the center grades to a microgranite near the contact with limestone beds; the sedimentary rocks are not influenced by contact metamorphism except over a very thin interval.

AGE

Supposedly, the emplacement of the laccoliths is of the same age as the Trap Series, hence mainly Tertiary.

RECENT GRANITES

Gray-white granite hills protrude locally above the general topography carved in the Trap Series. These intrusive massifs deform the Trap Series on their flanks, and thus they are dated as post-Trap. Some intrusions reach 10 km in length and a few kilometers in width, but others may be less extensive and appear as lenticular dikes from 0.1 to 1.5 m wide.

Silicic granitic intrusions (leucocrats, holocrystallines) enclose crystals of tourmaline (Jabal Ḥufāsh) or amphibole (Jabal Ṣabir, fig. 12).

RECENT VOLCANOES

Recent (Holocene) volcanoes are those which have retained their typical shape (crater or cone) and whose direction of flow has been influenced by the existing topography.

Recent volcanoes are grouped in three volcanic fields: (1) Ṣan'ā-'Amrān, (2) Ṣirwāḥ-Ma'rib, and (3) Dhamār-Radā'. Isolated volcanoes are present elsewhere throughout the country.

In the Ṣan'ā-'Amrān volcanic field it is possible to distinguish several extrusive phases by comparing the development of river terraces to the southwest of 'Amrān. North of Ṣan'ā there are also volcanoes of historic time.

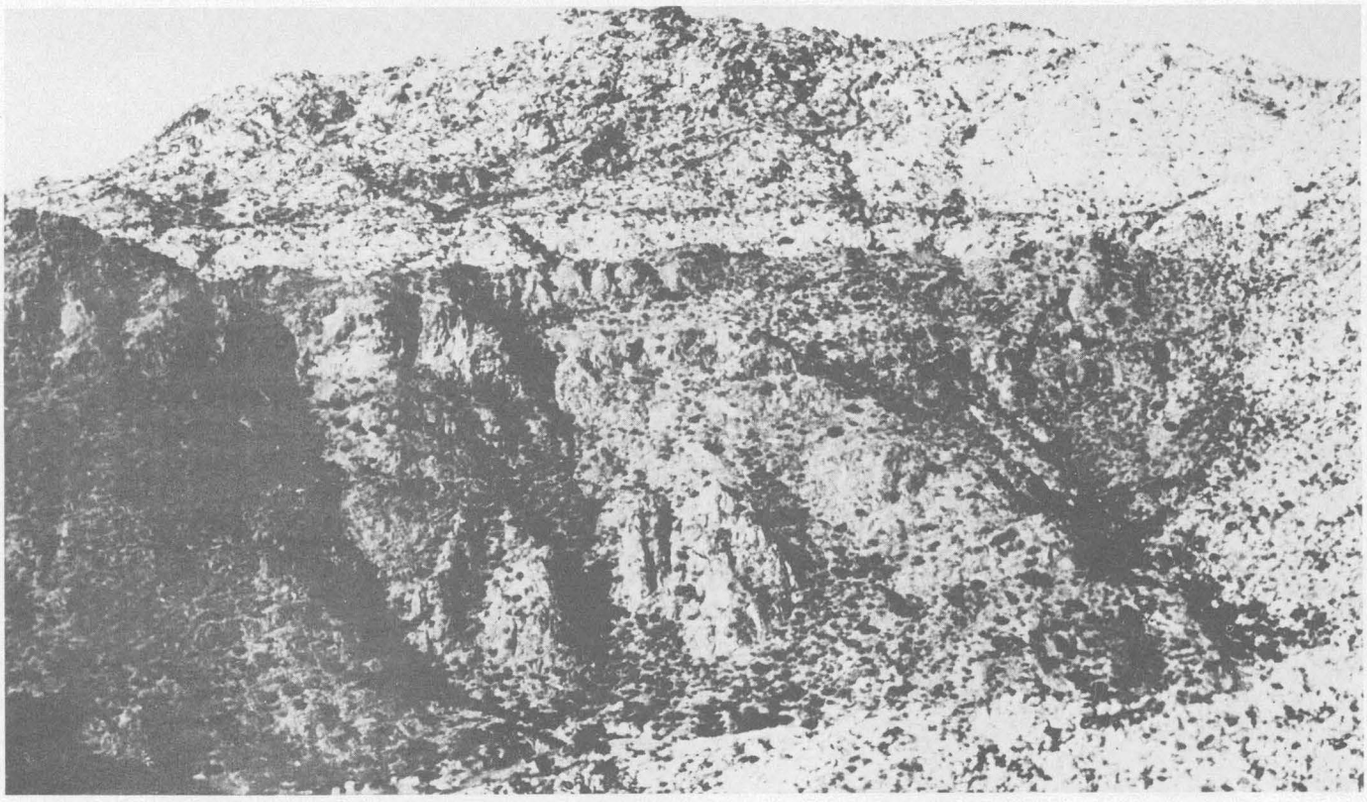

FIGURE 10.—Laccolith in the Kohlan Series in the upper course of Wādī Surdūd.

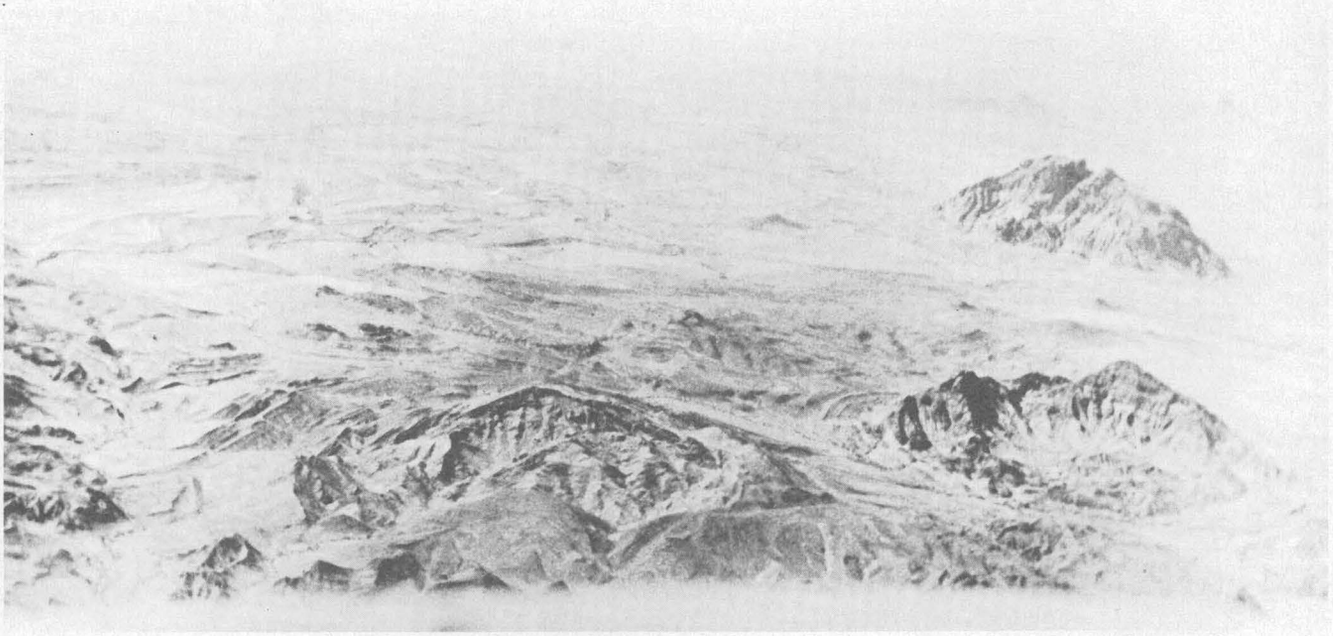

FIGURE 11.—Laccoliths in Al Jawf region.

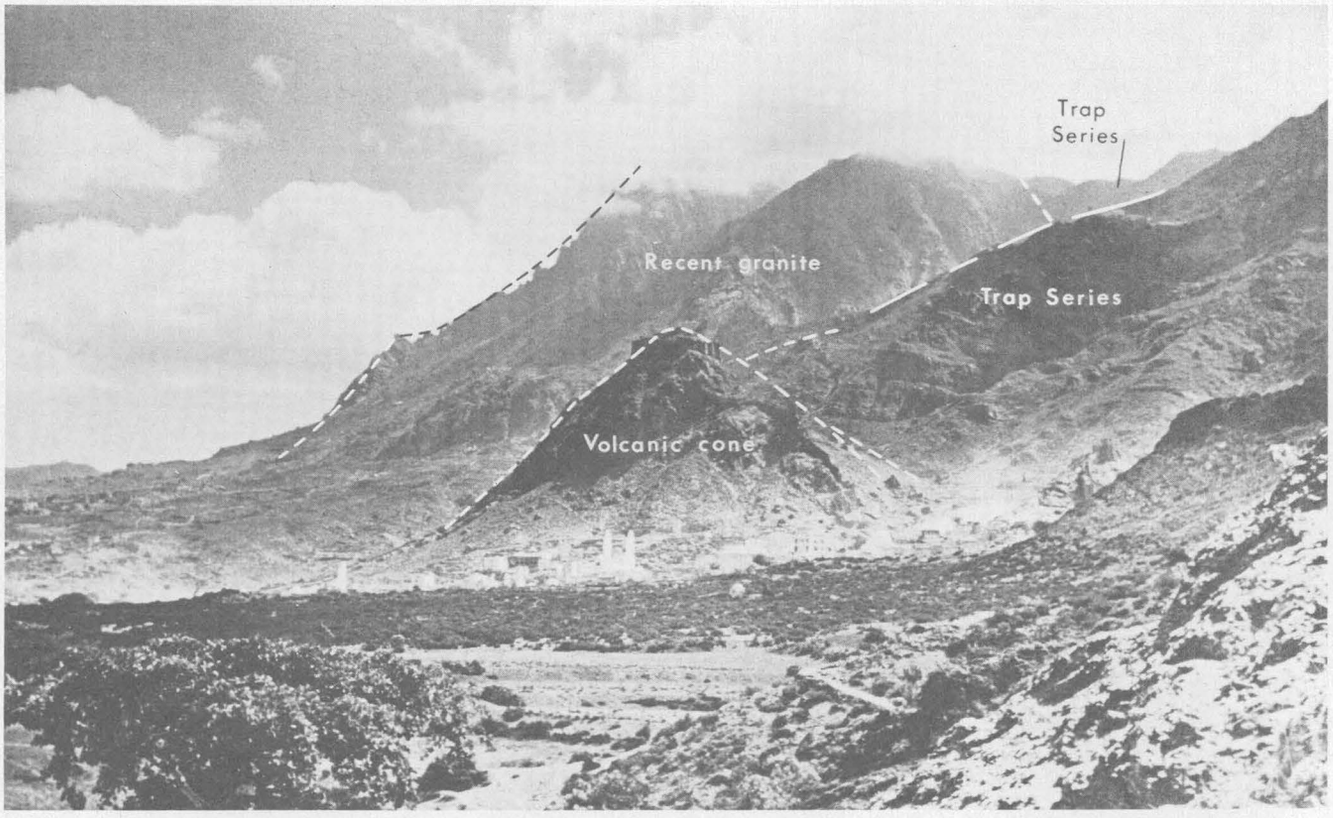

FIGURE 12.—Recent granitic massif of Jabal Ṣabir and city of Ta'izz at base of volcanic cone.

Volcanoes in the Ṣirwāḥ-Ma'rib field are of several types. South of the Ṣirwāḥ-Ma'rib road are volcanoes having large cones of light-yellow tuffs surrounding the central peaks. These volcanoes have supplied thick stratified deposits of white-yellow tuff which extend for several kilometers in the direction of Wādī Adhanah. North of the road lie basaltic volcanoes with numerous adventitious craters, characterized by long flows which thin to the south.

About 3 hours walk east of Ṣirwāḥ is a depression of an old crater; the tuff and agglomerate beds dip gently to the exterior and enclose blocks of gneiss and granite up to 50 cm in diameter, attesting to the violence of the explosive phase.

Volcanism in Dhamār-Radā' (fig. 13) is the most recent in Yemen and the field still contains solfataras (sulfurous vents). The volcanic field is related to an east-west-trending fracture zone, along which are the main centers. Small volcanoes rise from the floor of the depression, especially in the eastern part. Seismic shocks are very numerous in this area.

STRUCTURE

The surface features in Yemen fit into two large very distinct categories: (1) the folded metamorphic basement of Precambrian age in unconformable contact with (2) the unmetamorphosed subhorizontal sedimentary rocks. Exposures of the lower beds of the sedimentary rocks as well as the basement depend largely on erosive activity.

Orogenic movements, generally with a great radius of curvature, have locally influenced the structure of the country. For example, the area between Ash Sharafah and Ma'rib is a large dome plunging to the north.

Synclines occur particularly in the north—north of Wādī Mawr and in the 'Amāsīyah area, south of Ṣa'dah. The area covered by the Trap Series corresponds in reality to a deep depression. The shape of the depression is most pronounced at the eastern border of the Trap Series, especially in the vicinity of Jabal Ṭiyāl.

Other undulations are less striking, as for example, the east-west-trending anticline at Jabal Ḥaḍūr ash Shaykh and Jabal Muṣawwar. The Ṣan'ā area is a large syncline which extends from Wādī al Ahjar in the west to Jabal Ṭiyāl in the east and is the site of the old Jurassic basin.

From the fact that the coastal, or At Tihāmah, part of Yemen is a graben and the eastern part a horst, it is deduced that the general structure must be dominated by subvertical faults oriented preponderantly from the north-northwest to the south-southeast, subparallel to

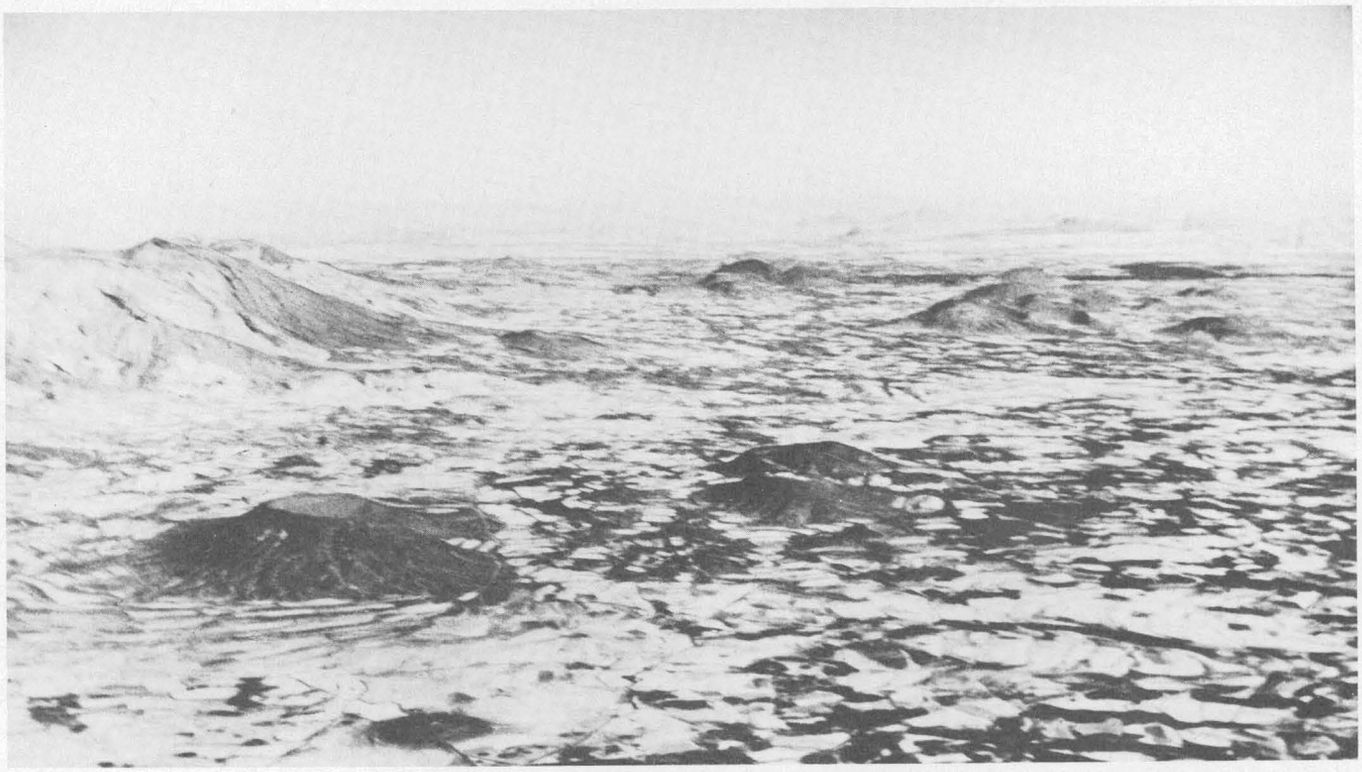

FIGURE 13.—Recent volcanoes near Radā'.

the Red Sea graben and at right angles to the Gulf of Aden, which trends east-northeast–west-southwest.

Innumerable faults, in fact, cut through the country, many bounding secondary grabens and horsts. The whole zone of contact between the Red Sea plain and the mountainous region is marked by faults trending north-northwest–south-southeast. One graben parallel to the Red Sea forms the main Al Jawf depression in the northeast, which is joined by a graben that follows the alinement of the Gulf of Aden, and forms the Ramlat as Sab'atayn desert. Tectonic alinements are also oblique to the former directions; this is true of the 'Amrān graben and the secondary graben between Ḥarīb and Ma'rib. Many secondary grabens in the area covered by the Trap Series are sometimes difficult to distinguish from the fluviatile flat-bottomed valleys covered by thick alluvium (plains of Ṣan'ā, Ma'bar, Yarīm, Al Janadīyah, and others). However, grabens are readily distinguished in places where recent volcanoes along the bordering faults have spread lavas toward the depressed part (Dhamār, Radā', and 'Amrān grabens) (fig. 14). These grabens are characterized by a system of faults which form steps along the margins and small horsts which rise in the graben floors. In many places the steps look like large landslides on the sides of the horst.

Besides the system of parallel faults, there is in places a system of perpendicular faults outlining blocks which could be large horsts (north of Ta'izz) and small isolated massifs (Jabal Kanīn). The faults are easily located in the sedimentary series where they bring heterogeneous rocks into contact (fig. 15) and thus permit an evaluation of the throw of the fault. By contrast the faults are more difficult to study in the Trap Series.

Tectonic deformation along faults is not limited to epeirogenic movement related to the formation of the Red Sea. The fact that south of Wādī Surdūd the Trap Series rests directly on the Kohlan Series and that the Amran Series and Tawilah Group disappear suddenly along the faults (fig. 16) proves that the generally east-west oriented faults locally deformed the country long before the deposition of the Trap Series. Faults are so numerous locally that they cannot be adequately depicted on a map. The most tectonically active valley was the Wādī Surdūd, especially its upper and middle courses. Although the dip of the faults is generally steep, some have the appearance of overthrusts (for example, between Maḥwad and Aṭ Ṭawīlah where the Amran Series is thrust over the deformed Tawilah Group for a long distance).

Magma has often penetrated along faults, and the basalt has simply filled up the open fissures. Secondary cracks cut the basalt dikes, as is evinced near Ḥaydān, west of Ta'izz, where the center of a basalt dike cutting Cretaceous sandstone contains a vertical bed 50 cm thick composed of detrital fragments. In other places basaltic intrusions along faults have torn off large fragments of the confining rocks, as for example along the faults which outline the horsts north of Ta'izz.

Tectonic deformation possibly occurred after the emplacement of the dikes. In fact, west of Aṣ Ṣafīyah (north of Ta'izz), basalt fragments are intermingled with blocks of Cretaceous sandstone (2 to 3 m wide)

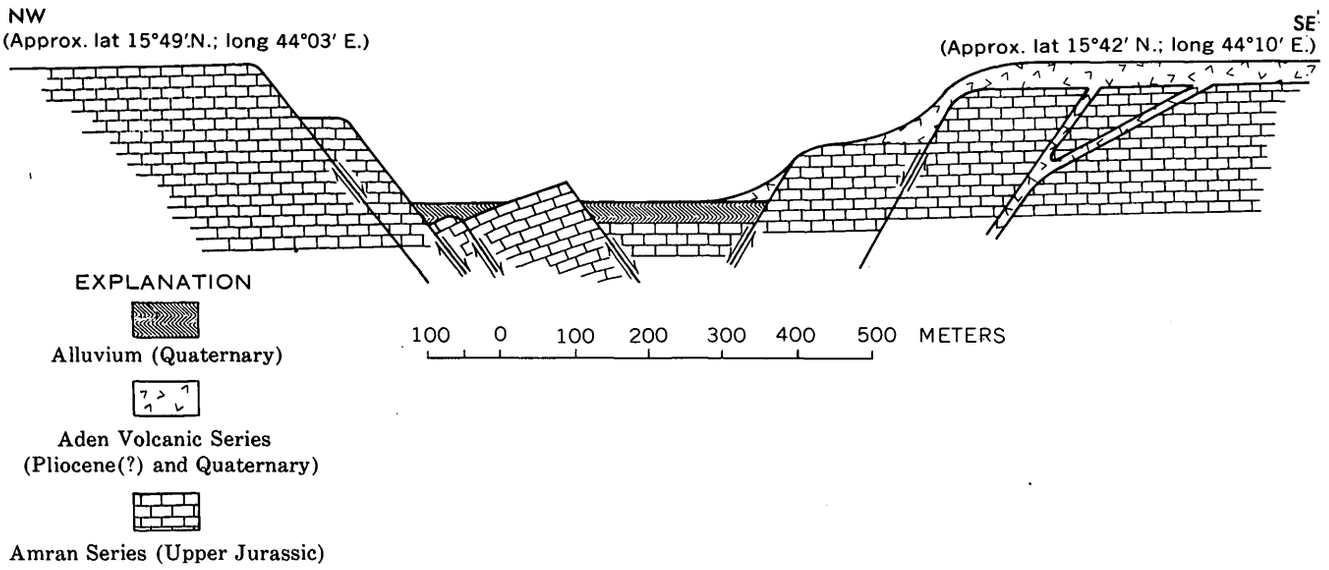

FIGURE 14.—Profile of 'Amrān graben. Surface of alluvium is at elevation of 2,100 m; surface of the Amran Series to the northwest is at 2,450 m.

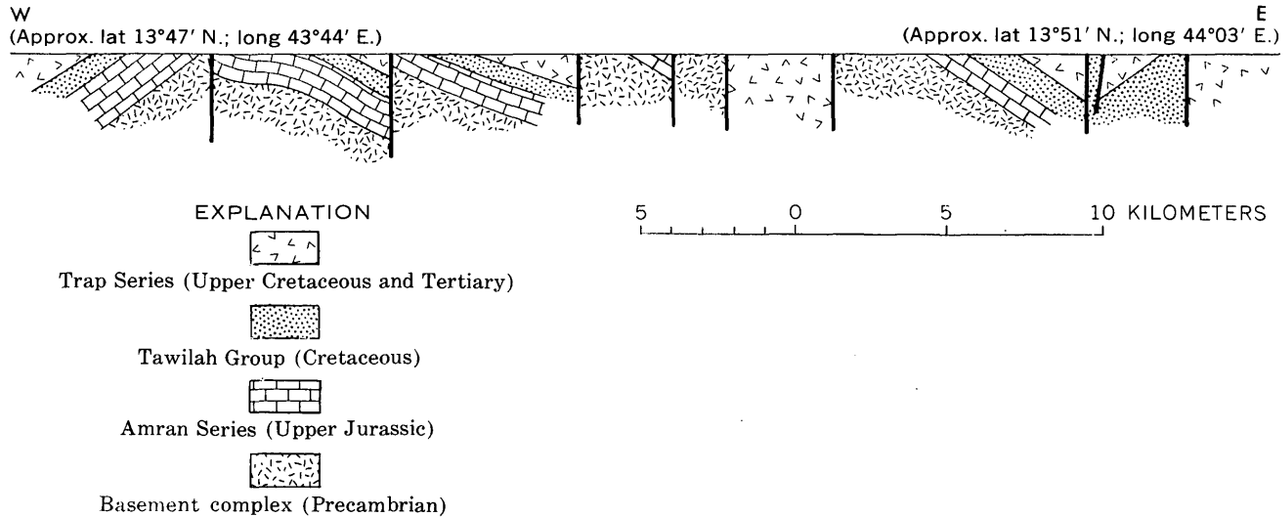

FIGURE 15.—Schematic profile of north of Ta'izz showing horst through Trap Series.

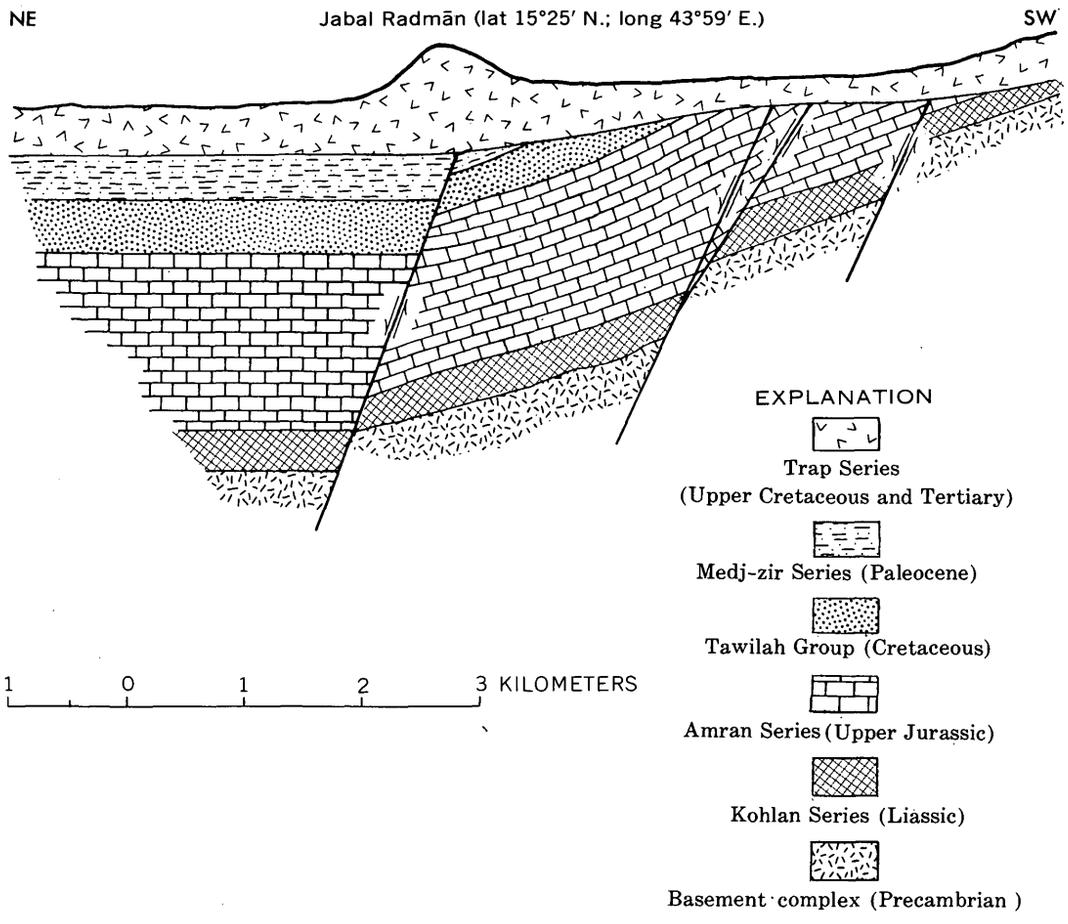

FIGURE 16.—Structure section in vicinity of Jabal Radmān.

along major faults forming a thick breccia zone. Many of the breccias along the faults are restricted and disappear in a short distance as along the Kawkabān fault. The fault traces are indicated by abrupt changes in dip; some subhorizontal beds become vertical near a fault contact (fig. 17). Faults that can be followed for a great distance are generally cut by small right-angle faults of much less throw and later origin than the main fault.

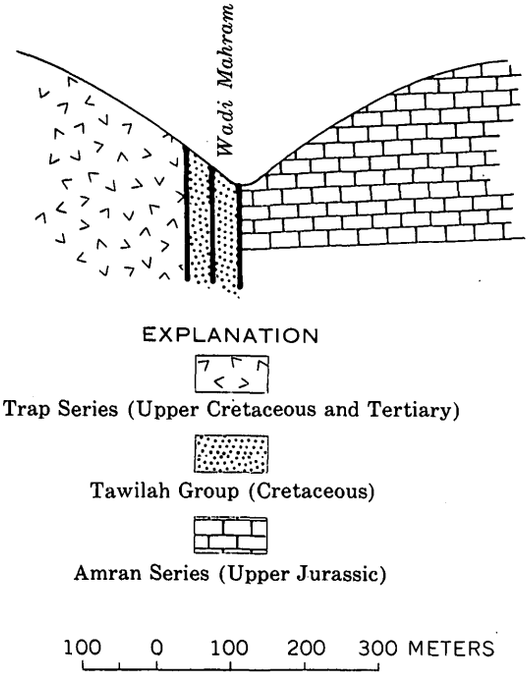

FIGURE 17.—Profile of Wādī Mahram (lat 15°20′ N.; long 43°55′ E.) showing fault contacts of Trap Series, Tawilah Group, and Amran Series.

Southwest of Maḥwad, not far from the recent granites of Jabal Ḥufāsh, sandstones of the Tawilah Group are bounded on two sides by faults. This is the only locality known to date where the sandstones are partially changed to quartzite by dynamic or contact metamorphism.

Thermal springs related to faults (especially along the Red Sea) explain the existence of many small communities called Ḥammām 'Alī. Hot springs are most frequently found in the Trap-covered areas, although some hot vapors are emitted from caves in the limestone plateau north of Ḥūth (near Al Ḥarf).

Mineralization along faults is very rare and is present only in the north of the country where faults affect the basement and the Jurassic limestone. Hematite deposits occur just east of Ṣa'dah and about 30 km northwest of Ṣa'dah near Majd. Ilmenite deposits are found in the Wādī Akwām basin northeast of Ṣa'dah.

Toward the end of the Mesozoic, extrusion of basalt began in conjunction with the formation of the Red Sea. However, it was only from the Oligocene on that the graben took the form of a depressed area without outlet.

Major lava flows in association with fracturing, very active during the Oligocene and Miocene, extended over the southwestern part. In the same epochs the unstable zone of the Red Sea subsided in a series of secondary grabens, now filled mainly by salt and terrigenous deposits carried by rivers which adjusted to the new topography. At nearly the same epochs laccoliths were injected in the northern part of the country.

Deformation along faults during the Pliocene and Pleistocene played the most important role in the morphology. Warping caused the formation of an outlet of the Red Sea to the ocean and accentuated the horst scarp by favoring the development of rivers and increasing headward erosion.

During the calmer and drier period of the Holocene (Recent), corals developed in the Red Sea and rivers continued to fill the east part of At Tihāmah while eolian deposition predominated toward the coast.

GAZETTEER

Published sources listing Yemen place names in the original Arabic are few and incomplete. The forms used in this work were transliterated in the system of the Board on Geographic Names byJ ames P. Mandaville, Jr., Arabian Affairs Division, Arabian American Oil Co. Spellings are based on written sources except those which could not be confirmed and are followed by a question mark.

The coordinates listed below refer to the middle courses of wadis, the highest points of mountain massifs, and the approximate centers of regional features.

Name	*Lat N.*	*Long E.*
Jabal 'Ablah(?)	16°56′	43°48′
Wādī Adhanah	15°12′	45°07′
Wādī al Ahjar	15°28′	43°52′
Wādī Akwām(?)	17°02′	43°48′
'Amāsīyah	16°36′	43°50′
'Amrān	15°40′	43°56′
Bājil	14°58′	43°15′
Jabal Balaq	15°30′	45°19′
Wādī Banā	14°05′	44°32′
Jabal Barat	16°47′	43°52′
Al Bayāḍ	15°13′	44°36′
Jabal Dakhan(?)	15°34′	45°00′
Jabal Dalhān(?)	17°07′	43°42′
Jabal Ḍawrān	14°45′	44°11′
Aḍ Ḍayq	15°14′	44°45′

Name	Lat N.	Long E.
Dhamār	14°31′	44°28′
Al Gharās	15°35′	44°24′
Ḥajjah	15°40′	43°34′
Ḥammām 'Alī	14°42′	44°08′
Al Ḥarf	16°24′	44°11′
Ḥarīb	14°57′	45°30′
Ḥaydān	13°41′	43°45′
Jabal Haylān	15°35′	45°12′
Al Ḥudaydah	14°46′	42°57′
Jabal Ḥufāsh	15°13′	43°28′
Ḥūth	16°18′	43°55′
Ibb	13°58′	44°11′
Al Janadīyah	13°40′	44°10′
Al Jawf / Wādī al Jawf	16°07′	44°30′
Jabal Kanīn	15°05′	44°30′
Kawkabān	15°32′	43°55′
Khamir	16°04′	43°58′
Wādī Khawbah(?)	15°19′	43°54′
Khawbat 'Alī	15°59′	44°01′
Khusrān(?)	16°41′	43°57′
Kuḥlān	15°42′	43°42′
Wādī Lā'ah	15°32′	43°34′
Jabal al Lawdh	16°07′	45°07′
Ma'bar	14°51′	44°15′
Jabal Maflūq(?)	16°38′	44°11′
Wādī Mahram(?)	15°20′	43°55′
Maḥwad(?)	15°29′	43°32′
Majd(?)	17°06′	43°33′
Majzir(?)	15°34′	44°36′
Ma'rib	15°29′	45°28′
Wādī Mawr	15°48′	43°18′
Mujabjib(?)	13°46′	43°44′
Al Mukhā	13°19′	43°14′
Jabal Muṣawwar	15°36′	43°38′
Wādī Najrān	17°29′	44°08′
Wādī Nasīm(?)	15°23′	43°56′
Jabal an Nu'aym(?)	16°55′	43°30′
Radā'	14°30′	44°56′
Jabal Radmān	15°25′	43°59′
Wādī Raghwān(?)	15°48′	45°10′
Jabal Ramid(?)	16°16′	44°07′
Ramlat as Sab'atayn	15°30′	45°50′
Rawḍah	15°27′	44°13′
Jabal Ṣabir	13°31′	44°03′
Ṣa'dah	16°58′	43°45′
Ṣāfir	15°41′	46°09′
Aṣ Ṣafīyah	13°52′	44°03′
Aṣ Ṣafrā'	16°45′	43°51′
Ṣafwān	14°09′	44°35′
Ṣan'ā	15°23′	44°12′
Jabal ash Sharafah	15°29′	44°42′
Ḥaḍūr ash Shaykh	15°36′	43°50′
Jabal Shu'ayb	15°19′	43°57′
As Sinnārah	16°55′	43°48′
Wādī as Sirr	15°33′	44°23′
Ṣirwāḥ	15°27′	45°12′
Wādī Surdūd	15°21′	43°41′
Ta'izz	13°34′	44°02′
Aṭ Ṭawīlah	15°30′	43°42′
At Tihāmah	-------	-------
Jabal Ṭiyāl	15°29′	44°42′
Ath Thillah	15°37′	43°54′
Wādī al 'Urr	15°17′	43°55′
Wadi Wakhd(?)	16°34′	44°03′
Wādī Wa'lān	15°05′	44°19′
Yarīm	14°17′	44°26′
Zabīd	14°10′	43°18′
Zarājah	14°54′	44°19′

SELECTED BIBLIOGRAPHY

Basse, Éliane, 1930, Contribution à l'étude du Jurassique supérieur (faciès corallien) en Ethiopie et en Arabie méridionale: Soc. Géol. France Mém., new ser. 6, pt. 3/4, no. 14, p. 105–148.

Basse, Éliane, Karrenberg, Herbert, Lehman, J. P., Alloiteau, James, and LeFranc, J. P., 1954, Fossiles du jurassique supérieur et des "grès de Nubie" de la région de Sanaa (Yemen): Soc. Géol. France Bull., ser. 6, v. 4, p. 655–687.

Behn, Ernst, 1910, Jemen, Grundzüge de Bodenplastic und ihr Einfluss auf Klima und Lebewelt: Marburg, Germany.

Beneyton, M. A., 1913, Mission d'études au Yémen: La Géographie, v. 28, no. 4, p. 201–219.

——— 1914, Railway surveys in the Yemen (with plate) Geog. Jour., v. 43, no. 1, p. 66–68.

Bent, J. T., 1900, Southern Arabia: London, Smith, Elder & Co., 455 p.

Blanckenhorn, Max, 1907, Die Hedschaz-Bahn auf Grund eigener Reisestudien: Gesell. Erdkunde, Berlin Zeitschr., p. 218–245, 288–320.

Botez, Ghorge, 1912, Rapport définitif sur les études géohydrologiques faites en Yémen (Arabie): Bukarest, Universala.

Botez, Ghorge, and Lange, H. G., 1925, Studii geohidrologice in Vilaetul Yemen (Schita Geologice, 1911): Inst. Geol. al Românici Anuarul, v. 11, p. 348.

Botta, P. E., 1841, Rélation d'un voyage dans l'Yémen: Paris, 148 p.

Brown, G. F., and Jackson, R. O., 1959, Geologic map of the Asir quadrangle, Kingdom of Saudi Arabia: U.S. Geol. Survey Misc. Geol. Inv. Map I–217A.

——— 1960, The Arabian Shield: Internat. Geol. Cong., 21st, Copenhagen 1960, Rept., pt. 9, p. 69–77.

Burchardt, Hermann, 1926, Aus dem Jemen (Festgabe für den Vierten Deutschen Orientalistentag in Hamburg): Leipzig, Deutsche Morgenländische Gesellschaft, in Kommission bei F. A. Brockhaus, 74 p.

Burr, Fréderic, 1841, Lettre sur la géologie d'Aden et sur la côte d'Arabie: Soc. Géol. France Bull., v. 12, p. 419–421.

Bury, G. W., 1911, The land of Uz, by Abdullah Mansur (G. W. Bury): London, McMillan & Co., 354 p.

Comucci, Probo, 1929, Sopra alcune rocce vulcanice della regione di Sanaa (Arabia): Soc. Toscana sci. nat., Mem., no. 40, p. 70–78.

——— 1933, Rocce dello Iemen raccolte dalla missione de S. E. Gasparini: Periodico Mineral., v. 4, no. 1, p. 89–131.

Cox, L. R., 1929, Notes on the post-Miocene Ostreidae and Pectinidae of the Red Sea region: Malacological Soc. London, Proc., v. 18, p. 165–209.

——— 1932, Fossils, *in* Thomas, Bertram, Arabia Felix—Across the empty quarter of Arabia: Toronto, Jonathan Cape, app. 2, p. 364.

Dacqué, Edgar, 1910, Der Jura in der Umgebung des lemurischen Kontinents: Geol. Rundschau, v. 1, p. 148–168.

Deflers, Albert, 1889, Voyage au Yémen: Paris, Paul Klincksieck, 246 p.

Fricke, Karl, 1953, Bergbau auf Alabaster und Gips im Jemen: Glückauf, v. 89, no. 41, p. 1061–1062.
Geukens, F. P. M., 1954, Een dag in Yemen: Onze Alma Mater, Louvain, v. 3, p. 16–20.
——— 1955, Notes géologiques sur un récent voyage au Yémen: Soc. Géol. Belgique Bull., v. 64, no. 2, p. 339–349.
——— 1960, Contribution à la géologie du Yémen: Inst. géol. Louvain, Mém., v. 21, p. 122–179.
Glaser, Eduard, 1913, Reise nach Mârib: Wien, A. Hölder, 214 p.
Gumprecht, T. F., 1849, Die vulcanische Thätigkeit auf dem Festlande von Afrika, in Arabien und auf den Inseln des Rothen Meers: Berlin.
Joleaud, Léonce, 1926, Sur l'origine des cassures africaines: Liège, Livre Jubilaire Soc. géol. Belgique, p. 85–88.
Karrenberg, Herbert, 1956, Junger Magmatismus und Vulkanismus in Südwestarabien (Jemen): Internat. Geol. Cong., 20th, Mexico City 1956, Resumenes, sec. 1, pt. 1, p. 171–185.
Lacroix, Alfred, 1900, Sur les granites et syénites quartzifères à aegyrine, arfvedsonite et aenigmatite de Madagascar: Acad. sci. [Paris] Comptes rendus, v. 130, p. 1208–1211.
Lamare, Pierre, 1923a, Note préliminaire sur la structure de la région du Yémen: Soc. Géol. France, Sommaire des Séances, Comptes rendus, ser. 4, v. 23, mtg. 19, p. 61.
——— 1923b, Observations géologiques sur l'Yémen: Acad. sci. [Paris] Comptes rendus, v. 176, no. 14, p. 956–957.
——— 1923c, Sur l'existence de granites alcalins dans le Schammar (Arabie) et sur la constitution géologique de cette région: Soc. Géol. France, Comptes rendus, ser. 4, v. 23, p. 188–190.
——— 1924a, Les explorations récentes de l'Arabie: La Géographie, v. 41, p. 162–166.
——— 1924b, L'Arabie heureuse; le Yémen: La Géographie, v. 42, no. 1, p. 1–23.
——— 1925, Le volcanisme dans le Yémen: Bull. Volcanol., no. 3/4, p. 109–112.
——— 1930a, Les manifestations volcaniques post-crétacées de la Mer Rouge and des pays limitrophes: Soc. Géol. France Mém., new ser. 6, no. 14, p. 221–223.
——— 1930b, Nature et extension des dépôts secondaires dans l'Arabie, l'Ethiopie et les pays Somalis: Soc. Géol. France Mém., new ser. 6, no. 14, p. 49–65.
——— 1930c, Sur la structure des montagnes environnant Sanaa: Soc. Géol. France Mém., new ser. 6, no. 14, p. 69–93.
——— 1930d, Resultats géographiques d'une mission au Yémen: La Géographie, v. 54, p. 293–323.
——— 1931a, Resultats géographiques d'une mission au Yémen: La Géographie, v. 55, p. 34–64, 200–214.
——— 1931b, La géographie naturelle du Yémen: Assoc. Géographes français Bull., no. 46, p. 4–6.
——— 1933, Travaux géographiques et géologiques récents sur l'Arabie méridionale: Ann. Géog. v. 42, no. 240, p. 623–630.
——— 1936, Structure géologique de l'Arabie: Paris and Liège, C. Beranger, 69 p.
——— 1955, Observations à la note de Mme. E. Basse et de MM H. Karrenberg, J. P. Lehman, J. Alloiteau et J. P. LeFranc, intitulée—Fossiles du jurassique supérieur et des "grès de Nubie" de la région de Sanaa (Yémen): Soc. Géol. France Bull., v. 5, p. 294–295.
Lamare, Pierre, and Carpentier, C. A., 1932, Végétaux fossiles du Yémen: Soc. Géol. France Bull., ser. 5, v. 2, p. 83–92.
Lipparini, Tino, 1954, Contributi alla conoscenza geologica del Yemen: Italia Serv. Geol. Boll., v. 76, pt. 1, p. 93–118.
MacFadyen, W. A., 1930, The undercutting of coral reef limestone on the coast of some islands in the Red Sea: Geog. Jour. v. 70, p. 27–34.
MacFadyen, W. A., Cox, L. R., and Brighton, A. G., 1930, The geology of the Farsan Islands, Gizan and Kamaran Island, Red Sea: Geol. Mag., v. 67, p. 310–315; 1931, v. 68, p. 1–13, 323–333.
Manzoni, Renzo, 1884, Il Yemen, Tre anni nell'Arabia felice: Rome, 446 p.
Philby, H. St. J. B., 1938, The land of Sheba: Geog. Jour., v. 92, no. 1, p. 1–21; no. 2, p. 107–132.
——— 1939, Sheba's daughters: London, Methuen & Co., 485 p.
Pirenne, Jacqueline, 1958, A la découverte de l'Arabie: Paris, Le Livre Contemporain, 327 p.
Pocl, L. Van de, 1960, Pélécypodes et gastropodes fossiles du Yémen (récoltes F. Geukens): Inst. géol. Louvain Mém., v. 21, p. 205–246.
Raisin, C. A., 1909, Notes on the geology of the Perim Island: Geol. Mag., new ser., v. 9, p. 206–210.
Rathjens, Carl, and Wissmann, Hermann von, 1929, Sanaa, Eine südarabische Stadtlandschaft: Gesell. Erdkunde, Berlin Zeitschr., no. 9/10, p. 329–353.
——— 1934, Südarabien-Reise, v. 3; Landeskundliche Ergebnisse: Hamburg, Friederichsen, DeGruyter & Co., 229 p.
Roman, D. R., 1923, Contributions à la lithologie de l'Yémen—1, Roches de profondeur et roches filoniennes non différenciées: Acad. sci. [Paris] Comptes rendus, v. 177, p. 1126–1128.
——— 1924a, Les bostonites et camptonites de l'Yémen: Acad. sci. [Paris] Comptes rendus, v. 179, p. 469–472.
——— 1924b, Sur quelques roches d'épanchement de l'Yémen: Acad. sci. [Paris] Comptes rendus, v. 179, p. 772–775.
——— 1925, Studii petrograficie in Yemen (Regiunea Hodeida-Sanaa): Inst. Geol. al Romăniei Anuarul, v. 10, p. 301–348.
Rossi, Ettore, 1938, Itinerari Yemeniti: Reale Soc. Geog. Italiana Boll., 75, ser. 7, v. 3, p. 280–297.
Scarsella, Franco 1941, Le grandi linee della geologia dell'A.O.I.: Annali Africa Italiana, v. 4, no. 1.
Schmidt, Walther, 1913, Das südwestliche Arabien: Angew. Geographie, ser. 4, no. 8, 136 p.
Scott, Hugh, 1939, A journey to the Yemen: Geog. Jour., v. 93, pt. 2, no. 2, p. 97–125.
——— 1942, In the high Yemen: London, J. Murray, 260 p.
Smith, W. C., 1932, Meteorites, rocks and minerals, *in* Thomas, Bertram, Arabia Felix—Across the empty quarter of Arabia: Toronto, Jonathan Cape, app. 2, p. 365–368.
Sujkowski, Zbigniew, 1931, The influence of the desert on the Red Sea deposits: Soc. Sci. et Lit. Séance, Comptes rendus, Warsaw, v. 25, p. 261–277; republished 1932, Geol. Mag., v. 69, p. 311–314.
Werdecker, Josef, 1939, A contribution to the geography and cartography of north-west Yemen: Soc. royale géog. d'Egypte Bull., v. 20, no. 1, p. 160.
Wissmann, Hermann von, 1941, Der geologische Bau Arabiens, *in* Arabien und seine kolonialen Ausstrahlungen. Lebensraumfragen europäischer Völker 2, Europas koloniale Ergänzungsräume: Leipzig, p. 376–379.
Wissmann, Hermann von, Rathjens, Carl, and Kossmat, Franz, 1942, Beiträge zur Tektonik Arabiens: Geol. Rundschau, v. 33, no. 4–6, p. 221–353.
Wyllie, B. K. N., 1932, Analyses of water, sand and salt: *in* Thomas, Bertram, Arabia Felix—Across the empty quarter of Arabia: Toronto, Jonathan Cape, app. 2, p. 368–369.