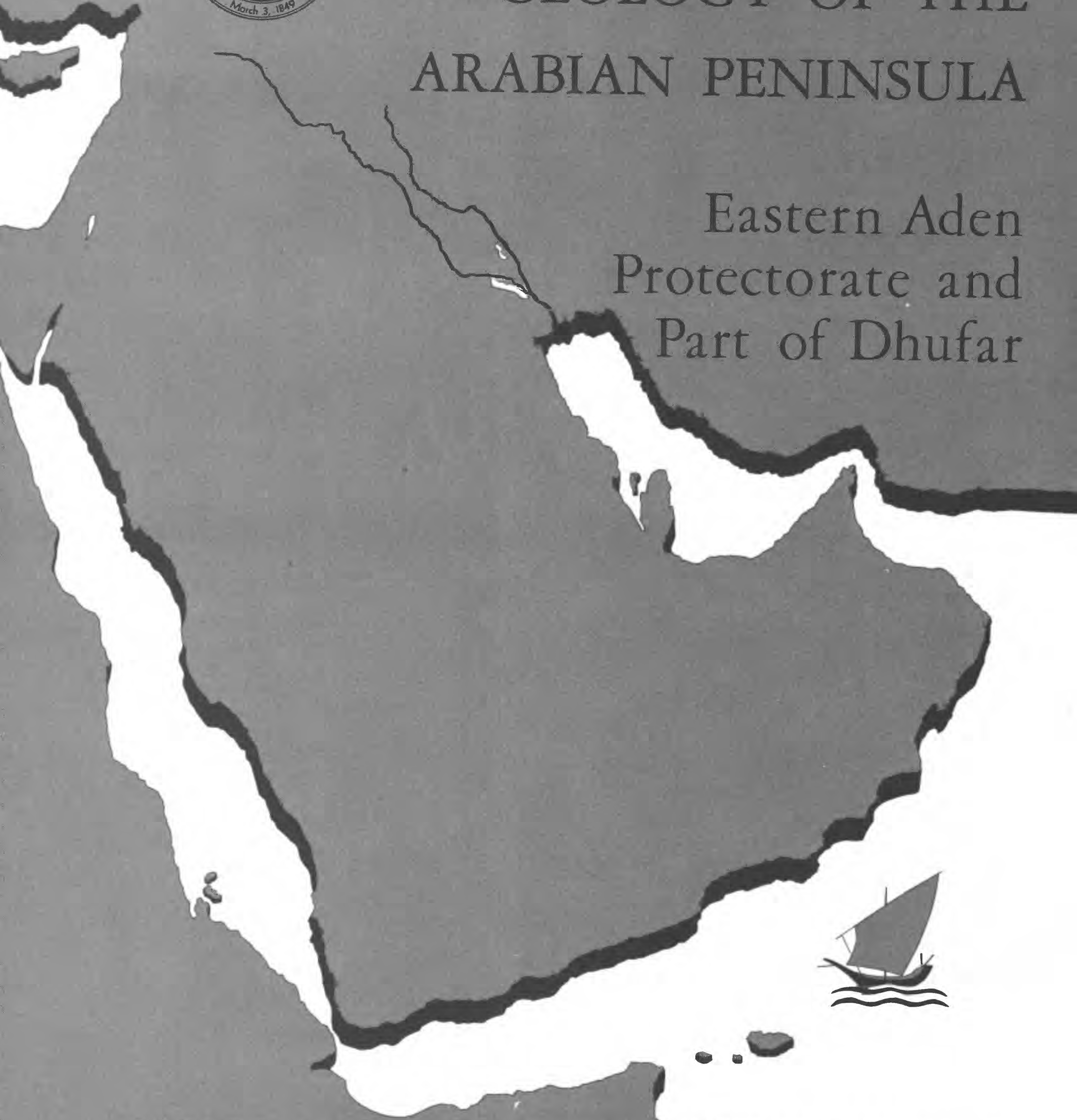
GEOLOGY OF THE ARABIAN PENINSULA

Eastern Aden Protectorate and Part of Dhufar



GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-H

Geology of the Arabian Peninsula

Eastern Aden Protectorate and Part of Dhufar

By Z. R. BEYDOUN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-H

A review of the geology of the Eastern Aden Protectorate and part of Dhufar as shown on USGS Miscellaneous Geologic Investigations Map I-270A, "Geologic Map of the Arabian Peninsula," 1963

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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 Enblish. 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, geologist, 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 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

O. A. SEAGER,
Arabian-American Oil Co. (Retired).

W D Johnston Jr.

W. D. JOHNSTON, JR.,
Former Chief, Foreign Geology Branch,
U.S. Geological Survey.

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

GEOLOGY OF THE ARABIAN PENINSULA

EASTERN ADEN PROTECTORATE AND PART OF DHUFAR

By Z. R. BEYDOUN [1]

ABSTRACT

This account is divided into four parts. The first outlines the position of the Eastern Aden Protectorate and part of Dhufar and (a) includes an account of previous geological work carried out, (b) outlines the fieldwork since 1953 done for the Iraq Petroleum Company, Ltd., and associated companies under the leadership of the author, the results of which form the body of this account, and (c) incorporates earlier results with acknowledgment of the very substantial contribution of colleagues and specialists.

The second part discusses geography of the area and accessibility and operating conditions.

The third part describes and discusses the stratigraphy. Basement, Jurassic, Cretaceous, and Tertiary sedimentary rocks are divided into lithostratigraphic units for which description, faunal lists where applicable, regional correlation of formations with neighboring countries, and economic aspects of various formations are given. Sedimentary and intrusive-extrusive Precambrian and lower Paleozoic(?) (basement) rocks are classified and described, and a probable reconstruction of basement events from field and laboratory observations is given. The basement rocks were in part subjected to low-grade metamorphism, folded, faulted, cleaved, and maturely eroded. Intrusive activity may have extended into the Upper Silurian, as suggested by some isotope age determinations. The oldest rocks overlying the basement peneplain are Middle and Upper Jurassic(?); these consist of basal sands, limestones, marls, and local evaporites. The Cretaceous transgression advanced from the east, and the oldest datable sedimentary rocks are Barremian. Lower to Upper Cretaceous sediments were laid down over the entire area, being predominantly clastics in the west and carbonates in the east, but intertonguing. The Tertiary Period began with a widespread Paleocene transgression during which cliff-forming limestones were deposited over the whole area; these were followed by lower and middle Eocene shales, limestones, and evaporites, and then by regional uplift and geanticlinal folding and faulting. Oligocene and Miocene clastics, reef limestones and local evaporates were then deposited in coastal embayments.

The fourth part discusses structure, including (a) a general introduction, (b) description of structural development of the area in the Tertiary, as those events were responsible for the present broad structure of the territory, (c) an interpretation of the Tertiary structure in the area and across the Gulf of Aden in former British Somaliland, (d) examination of evidence from the Somali side with discussion of earlier views, and (e) a brief outline of structural history of the Eastern Aden Protectorate and Dhufar.

In the interpretation of the Tertiary structure, the development of the biaxial Ḩaḑramawt arch (Hadhramut arch) and a comparable Somali arch are attributed to regional compression which buckled the whole thickness of the crust. Important block and step faulting which followed buckling collapsed the flanks of the arches facing the Gulf of Aden.

INTRODUCTION

LOCATION

The area treated here is the Eastern Aden Protectorate (E.A.P.) which comprises the Provinces of Ḩaḑramawt (Hadhramut [2]) in the west and Al Mahrah (Mahra) in the east. Also partly treated is the Province of Dhufar of the Sultanate of Muscat and Oman adjoining the E.A.P. on the east.

The E.A.P. occupies the eastern part of the strip of territory on the southern and southwestern part of the Arabian Peninsula known as the Aden Protectorate, which stretches from Bāb al Mandab straits at the southern end of the Red Sea, east-northeast along the southern edge of the Arabian Peninsula to the borders of Dhufar. The western part of the Aden Protectorate is known as the Western Aden Protectorate (W.A.P.).

The northern border with Saudi Arabia is largely undemarcated, but the presently operative boundary takes in the southern fringes of the sands of the Rub‘ al Khālī (Empty Quarter), giving the E.A.P. some 90,000 square miles of area.[3] The area of Dhufar is about a third of that of the E.A.P.

The Ḩaḑramawt Province consists of the Qu‘ayţī State of Ash Shiḩr (Qu'ayti State of Shihr) and Al

[1] Of the Iraq Petroleum Company, Ltd.

[2] Different spellings of place names which occur in parentheses are those preferred by the author and differ from spellings on the map. Generally they are given only the first time the word appears in the text.

[3] This includes the Wāḩidī State which, however, joined the South Arabian Federation in 1962 and is no longer an administrative part of the E.A.P. In early 1963 this federation became the Federation of Aden and Southern Arabia. See plates 3 and 4 for E.A.P. operative borders.

Mukallā (Mukalla), which is the largest and richest state and has its capital at Al Mukallā; the Kathīrī State of Say'ūn (Sayun), which is a much smaller state forming a wedge within the Qu'ayṭī State, has no access to the sea, and has its capital at Say'ūn in Wādī Ḩaḑramawt; and, for the purpose of this account, the Wāḩidī State, which occupies the southwest corner of the E.A.P. and has its capital at Mayfa'ah

The Al Mahrah Province occupies the eastern half of the E.A.P. and forms the mainland part of the Mahrī State of Qishn and Socotra. Except for its northern part, the territory is largely administered and nominally ruled by the Sultan resident in Ḩadībū, on Socotra Island. Dhufar is administered by a Walī in Salālah for the Sultan, though of late the latter has been in residence at Salālah.

PREVIOUS INVESTIGATIONS AND PRESENT WORK

Reports by various travelers in the second half of the 19th and the early part of the 20th centuries contributed something to the geological knowledge of the E.A.P. The first geological account for any part of the territory was by Carter (1852), who gave a good description of coastal geology and sections along the whole south Arabian coast as observed from the sea and from selected brief landings. Manuscripts of the 1898–99 Austrian expedition to south Arabia (for example, Kossmat, 1907) include observations on coastal geology at Balḩāf-Bi'r 'Alī, Wādī Mayfa'ah, Al Mukallā, the Mahrah coast, and Ra's Fartak (Fartaq); these manuscripts were used by Wissmann (Wissmann and others, 1942). Thompson and Ball (1918) spent a short time in the Al Mukallā area studying lignite prospects. Little (1925) spent about 6 months in 1919–20 making a geological investigation of the Al Mukallā region as far west as Wādī Ḩajr (Hajar); his report is the first systematic stratigraphic and paleontological account of Ḩaḑramawt. Lees (1928) gave a more recent account of Dhufar geology since Carter (1852), in his paper on Oman and southeast Arabia.

In 1931 and 1939 Hermann von Wissmann and van der Meulen took part in two expeditions in the E.A.P. The first crossed up into the Wādī Ḩaḑramawt basin from Al Mukallā, returning by the Wādī Ḩajr basin. The second was an overland crossing through the W.A.P. to the 'Iyādh ('Ayad) salt dome and across to the Wādī Ḩaḑramawt basin via the western part of the Southern Plateau. From Wādī Ḩaḑramawt the first penetration northward over part of the Northern Plateau was made as far as Tamīs; from there, the expedition turned back to Wādī Ḩaḑramawt and the coast. Traverse mapping along routes followed, and tectonic and some stratigraphic investigation based on Little's stratigraphic conclusions were carried out (Wissman, 1932; Wissman and others, 1942).

In 1937–38 Miss Freya Stark led an expedition including Miss E. A. Gardner, geologist, and Miss G. W. Caton-Thompson, archeologist, which carried out work in the Wādī 'Amd and Wādī Daw'an areas of Ḩaḑramawt and visited other parts; the geological studies were mainly concerned with Pleistocene to Recent deposits (Caton-Thompson, 1938; Caton-Thompson and Gardner, 1939).

Simultaneously with the Stark expedition, R. W. Pike and H. R. Wofford were carrying out the first general geological reconnaissance of the territory for the Iraq Petroleum Company, Ltd. (I.P.C.). This was a combined air and ground expedition of about 6 months duration. Some structural mapping was done in Wādī Ḩaḑramawt, on a part of the Southern Plateau, and in the area between Ash Shiḩr and Al Mukallā; some stratigraphic work, based on Little's stratigraphic divisions, was done in these areas and in the Nā'ifah (Nayfa) area of Wādī Ḩajr.

R. W. Wetzel and D. M. Morton in 1947–48 made the first detailed stratigraphic study in the E.A.P. for I.P.C. Their expedition concentrated mainly on the southern part of the Al Mahrah Province of the E.A.P. from Muṣayni'ah (Musayna'ah) to Damqawt near the Dhufar border, and in the Wādī al Jiz' (Jesa') and Al Masīlah (Wādī al Masīlah) basins. Some work was done in the vicinity of Al Mukallā and in Wādī Ḩaḑramawt and along the two routes between them. The area west of Al Mukallā was not visited, but Dhufar was examined. This expedition stayed some 4 months in E.A.P. and 2 months in Dhufar; it established the basis of currently used E.A.P. stratigraphy, completely revising Little's (1925) Tertiary divisions and adding considerably to the Cretaceous stratigraphy. C. S. Fox spent a few weeks in 1947 on a geological reconnaissance of Dhufar for the Government.

Another expedition by Wetzel and Morton in 1949 visited Ḩaḑramawt, concentrating on the salt-dome areas of Shabwah and 'Iyādh in the western part of Ḩaḑramawt, and on the adjoining Bayḩān area of the W.A.P. Some further work was done in the vicinity of Al Mukallā. The expedition was of some 2 months duration.

Beginning late 1953, various expeditions for the I.P.C. led by the author worked for six consecutive field seasons in the E.A.P., carrying out geological mapping and stratigraphic and structural investigation throughout most of the territory. Similar but more limited fieldwork (unpub.) was done in Dhufar by Dhofar Cities Service geologists after 1953.

During the course of the recent E.A.P. work, reconnaissance topographic mapping was done to supplement the limited reliable maps available (Bunker, 1953; Thesiger, 1947, 1948, 1949; Wissmann, 1959) and to serve as base for the geological map. Reconnaissance geological mapping of the northern part of the E.A.P. was based on traverses tied to astronomical fixes, supplemented by measuring stratigraphic and structural sections and by sampling at various localities. Some detailed geological mapping with plane table and telescopic alidade was also done. However, since much of the E.A.P. is covered by very gently dipping Tertiary sedimentary strata, with older rocks exposed only in deeply cut gorges, in the much faulted southern part, and in the western borders, the work became a stratigraphic investigation and a study of tectonic behavior. Emphasis was on facies and thickness changes in Mesozoic sedimentary rocks, but with considerable work on older and younger rocks. For this the coastal areas were ideal. The southwestern and southeastern parts of the territory were also mapped from aerial photographs, and geological interpretation was done by the author.

A great number of stratigraphic sections were sampled and measured, and a considerable number of field samples were collected both for paleontological study and for field correlation and microfacies comparison; the majority of these samples have been sectioned and have been examined by specialists.

The present work is the result of all the above geological investigations carried out in the E.A.P. between 1953 and 1959 by the author with the collaboration, assistance, and specialist work of colleagues in and outside the I.P.C. Revisions of conclusions in those reports have been made by the author in the light of new field evidence as it became available.

Group, formation, and member divisions of lithostratigraphic units have been described by the author, revising nomenclature by Wetzel and Morton and incorporating new names from the recent work; the results are given in the text and illustrations of this paper.

Geophysical work in the northern part of the E.A.P. by the I.P.C. was done from late 1955 until early 1960. This work consisted of a gravity survey for four field seasons terminating in 1959, an airborne magnetometer survey in 1956, and a short season of seismic survey terminating in April 1960.

Some shallow-hole water-well drilling was also carried out between 1956 and 1959; the deepest well drilled was 602 feet. Information from the eight boreholes drilled did not contribute much more to the stratigraphy than was already known from surface investigations.

GENERAL ACKNOWLEDGMENTS

The author wishes to make the following acknowledgments: To the management of I.P.C. for permission to publish this account and for the original preparation of most of the illustrations in their London office in 1961; to the Director of the Overseas Geological Surveys and the Controller of Her Britannic Majesty's Stationery Office, London, for permission to reproduce some of the text and illustrations under Crown copyright from a previous paper by the author (Beydoun, 1964); to the following colleagues who shared in the fieldwork for varying periods with the author, and but for whose help and cooperation results would have been far less detailed, Messrs. E. K. Elliott (1954–57), F. Gosling (1957–58), E. M. Melville (1953–54), B. G. Light (1957–58), A. P. Humphries (1953–54), the late G. B. Todd (1953–54), and P. E. J. Taylor (1956–57); to Mr. N. H. Stansfield for astronomical fixing and survey assistance (1954–55); to the following former and present I.P.C. colleagues whose earlier work the author has freely drawn upon, Messrs. R. W. Pike and H. R. Wofford (1937–38), Dr. M. Chatton, Dr. A. H. Smout, Mr. A. J. Standring, Prof. R. G. S. Hudson, F.R.S., Mr. F. Gosling, Mr. G. F. Elliott, and especially Messrs. R. W. Wetzel and D. M. Morton (1948–50) for their work in the E.A.P. and Dhufar, since it forms the stratigraphic basis for the territory.

Special acknowledgment goes to Dr. F. R. S. Henson for guiding and coordinating the author's work in the field, for invaluable discussions and opinions concerning results both in the field and the office, and for access to his unpublished material, and to the following specialists, not of the Iraq Petroleum Company, for determinations, opinions, and criticism, Prof. K. C. Dunham, F.R.S., Dr. K. J. Ackerman, Dr. F. J. Fitch, Dr. M. K. Wells, the late Dr. L. F. Spath, the late Dr. W. J. Arkell, F.R.S., Dr. L. R. Cox, F.R.S., Dr. K. Joysey, Dr. W. N. Edwards, Dr. K. S. Sandford, Dr. H. G. Reading, Dr. D. York, and Dr. N. J. Snelling.

To all these, the author very gratefully records his thanks.

GEOGRAPHY

MOUNTAINS, PLATEAUS, AND PLAINS

A discontinuous coastal plain of variable width is bordered by the coastal mountain belt. The plain is composed largely of gravel flats and alluvium interrupted by cliffs of older rock and some tracts of Recent lavas and Pliocene and Recent raised beaches, terraces, and dune areas. The coastal mountain belt is the block-faulted southern flank of the Ḩaḑramawt structural arch, the faults giving rise to a mountainous region of rugged relief. The mountain belt is wide in the west but is narrower and somewhat diminished in height eastward. In the western part where the basement is exposed, the country is rough and broken by a complicated system of faults involving basement, Mesozoic, and Tertiary rocks. Elevations reach nearly 2,000 meters above sea level in places. To the east in Al Mahrah the Tertiary and Cretaceous beds are involved in a marked development of fault scarps, giving the area steep but more regular relief.

Forming the relatively unfaulted northward continuation of the coastal mountains is the Southern Plateau or Jawl; it forms the axial area and flank of the structural South Ḩaḑramawt arch. Its northern boundary is in the Wādī Ḩaḑramawt-Al Masīlah and the Wādī al Jiz' (Wadi Jeza') structural depressions. The structural trend of this plateau is a very gentle tilt northward and eastward. The plateau is a tableland of Paleocene limestone capped by mesas and cuestas of Eocene age, and it is cut by an intricate network of drainage which has excavated deep gorges to expose underlying Cretaceous sedimentary rocks in many places. Its western end is abruptly truncated in an escarpment bordered by the plain of Jaww Kudayf (Khudayf). In the east, the north-south coastline from Ra's Fartak truncates it, and it is bordered by Al Qamar Bay. Al Masīlah cuts across its eastern part obliquely, across the plunge of the axis of the South Ḩaḑramawt arch.

Separated from the Southern Plateau by the Ḩaḑramawt-Al Jiz' synclinal basin is the Northern Plateau or Jawl. It follows the pattern and description of the Southern Plateau, being virtually its northward extension; the Northern Plateau slopes from an axial region southward toward the Wādī Ḩaḑramawt-Al Jiz' syncline and very gently northward to the Rub' al Khālī desert. This plateau is the physiographic representation of the structural North Ḩaḑramawt arch. Like the Southern Plateau, the Northern Plateau is also gently tilted eastward, being highest in the west (calculated 1,200 m), where it also is abruptly truncated by an escarpment line trending northeast, which separates it from the Western Plains; this escarpment is probably fault controlled at depth. Eastward the plateau merges into the Al Qarā' Mountains and Najd of Dhufar. The plateau is also a Paleocene tableland capped by mesas and cuestas of Eocene, but here younger Eocene sedimentary strata are preserved over a much wider area. In the west in deep gorges and along the escarpment line, Cretaceous sedimentary rocks are exposed. Faulting is hardly apparent on the surface. The southern side of the Northern Plateau in Dhufar is formed by the coastal mountain escarpment which is in part faulted.

Bordering the western edges of the Southern and Northern Plateaus are two tracts of plain. The Jaww al Kudayf Plain extends from the western end of the Southern Plateau escarpment westward to the edge of the basement area of the W.A.P. It is an area of light gravel and sand ranging from some 950 to 800 m above sea level and includes within it the hills of the Shabwah and 'Iyādh areas—salt domes and Cretaceous outliers. Drainage from the Southern Plateau and from the Al Kawr ranges of W.A.P. enters this plain and flows northward toward the Ramlat as Sab' atayn sand-dune region which forms its northern boundary. Near the Southern Plateau, extensive gravel and scree terraces can be seen. Faulting, which has affected the Southern Plateau, has been responsible for uplifting the salt domes of the area.

The Western Plains adjoins the western extremity of the Northern Plateau and is bordered respectively on the north and south by the sand dunes of the Rub' al Khālī and Ramlat as Sab' atayn sand deserts; the area is some 900 m (in the west) to 650 m (in the northeast) above sea level and stretches into Yemen and Saudi Arabia. Scattered low hills and mesas of Cretaceous rocks occur, some with a capping of Paleocene limestone; the main belt of these hills stretches from the Al 'Abr area northward to the Ash Sharawrah scarp and breaks up the Western Plains into two flat areas of gravel and sand. In the western part, basement igneous and metamorphic rocks are preserved above the surrounding gravels and blown sand of the plain.

Stretching between the Rub' al Khālī sand desert in the north and the dissected gently dipping north flank of the Northern Plateau is an area of flat gravel plain, in places broken by low eroded ridges and scree hills of Eocene age and by migratory small sand dunes; this area can be termed the "Northern Plains." It is in fact a continuation of the flank of the North Ḩaḑramawt arch. In the west the area begins approximately at long. 49° E. where it is narrow, but it becomes progressively wider eastward until it is about 60–80 kilometers wide near the Dhufar border. The plain continues eastward across the Dhufar to south Oman, to merge into Jiddat al Ḩarāsīs. Drainage from the Northern Plateau of the E.A.P. and Dhufar cuts it in very broad, shallow widyān (dry water courses). Elevations are between 550 m above sea level in the west and about 250 m in the east.

SAND-DUNE AREAS

The Rub' al Khālī sand desert (the Empty Quarter) is a huge area of sands, only the southern fringes of which fall in the E.A.P. and Dhufar. Here the dunes are mainly distributed in parallel to subparallel ridges called locally 'urūq, separated by narrow, flat stretches of gravel, gypsum, or silt, referred to locally as shuqūq. The trend of the southern border of the Rub' al Khālī is east-northeast, which also is roughly the trend of the dune ridges, some of which are as much as 150 m high. Areas of confused dunes, "block" dunes, and dune massifs occur at various localities along the southern fringes, particularly at the mouth of Wādī Makhyah (Wādī Ḫazar, long. 49° E.) where periodic floods and possibly funneling of winds may be responsible.

Slip faces of dunes are generally south (Bunker, 1953), but some northward slip faces have been observed. Crescent dunes as outliers are common (for example, at the mouth of Wādī Khuḏrah). Although some migration of dunes takes place, for the main dune ridges the migration seems to be offset by seasonal changes in wind directions, so that migration in any specific direction is difficult to detect. Brown (1960) mentioned south and southeast to east as the dominant directions of sand movement indicated for the southwest part of the Rub' al Khālī. Bagnold (1951) mentioned that the wind blows from both northerly and southerly quadrants, winds from the easterly and westerly quadrants being infrequent. This would account for counterbalancing of sand migration to some extent, though the effect of thermal disturbances and the inland effect of the southeast (winter) and southwest (summer) monsoons must also be contributing factors. As yet no consistent records have been kept and any conclusions remain speculative, being based on observations made in the field at irregular intervals.

A much smaller sand area than Rub' al Khāli and isolated from it is Ramlat as Sab'atayn sand desert. It stretches eastward from the foothills of Yemen and Bayḫān where it is some 100 km in width, into the Wādī Ḫaḏramawt basin, roughly occupying the western extension of the Wādī Ḫaḏramawt structural trough. The dunes lose both height and lateral extent eastward until they die out as low isolated patches of sand some 5 km in width near Shibān in Wādī Ḫaḏramawt. The Ramlet as Sab'atayn area is again one of dune ridges which, however, are less regular than those of the Rub' al Khālī; they roughly trend east-northeast in the west, are some 50 m in height, and arch and become irregular in the east. Various hill outcrops of Cretaceous and metamorphic rocks rise above the dunes in some parts, and in Yemen and Bayḫān two salt domes occur within the sand area. As in the Rub' al Khālī, the shuqūq often show silt surfaces, remnants of ancient drainage; in some parts pumice bombs have been found on the surface, though no volcanoes are known from anywhere in the vicinity. These have probably been transported by flood water from the vicinity of Ma'rib in Yemen.

Migration of sand is largely offset by seasonal changes in the prevailing winds and by thermal disturbances (see previous discussion).

There are only two other noteworthy sand-dune areas in the E.A.P., the bigger in the Wādī Mayfa'ah basin in the Wāḫidī State and the smaller in the vicinity of Qishn in south Al Mahrah.

DRAINAGE

With two exceptions the drainage system of the E.A.P. consists of dry water courses or widyān, which only flow in times of heavy rains in flash floods. Some are very deeply cut, with sides more than 300 m in elevation above the water course; others are wider with less steep sides; and others are broad and flat. Wādī Ḫajr is perennial from its headwaters to the sea, and parts of Al Masīlah are perennial though not, however, reaching the sea. The coastal widyān of Dhufar are short and a number have water until they enter the salālah plain.

The drainage system can be divided into coastal widyān, the Wādī Ḫaḏramawt-Al Masīlah and Wādī al Jiz' systems, and widyān flowing to the Rub' al Khālī.

Coastal widyān, with some exceptions, flow in a general southeast direction turning more southerly near the coast; most of these widyān are less than 100 km in length. They head in the coastal mountain belt or the Southern Plateau and cut back to the watershed. The majority of the widyān are torrential and have steep gradients; in the main they are not easily traveled by motor transport.

The widyān flowing to the Rub' al Khālī sand desert are on the whole long and shallow and trend in a north-northeast direction, though Wādī 'Atinah in Dhufar runs east-northeast parallel to the edge of the Rub' al Khālī. They head in the vicinity of the axis of the North Ḫaḏramawt arch, which also forms the highest part of the Northern Plateau and of the Al Qarā' Mountains of Dhufar. In the west they cut through Paleocene limestone to Cretaceous sandstone in places, but eastward they expose only Eocene beds. Most of them cut across the Northern Plains, but some lose identity before reaching the Rub' al Khālī.

The Wādī Ḫaḏramawt-Al Masīlah and Wādī al Jiz' systems collect drainage from the greater part of the plateaus. They roughly occupy (except for the lower part of Al Masīlah) the structural synclinal depression between the North and South Ḫaḏramawt arches. Wādī Ḫaḏramawt in its western end is really a wide basin some 50 km in width, forming part of the Western Plains and the Jaww al Kudayf Plain, with the dune area of the Ramlat as Sab'atayn in between. The Wādī narrows rapidly eastward until it is only some 2–3 km wide below Tarīm, its canyon walls being the escarpments of the Northern and Southern Plateaus. The tributaries debouching into Wādī Ḫaḏramawt-Al Masīlah are generally long and very deeply cut gorges that are gentle in gradient, commonly filled with loess or alluvium, and generally accessible. These gorges, like Wādī Ḫaḏramawt-Al Masīlah, have cut through the Paleocene limestone tableland to expose in places the Cretaceous below, and the cliffs forming the sides are about 300 m or more in height, becoming lower eastward. The southern tributaries are longer than the northern ones. The tributaries rise near the axes of the South and North Ḫaḏramawt arches, collect in the Wādī Ḫaḏramawt synclinal area, flow easterly, and, as Al Masīlah, obliquely cut across the eastern plunge of the South Ḫaḏramawt arch to reach the sea in south Al Mahrah.

Widyān flowing northward in the Jawwal Kudayf plain and southward in the Western Plains die out in the Ramlat as Sab'atayn sand desert, but underground their floodwater joins the Ḫaḏramawt-Al Masīlah system.

The gentle syncline of Wādī Ḫaḏramawt continues eastward across low-relief country to take in the Wādī al Jiz' system. This forms the gathering drainage for widyān from the eastern parts of the Northern and and Southern plateaus and flows eastward to the sea in Al Qamar Bay. The Al Jiz' basin is one of more gentle relief than that of Wādī Ḫaḏramawt, and the tributary widyān are less deeply incised.

Wissmann, Rathjens, and Kossmat (1942) and Bunker (1953) have discussed the physiography and morphology of the Wādī Ḫaḏramawt system in some detail.

MORPHOLOGY AND STRUCTURE

The structural sequence of events is briefly outlined here but is dealt with in more detail on page H41. General uplift of the E.A.P. and Dhufar, with resultant upwarping and faulting, occurred in the terminal Eocene. The North and South Ḫaḏramawt arches and the synclinal downwarp of the Ḫaḏramawt-Al Jiz' region were elevated at that time; further movement occurred in the late Miocene and more faulting occurred in the Pliocene. The present-day drainage system was thus initiated with the main terminal Eocene uplift and established in the late Miocene (early Neogene). Wissmann, Rathjens, and Kossmet (1942) believed that uplift in Yemen occurred earlier, the Paleocene shoreline lying somewhere in the W.A.P. and Yemen. Progressive arching in the E.A.P. and Dhufar continued in the Eocene until final emergence, the sea retreating, probably slowly eastward at first and then more rapidly, although oscillations in structural development likely occurred. Structural embayments in the Oligocene and Miocene enabled sea water to encroach a little onto the landmass, but further movement in the late Miocene (early Neogene) with accompanying step and block faulting gave the final touches to an established morphology and drainage system. Oscillations in the Pliocene and later have caused rejuvenations of drainage and further cutting of the widyān that are tributary to Wādī Ḫaḏramawt. Some southward shift of the axis of the North Ḫaḏramawt arch, as previously postulated (Wissmann and others, 1942) for the Ḫaḏramawt syncline, may have occurred and would account for the deep cutting of the heads of the northern tributaries to Wādī Ḫaḏramawt.

Thus, the terminal Eocene and Miocene (early Neogene) structural movements initiated and then established and controlled the morphology and physiography of the region. Pedimentation in the extreme western part due to slow uplift in the Paleocene commenced to lay bare the Western Plains and expose the basement of the Ar Rayyān-Ath Thanīyah-Bayḩān areas. Uplift together with cuesta formation, in the west of the E.A.P. probably started at the end of the middle Eocene.

CLIMATE AND VEGETATION

The E.A.P. is affected by the monsoon winds of the Indian Ocean region, but these, because of regional physical considerations, do not bring regular rainfall to the territory. The Salālah area of Dhufar is, however, blessed with regular summer monsoon rain.

The monsoons blow in two seasons. The winter monsoon from October to April blows from the southeast or east-southeast; winds are moderate and, although rough seas are frequent, there are often periods of calm. Clouds are frequent, but rain is sporadic and often occurs only as localized showers. The end of the winter monsoon may, however, bring heavy rain over a great part of the area, but such heavy rain is the exception rather than the rule. The summer monsoon from June to August blows from the southwest; winds are violent, the seas are very rough, and gusts may reach 100 km an hour. Only sporadic rain falls in the E.A.P. Though the chances of widespread rain are greater during the summer monsoon than during the winter monsoon, 2 or 3 years may pass between worthwhile falls. No reliable records of rainfall are available but along the coast the average annual rainfall is probably 3–4 inches, much of which may fall in one storm. In coastal Dhufar, because of regular rainfall, the coastal slopes are lush with vegetation and streams and pools abound. The streams mainly flow underground on entering the plain.

In the interior of the plateaus, diurnal range in temperature is as much as 50°F. Frost is common in January and February, whereas day temperatures can rise to 90°F or more. In the summer the night temperatures are much higher and the day maximum can reach 130°F. Along the coast the diurnal range is less, winter minimum being around 50°F and maximum being about 85°F. In the summer the maximum is higher, but the humidity is often less when the violent monsoon is blowing. The months of May and September are those between the monsoons and are of very high humidity and heat and little or no breeze.

At various times in the interior, cold dust-laden winds coming from the heart of Arabia blow from the north for a few days at a time in the winter, and similar hot sand-laden winds blow in the summer. The effects of the monsoons are less regular in the extreme north. Dusty conditions are general in the summer and visibility between June and September is generally poor or very poor.

The vegetation of the E.A.P. is on the whole sparse, the plateaus being mainly barren except in wādī beds where a flora of bunch grass, camel thorn, acacia, tamarisk, and ilb grows. In the main widyān and parts of the coast where water is available for irrigation or where floodwaters are used, date palms, millet and other grain, some cotton, vegetables, and tobacco are grown, and thick concentrations of deciduous trees occur in places. Coastal Dhufar being more blessed by regular rain has a much more lush natural vegetation which is, however, basically similar to that of the E.A.P. Dhufar is the ancient home of the frankincense tree.

ACCESSIBILITY AND OPERATING CONDITIONS

Ḩaḑramawt and northern Al Mahrah possess a number of important dirt motor tracks which link the coast to the interior, to W.A.P., and to Aden. South Al Mahrah possesses no motor tracks. In Dhufar tracks link the Salālah area with the north and with Ra's Naws (Ras Nus) in the east.

Al Mukallā is the main port for Ḩaḑramawt and supplies the Quʻayṯī and Kathīrī States. It has limited dock facilities for coastal steamers and sailing dhows, but some large cargo-passenger ships make regular calls there.

Generally, the greater part of the E.A.P. is accessible to Land Rovers or an equivalent type of vehicle. Most widyān can be used over at least parts of their lengths, some with comparative ease, and some with difficulty requiring improvised road building or track clearing. The Northern Plateau is navigable over all its extent in this way, though the extreme west is not easy. The same remarks apply to Dhufar.

West of long. 49°30′ E., the Southern Plateau, is largely accessible to vehicles of the Land Rover type, but much of the way is very winding owing to the dendritic pattern of deeply cut widyān. Eastward the area is largely inaccessible.

The E.A.P. is linked to Aden by regular air services calling at Al Mukallā and points in Wādī Ḩaḑramawt and Mayfa'ah. Dhufar has no regular air services, but a landing ground and station at Salālah handle oil-company aircraft and an occasional commercial flight.

Wireless stations at Al Mukallā and Say'ūn link the E.A.P. via Aden with any part of the world.

STRATIGRAPHY

GENERAL

TIME UNITS REPRESENTED

Time units represented in the E.A.P. (and Dhufar) include rocks of Precambrian age and some sedimentary rocks of probable early Paleozoic age; intrusive rocks of early Paleozoic age are found in several localities. A long time gap exists between these early rocks which are grouped together under the term "basement," and the next time units present; these are Mesozoic sedimentary rocks of the Jurassic Period overlain by strata of the Cretaceous Period. The Cenozoic Era is represented by widespread Paleocene and Eocene sedimentary rocks.

GENERAL DISTRIBUTION OF SYSTEMS AND DOMINANT ROCK TYPES

The basement rocks crop out in the southwest part of the area from Al Mukallā westward into W.A.P. and in the Jabalath Thanīyah area of the Western Plains. These rocks range from metamorphic gneisses and schists and rocks affected by granite invasion in the western part to less highly metamorphosed and unmetamorphosed sedimentary rocks in the eastern part; in this eastern area are large expanses of extrusive rocks. Intrusive bodies ranging from intermediate to silicic occur in various parts of the basement area. Farther east in Al Mahrah, a limited exposure of the Precambrian and Paleozoic igneous rocks and some Precambrian(?) and early Paleozoic(?) metasedimentary rocks occur at Raʻs Sharwayn. No further exposures are seen till the coastal part of Dhufar is reached. There, in limited outcrops near Al Ḩawṭah (El Hota)—[west of Raʻs Sājir (Sajar) and ʻAyn Sārit]—are a series of graywackes, sandstones, shales, and mudstones of probable early Paleozoic age. A little to the east, from Mirbāṭ (Murbat) to Ra's Naws and in the Kuria Muria Islands offshore, and older basement of Precambrian gneisses, schists, intrusives, and dikes and sills is partly overlain by a clastic succession of probable Ordovician age which wedges out eastward.

All these rocks, with the exception of the probable Ordovician clastics of the Mirbāt area, were maturely eroded and peneplaned so that the Mesozoic sediments transgressed onto this mature surface quite extensively. The lowest Jurassic sediments were clastics of Early and Middle Jurassic(?) age; this phase was soon replaced by deposition of neritic carbonate of Late Jurassic age which locally gave place to evaporites before the Jurassic Period ended with widespread deposition of carbonate, followed by block faulting, uplift, and erosion. The Jurassic rocks are exposed in the southwestern part of the area and extend into W.A.P.; they are brought up as salt domes in the western part of the E.A.P. and parts of Bayḫān (W.A.P.) and eastern Yemen. Jurassic rocks are absent from a broad north-trending belt running through Al Mukallā, as well as from Dhufar (with the exception of some clastics), they were probably removed from some of the Al Mukallā belt by erosion prior to the Cretaceous and in other areas probably never were deposited, as would seem to be true in most of Dhufar. Elsewhere, Jurassic rock exposures are limited by the thick Cretaceous and Tertiary cover in coastal Al Mahrah.

Cretaceous sedimentary rocks are exposed over most of the territory and in coastal Dhufar, and can be seen wherever faulting or erosion of the Tertiary blanket has been sufficiently strong. They are primarily clastic in Ḩaḑramawt and into W.A.P., primarily carbonate in Al Mahrah to the east, and occupy an in-between position in western Al Mahrah Eastern Ḩaḑramawt, as also appears to be true in Dhufar. The age range is from Barremian to Maestrichtian.

The Tertiary sedimentary strata blanket most of south Arabia and range in age from Paleocene to middle Eocene; Oligocene and Miocene strata are more restricted in occurrence. In the E.A.P. the Paleocene is entirely a carbonate succession, but the lower Eocene shows intercalations, first of shales and then of evaporites, over a wide area; the middle Eocene shows a return to carbonate deposition with shale intercalations before regional uplift took place in the upper Eocene. In the eastern part of the E.A.P. and in Dhufar, carbonate deposition extends well into the lower Eocene, to be followed by evaporites and then more carbonates and fewer shales in the middle Eocene. Oligocene and Miocene deposits occupy restricted areas in present coastal regions, having been deposited in embayments in the coast. They are heterogeneous deposits in Ḩaḑramawt, ranging from coarse clastics to carbonates and evaporates, and in Dhufar they are thick chalky limestone and chalks succeeded by Miocene clastics and reef deposits.

Beach deposits, river terraces, and lacustrine and eolian deposits mark the termination of the Tertiary throughout the area and the start of volcanicity in coastal E.A.P. that persisted locally to Recent times.

The broad geomorphic expression of the territory has already been discussed in the preceding geographical sections and the influence of structure on morphology has been mentioned.

MAJOR UNCONFORMITIES

Several major time gaps are present; some are of striking clarity in the field and some are determinable by faunal examination only. These are dealt with in detail in the stratigraphic descriptions but are briefly summarized here.

Within the basement groups, several unconformities are probably represented. A major unconformity exists between the basement rocks and the Jurassic sedimentary rocks, and probably represents more than one erosion phase spanning a time gap from early Paleozoic to Early Jurassic. The next major time gap is between Late Jurassic and Cretaceous; the terminal Jurassic was generally followed by block faulting and differential erosion and planation, with the result that in places some of, or all, the Jurassic is removed. It is most probable also that the basal Cretaceous (Neocomian) is absent throughout the area, though some of the unfossiliferous pre-Barremian clastics may be partly Neocomian. Within the Cretaceous an unconformity probably exists between the Cenomanian and Senonian, and it is likely that there is no Turonian in the region, though this is difficult to establish on a faunal basis.

Another unconformity without angularity occurs between the Upper Cretaceous and the Paleocene, but this is not a major time gap, as only part of the Maestrichtian was removed. The next major time gap is at the end of the middle Eocene when general uplift took place over most of the area. The more restricted Oligocene and Miocene deposits may rest on any of the older rocks exposed.

HISTORY OF SEDIMENTATION

Little is known of the sedimentation history of the Precambrian and early Paleozoic rocks, but the early intrusive and metamorphic phase was followed by a period of intense eruptive activity at the close of which a succession of clastic and carbonate rocks was deposited over much of the area. Intrusive activity probably accompanied and followed the eruptive phase, continuing into a period of powerful orogenic movements which folded the sedimentary rocks, and resulted in mineral reconstitution in most, and cleaved all rocks. Dike injection and granitic emplacement continued for some time as mature erosion and peneplanation of the basement was taking place. The history of the periods from this time to the Jurassic is not known.

The Jurassic transgression appears to have come from the south and the basal clastics filled irregularities in the basement floor. During neritic carbonate deposition, the zone of maximum subsidence centered on Yemen, trending south to the Berbera area of Somalia. With the development of evaporites in restricted basins and simultaneous open-sea deposits, the zone of maximum subsidence shifted eastward to the E.A.P. During the Tithonian, Yemen slowly emerged while widespread carbonate deposits covered the E.A.P. Shallowing and emergence followed, accompanied by block faulting which divided much of the southern part of Arabia into major north-trending highs and lows that were differentially eroded. The land surface was then gently tilted eastward.

The Cretaceous transgression came from the east, spreading the seas over a planed or eroded Jurassic floor, and where this had been removed, onto the basement. The area of greater subsidence was in east Al Mahrah, and continental deposits were laid in the west in Yemen. Regressions and transgressions and pinchouts within the Cretaceous were interrupted by local uplifts in the Al Mukallā area, Ra's Sharwayn, and other areas, and the Cretaceous ended with shallowing and some emergence to be followed by the strongly transgressive Paleocene. Again the transgression was from the east, and after some regression and local deposition of evaporites, general uplift led to the start of the present structural development of south Arabia. Tertiary sedimentation from the later Paleocene began to be influenced by this structural growth, the result being the formation of the biaxial Ḩaḑramawt area.

Plates 1, 2, 3, and 4 give a general picture of the broad sedimentation patterns, as reflected in isopachs, from the Jurassic to the Eocene uplift.

NOMENCLATURE

Nearly all the geological knowledge of the area has been acquired in the last four decades mostly in the period since 1947 (see p. H2–H3). Much of this very recent period has been one of revision and experimentation with nomenclature and correlation based on lithostratigraphic division of rock units. Revision of early work and an establishment of a system of nomenclature was achieved in 1948 as a result of R. W. Wetzel's and D. M. Morton's fieldwork, but subsequent fieldwork in new areas of the E.A.P. led to further revisions of nomenclature and correlation by the author, and the introduction of new names.

The nomenclature described in this account has been designed to incorporate and use published names from neighboring areas where these apply to the Aden Protectorate without much change, and to define new nomenclature for the area where correlation with neighboring countries is not straightforward. Thus, the lithostratigraphic units used here are intended to be of regional rather than local value, despite the fact that defined units from neighboring areas have not generally been carried through into the E.A.P. The new terms are used where facies changes are so great, and intervening unknown areas so wide, that the carrying of such units would not be justified. When more regional information becomes available, other revisions may be made.

PRECAMBRIAN AND PALEOZOIC ERAS

BASEMENT

The term "basement" is applied here to the exposed igneous, metamorphic, and sedimentary rocks that were folded, or in part metamorphosed, cleaved, jointed, faulted, and then peneplaned before the first (Jurassic) marine sediments were deposited in the territory. The majority of basement outcrops are concentrated in the southwest. These rocks range from Precambrian to Paleozoic, but determination of a precise age is impossible.

Relatively little work has been done in the field on the basement rocks as compared with work on Mesozoic rocks; the present account embodies the field observations and incorporates preliminary field and laboratory observations by Prof. K. C. Dunham. Description is restricted to the area east of long 48° E., with two exceptions, the Jabal Sawād Bā Quṯmī area immediately to the west of long 48° E. at about lat 14°28′ N. and the Jabal ath Thanīyah area on the Yemen border at about lat 15°50′ N., long 46°20′ E.

Four principal types of basement rocks are exposed in this area of the E.A.P.:

1. A series of volcanic rocks: lava flows and associated tuffs.
2. A series of metamorphic rocks, primarily metasedimentary but including some metaigneous.
3. A series of virtually unmetamorphosed sedimentary rocks, which are considered to be equivalent to type 2.
4. Intrusive igneous bodies, major and minor, silicic to mafic.

All these rocks have been involved in tectonic movements and varied deformation prior to peneplanation.

The metamorphic rocks and unmetamorphosed sedimentary rocks of types 2 and 3 have been divided into groups and these into formations where possible.

GHABAR GROUP

The Ghabar Group has been divided into four formations, all consisting of unmetamorphosed or virtually

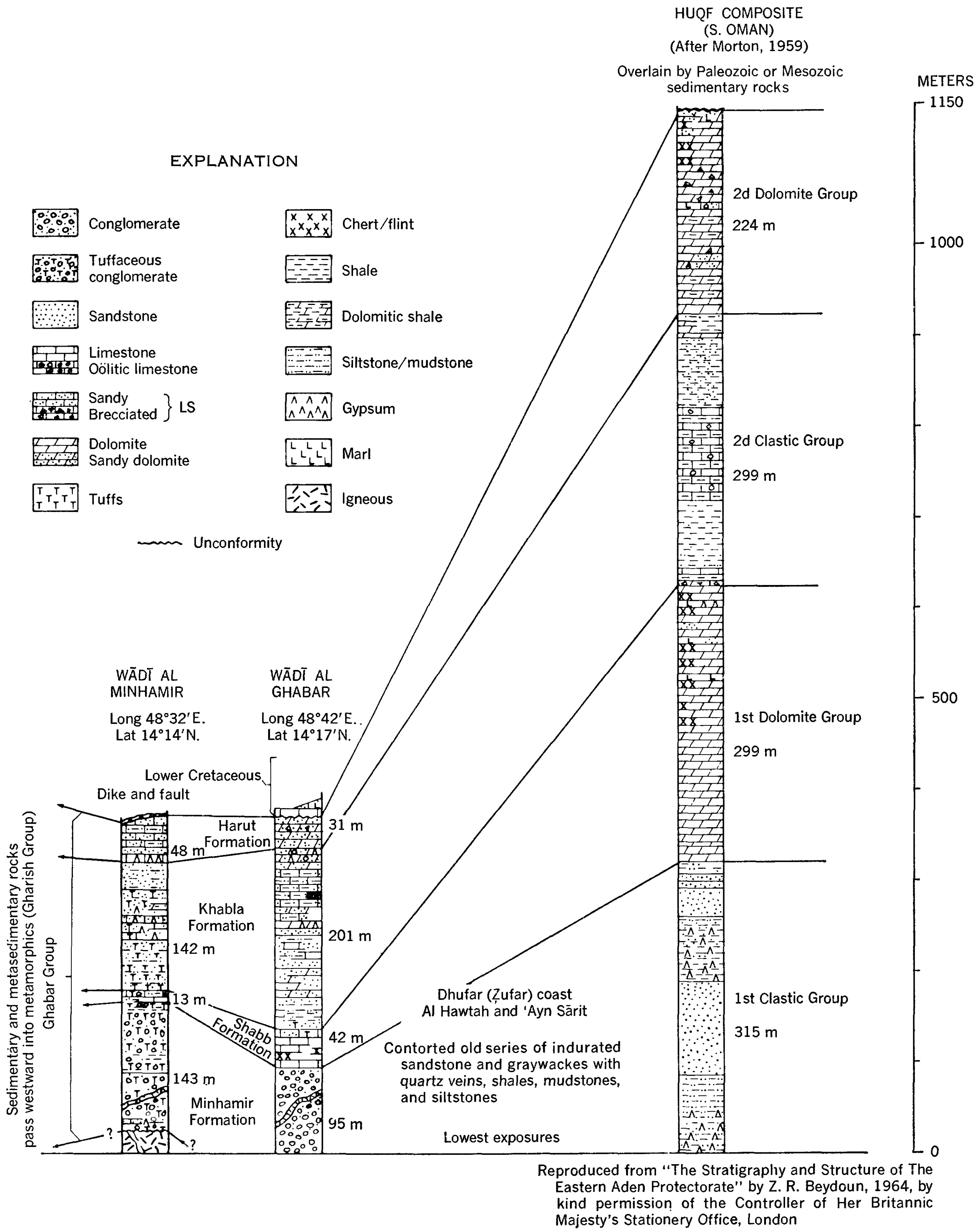


Figure 1.—Tentative correlation of Lower Cambrian(?) sedimentary rocks, from south Oman ('Umān) to southwest Ḩaḑramawt (E.A.P.).

unmetamorphosed sedimentary strata. It crops out in two small areas in the eastern part of southwest Ḩaḑramawt, namely in the Wādī al Ghabar type area (lat 14°17′ N.; long 48°42′ E.), and in Wādī Minhamir (lat 14°14′ N., long 48°32′ E.) (Wādī Ḩajr basin). Figure 1 shows the formations of the two areas and correlation between them. A third subordinate area where the beds have been involved in small-scale thrusting (probably the cause of low-grade metamorphism to the greenschist facies) is in Wādī Bā 'Aryaţ (lat 14°09′ N., long 48°48′ E.).

The formations of the Ghabar Group from base to top are as follows.

MINHAMIR FORMATION

At Wādī Minhamir the Minhamir Formation is 143 m thick; it consists of water-deposited lithic and crystal tuffs and some tuffaceous mudstone with pebbles of varying types of lavas, chiefly intermediate, but also with sparse metamorphic and cherty pebbles. Some dikes intrude. The Minhamir was probably formed from material eroded from a lava pile and deposited near at hand. There is no evidence that explosive activity was contemporaneous with deposition (K. C. Dunham, unpub. data, 1953–59). The formation rests on intermediate lavas, which form part of the Tha'lab Group; the contact appears to be disconformable.

In Wādī al Ghabar the formation is 95 m thick, and the base is not exposed. It consists of dull red tuffaceous limy conglomeratic sandstones with pebbles of crystal and lithic tuffs, silicified and calcareous tuffs, andesite, pyroxenite, diorite, porphyry, keratophyre, dolomite, chert, marmorized limestone, siltstone, and mudstone; granite and quartzite pebbles are sparse. Bedding and sorting of pebbles is evident and the formation is intruded by silicic and mafic dikes.

SHABB FORMATION

The Shabb Formation overlies the Minhamir Formation conformably and consists of platy, and thin-bedded, gray and pink limestones that are sandy in part and contain some chert bands along the bedding. In the Wādī al Ghabar section the formation is 42 m thick; at Wādī Minhamir the thickness is 13 m, and the limestone there encloses some gypsum. The formation is composed of chemical precipitates which represent the onset of an evaporation cycle.

KHABLA FORMATION

The Khabla Formation overlies the Shabb Formation conformably and gradationally, and the sequence at Wādī al Ghabar consists of 210 m of colored and gray dolomites and calcareous sandstones, siltstones, calcareous and dolomitic siltstones, some interbedded dolomites, and some gypsum. In Wādī Minhamir the sequence is mainly tuffaceous or arkosic sandstone that is better sorted and poorer in lava fragments than the Minhamir Formation (K. C. Dunham, unpub. data, 1953–59), and it is 142 m thick.

HARUT FORMATION

The Harut Formation overlies the Khabla Formation conformably and gradationally, and consists at Wādī al Ghabar of well-bedded sandy dolomites, massive calcareous quartzites, and platy shaly beds with beds of impure dolomite and fairly pure limestone; a thickness of 31 m is preserved. At Wādī Minhamir the preserved formation is 48 m thick where it consists of gypsiferous, silty, and sandy limestones. The presence of gypsum and the rounding of sand grains indicates an arid environment and the onset of a second evaporation cycle.

The Ghabar Group in these two areas shows no metamorphism except near dikes; tectonic movements, apart from producing strong folding, have resulted in no apparent mineral reconstitution, but have imposed an intense multidirectional cleavage system on all the beds.

GHARISH GROUP

The Gharish Group is a series of sedimentary works and some lavas that have undergone regional metamorphism to the albite-epidote-amphibolite facies, reaching grades with garnet and staurolite as index minerals (K. C. Dunham, unpub. data, 1953–59); it occurs in the Wādī Garīsh-Jabal Madbī area of southwest Ḩaḑramawt (near lat 14°10′ to 20′ N., long 48°4′ to 12′ E.).

Several hundred meters is exposed, but the total thickness has not been measured and is probably considerable. The group, prior to metamorphism, consisted of tuffaceous conglomeratic beds, tuffaceous sands and shales, thin-bedded limestones, and arenaceous beds. A period of tectonic movements took place after deposition and led to strong folding (as for the Ghabar Group) and also to mineral reconstitutions of the sedimentary rocks of this group. Patchy amphibolites developed from pyroclastics, whereas (a) quartz, biotite, and muscovite schists, (b) hornblende, epidote, and chlorite schists, (c) variable phyllites, and (d) some quartzites developed from clastics with admixture of tuff. Interbedded phlogopite marbles represent persistent thin-bedded limestones. Squeezed volcanic pebbles in amphibolite indicate a tuffaceous conglomerate prior to metamorphism.

The presence of conglomeratic pebbles in this group and the persistence of thin-bedded well-defined calcareous beds, as well as the occurrence of quartzites, suggest that the Gharish Group is the same as the unmetamorphosed Ghabar Group cropping out some 40 km to

223-233—66——3

the east (p. H9–H11). Metamorphism increases westward from the latter owing to regional tectonic factors; greater alteration is favored also by the presence of more pyroclastic components, the purer calcareous units being comparatively less altered. Unfortunately the stages of lithological transition from the Al Ghabar-Minhamir sector westward cannot be followed in the field because they are masked by an intervening area of younger strata and are in part removed at the sub-Jurassic unconformity; however, the impression gained in the field is that one series is exposed in the two areas. Thus, in the Wādī Gharīsh area a correlation of the amphibolite with squeezed pebbles with the Minhamir Formation of the Ghabar Group is suggested, while the well-defined calcareous beds and calcareous beds with quartzite of the Wādī Gharīsh area can be correlated with the Shabb and Harut Formations of the Ghabar Group.

The Gharish Group has been invaded in several stages by major and minor igneous masses and by various dikes and sills. These have also contributed to alteration by contact-thermal metamorphism, which locally may have continued after dynamothermal metamorphism ceased, as indicated by the growth of porphyroblasts through the foliation.

THANIYA GROUP

The Thaniya Group is exposed in the extreme west of Ḩaḑramawt along the Yemen border in a number of disconnected outcrops (Jabal ath Thanīyah area, near lat 15°50′ N., long 46°20′ E.). The thickness is probably considerable; the upper part consists of some volcanics associated with dark quartzites, graphitic calcschists, and thin-bedded phlogopite marbles of various types (Beydoun, 1960; unpub. data from the following: K. J. Ackerman, 1955, 1959; Fitch, 1955; Wells, 1955–56; and K. C. Dunham, 1953–59); these overlie thick-bedded calcareous rocks with chert bands. During a visit to Jabal ath Thanīyah, Geukens (1960) observed schists and quartzites which he mapped as Medina Series, overlain near the summit by younger crystalline limestone which he mapped as Jurassic (Geukens, 1960, pl. 8). No Jurassic has been found by the author, but Geukens' upper part may represent the equivalent of the Gharish and Ghabar Groups.

The Thaniya Group has undergone regional metamorphism to the albite-epodite-hornblende facies and has been invaded by dikes. Before metamorphism the rocks probably were various sandstones, siltstones, shales, limestones and dolomitic limestones, and associated lavas (unpub. data from the following: Ackerman, 1955, 1959; Fitch, 1955; and Wells, 1955–56).

The Thaniya and Gharish Groups are of about the same facies of metamorphism. While it is possible that the two groups are lateral variants, it is believed that the former represents an older Precambrian sedimentation and that before metamorphism the Thaniya Group was probably the source of limestone, chert, and other pebbles preserved in the basal Minhamir Formation of the Ghabar Group to the southeast.

INTRUSIVES AND EXTRUSIVES

The basement intrusive and extrusive rocks of the Eastern Protectorate crop out mainly in southwest Ḩaḑramawt, though scattered exposures occur in the Jabal ath Thanīyah area and a relatively small exposure occurs at Ra's Sharwayn in coastal Al Mahrah (lat 15°20′ N., long 51°37′ E.).

Many of these exposures consist of extrusive rocks (The Tha'lab Group) which have been considered to be the oldest exposed rocks in this area of southwest Ḩaḑramawt (K. C. Dunham, unpub. data 1953–59; Beydoun, 1960). Intrusive rocks, both major and minor, generally postdate the extrusives though some are considered as possibly contemporaneous, and a few, of which only pebbles are now seen, probably predate the volcanic episode. The occurrence of these igneous bodies has been provisionally classified as follows.

The presence of sparse granitic pebbles in the basal Minhamir Formation of the Ghabar Group (p. H11) indicates that granite was undergoing erosion somewhere in the territory at the start of sedimentation of the Ghabar and Gharish Groups. This granite may be from an earlier intrusive which is no longer exposed, and is possibly contemporaneous with, though it more likely predates the older volcanics of the Tha'lab Group.

THA'LAB GROUP

Rocks of the Tha'lab Group were extruded during a widespread phase of volcanic activity, and consist of a thick series ranging from olivene basalt, through microporphyritic pyroxene andesites and hornblende andesites to keratophyres and soda rhyolites; trachytes are scarce. Associated with the above are great quantities of pyroclastics ranging from fine-grained ashes to coarse and very coarse tuffs which include lithic, vitric, and crystal tuffs (K. C. Dunham, unpub. data, 1953–59). They constitute the remains of a very substantial volcanic episode; the vents through which these rocks were extruded have not been discovered. It appears that the volcanic suite of this group is predominantly of intermediate composition, namely andesites to keratophyres.

The extrusion of the Tha'lab Group mainly predated the deposition of the Gharish and Ghabar Groups, though some volcanic activity continued locally during the deposition of these two groups.

It is not known if the Tha'lab Group extrusion phase was contemporaneous with, or later than, deposition of the Thaniya Group; volcanics in the upper part of the Thaniya (p. H12) may belong to the same episode of volcanicity. It is suggested that the start of deposition of the Thaniya Group (and equivalent metamorphic rocks to the west in W.A.P.) preceded extrusion of the Tha'lab Group, but that sedimentation may have continued simultaneously with the extrusion of the Tha'lab Group.

During extrusion of the Tha'lab Group, intrusive activity probably also took place, but it is not known at present whether this consisted of major emplacement or was primarily restricted to dike injection.

Following the volcanic episode, and contemporaneous with the deposition of the Ghabar and Gharish Groups, intrusive activity continued. This apparently consisted of some major silicic emplacements into country rocks (Tha'lab Group) or granitization of the country rocks and the injection of dikes into the Ghabar Group; the dikes are restricted to the Minhamir Formation of the Ghabar Group in the Wādī al Ghabar sector. In the Kahtalih section (lat 14°18′ N., long 48°40′ E.) of the Wādī al Ghabar area, a silicic intrusion into the Tha'lab Group has resulted in a granite with partly digested fragments of Tha'lab volcanics. It is believed that from this body dikes were injected into nearby rocks of the Minhamir Formation.

A similar granite can be seen in the western edge of Jabal Jahmūm near Al Ma'ābir (lat 14°12′ N., long 48°35′ E.). Here also the emplacement is into rocks of the Tha'lab Group; aplite veins and dikes from the intrusion crisscross the country rock and the contact between the main intrusion and the country rock, and have resulted in the formation of hornfels.

Jabal Jahmūm also consists of a varied suite of intrusives including grandiorite and quartz and pyroxene diorites (Dunham, unpub. data, 1953–59). The igneous rock has a foliated "layered" appearance, and intrudes not only into the Tha'lab Group, but probably also into the Ghabar Group, a remnant of which is preserved to the southeast of the intrusion and which has been somewhat metamorphosed by the intrusion. The intrusion probably occurred in several stages, the last of which may postdate Ghabar Group sedimentation.

Jabal Sawād Bā Quṭmī (near lat 14°27′ N., long 48°45′ E.) is a major granite emplacement. This granite intruded Gharish beds preserved at its eastern end, and isolated remnants (which may include some older metamorphic rocks) occur along its southern and northern edges. The intrusion has a foliated appearance and the Gharish beds (and older metamorphic rocks(?)) dip outward from it. The granite has undergone different degrees of cleavage, suggesting that the intrusion occurred in stages, the last postdating the phase of tectonic deformation. Both the Gharish beds and the intrusion are riddled with mafic dikes and sills, the latter following foliations (layering) in the granite and bedding in the Gharish Group. They probably belong to a later stage of igneous activity.

In the Wādī Gharīsh area, pyroxenites and pegmatites(?) as well as silicic and mafic dikes were probably intruded during this stage.

In the Al Mukallā district granite has been intruded into the Tha'lab Group, and aplite dikes finger out from the main body.

The intrusions and dike injections have imposed contact thermal metamorphism on the country rocks, but the extent of this is no longer clear because of subsequent regional metamorphism. It is reasonably certain, however, that intrusive activity during this phase occurred locally in several stages, some postdating sedimentation of the Gharish and Ghabar Groups, but predating the kinematic phase.

Major earth movements took place some time after the sedimentation of the Gharish and Ghabar Groups and associated igneous activity. During and at the close of this period, intrusive activity probably occurred, and some of the intrusions discussed previously, including the pegmatites, may have been emplaced at the time. The movements strongly and isoclinally folded the sedimentary rocks (and possibly folded some of the volcanic rocks) and imposed an intense multidirectional cleavage system on all rocks—sedimentary, extrusive, and intrusive. This process was accompanied (possibly in stages) by mineral reconstitution of some of the sedimentary rocks. Why some rocks underwent more reconstitution and deformation than others is not understood, but this may be attributed in part to regional tectonic factors which produced a higher grade of metamorphism from east to west, and to the presence of more pyroclastic components in sedimentary rocks to the west, enabling higher alteration to take place in that direction.

In at least part of the region rocks of the Tha'lab Group show little evidence of regional metamorphism other than cleavage and jointing, and yet they were able to coexist with sedimentary rocks showing metamorphism to the greenschist and higher facies.

Intrusive activity continued for some time. Granite emplacements postdating the period of earth movements took place, and dike injection was common. At Jabal Ẓulm ash Shaybah (lat 14°10′ N., long 48°50′ E.) a large granite cupola can be seen that effected thermal-contact metamorphism of the Tha'lab Group lavas. The granite does not show multidirectional cleavage, but only normal rift and grain, which is considered to be postkinematic.

At Ra's Burūm (lat 14°18′ N., long 48°49′ E.), a large granite intrusion occurs in Tha'lab group volcanics; the granite here also shows normal rift and grain. One determination, by the potassium-argon method (N. J. Snelling, unpub. data, 1961–62), gave an age of 515±25 million years.

Contact zones between these intrusions and the country rocks appear sharp and free from mixed rocks, but xenoliths of lavas included in the granite bodies have been extensively feldspathized. The granites in some places tend to be contaminated by constituents derived from xenoliths or country rock (Dunham, unpub. data, 1953–59).

At Ra's Sharwayn, R. W. Wetzel and D. M. Morton (unpub. data, 1948–50), observed a small outcrop of faulted and partly decomposed granite, having cleavage planes and containing quartz and pegmatite veins and dikes, intruded into or overlain by a folded series of metasedimentary rocks. Unfortunately it cannot be ascertained what relationship this granite bears to the metasedimentary rocks. However, an age of 467±25 million years was determined from a pegmatite dike in this granite (Snelling, unpub. data, 1961–62, potassium-argon method). In view of the reported cleavage planes in the granite, it would appear to be prekinematic and therefore may be a remnant of an old intrusion more recently reactivated.

The strikes of folds and faults in the basement series are mainly north, trending a few degrees east or west of north; some also trend northwest, and less commonly, west-northwest and east-northeast. Strikes change direction abruptly in places, suggesting fault control (p. H45–H46), though in some places they are arcuate between two trends. The intensity of folding and its strike variation increases westward in the same direction as the increase in metamorphism.

Instrusions also tend to follow basement grains. For example, at the Jabal Sawād Bā Quṭmī intrusion, the sills and dikes strike approximately northwest to southeast, swinging to west-northwest with the strike of layering in the intrusive.

In Dhufar in the Mirbāṭ area, numerous dikes cut across the basement complex with north, northwest, and northeast trends and subordinate intermediate directions (Lees, 1928; Fox, 1947; Wetzel and Morton, unpub. data, 1948–50; Beydoun and Greenwood, 1966).

REGIONAL CORRELATIONS AND AGE

Evidence as to the regional correlation of the basement rocks of the E.A.P. is vague and conflicting. This has already been summarized by the author (Beydoun, 1960, 1964), but some reappraisal is given here.

In Somalia, the Inda Ad Series (of former British Somaliland), which is generally admitted to be very similar to the highest basement of the E.A.P. (Beydoun, 1960, 1964; F. R. S. Henson, unpub. data, 1954–60; Greenwood, 1961) has been referred alternatively to the Precambrian or the Paleozoic (Somaliland Oil Exploration Co., Ltd., 1954, summarizing earlier views). In south Oman an evaporite-clastic group assigned tentatively to the Lower Cambrian(?) (Morton, 1959) has been compared with the metamorphosed basement sedimentary rocks of the E.A.P. (Beydoun, in Morton, 1959; Beydoun, 1960, 1964; Henson, unpub. data, 1954–60).

The basement rocks of western Arabia have always been regarded as Precambrian in age. However, it is only in recent years that attempts to classify them stratigraphically have made some progress. Karpoff (1957, 1960) and Brown and Jackson (1960) place the youngest components of the basement complex in the late Precambrian. In the absence of paleontological evidence to the contrary, most geologists agree with this conclusion which recognizes the importance of the widespread peneplain at the base of the overlapping Cambrian and Ordovician sedimentary rocks in Saudi Arabia and Jordan. A minority view holds that the highest basement sedimentary and other rocks of western Arabia may be of an early Paleozoic age.

For the present there is no conclusive evidence to support or disprove these opinions. However, it may be useful to review some regional observations and suggestions which may serve as a basis for further investigation by others.

In the Al Kawr area of the W.A.P., extensive exposures of intrusive and metamorphic rocks occur. These have been described by Wissman, Rathjens, and Kossmat (1942, p. 281–284), who remarked that "an upper less metamorphic mass of strata is distinguishable from a lower mass, but no unconformity can be discerned between the two."

Greenwood and Bleackley (1966) have mapped a large area of Precambrian metamorphic rocks in the W.A.P. that consist variably of schist, gneiss, quartzite, chert, crystalline limestone, and granulite, which are no doubt in part equivalent to the Thaniya Group of the Jabal ath Thanīyah area and the gneiss-granite rocks and schists of the area to the north. These would also be partly equivalent to what has been described as the Medina Series in Yemen (Geukens, 1960). These Precambrian metamorphic rocks of W.A.P. extend eastward into the Wāḥidī State almost to long. 47°50′ E. in the Jabal Sawād Bā Quṭmī area. It is likely that some of them may be equivalent to the Gharish Group and therefore younger (Wissmann and others, 1942), but this is not possible to establish with the present state of the mapping.

At Ra's Sharwayn, R. W. Wetzel and D. M. Morton (unpub. data, 1948–50; see p. H14) observed a folded and peneplaned series of metasedimentary rocks (50 m) which consists of quartzitic and micaceous sandstones laterally associated and interbedded with mica schists. This sedimentary series could be of the same age as the Gharish Group or it may be older.

In Dhufar at Al Ḩawţah and 'Ayn Sārit (Beydoun, 1960, 1964; Wetzel and Morton, unpub. data, 1948–50) limited exposures of varicolored indurated graywacke sandstones, quartzites, and shales resemble the upper part of the Ghabar Group in the E.A.P. These rocks were derived from a silicic igneous or metamorphic terrain (K. J. Ackerman, unpub. data, 1955, 1959). The series is of unknown thickness (estimated at Al Ḩawţah as 3,000 m without taking into account any repetition in the monotonous sequence) and has been highly folded, intensely cleaved, veined with quartz, and peneplaned. No dikes were observed. This series is overlain unconformably by Mesozoic sedimentary rocks.

A more highly metamorphosed basement, cut by many dikes, appears farther east at Mirbāt in Dhufar and in the Kuria Muria Islands as described by Lees (1928) and Fox (1947). Its composition at Mirbāt seems to differ little from that of the higher grade metamorphic rocks of the Aden Protectorate, and it is likely that the sediments of Al Ḩawţah and 'Ayn Sārit could have been derived from it. At Mirbāţ intrusive bodies occur in the metamorphic series, among which are pegmatite and aplite injections followed by basic dikes; quartz veins are common (Beydoun, 1964). The basement series here has been peneplaned and is overlain by the Murbat Sandstone (Lees, 1928), which has undergone no metamorphism or deformation except faulting and which in turn is succeeded disconformably by Cretaceous deposits. The Murbat Sandstone is of unknown date, but it is presumably later than the folded sedimentary strata of 'Ayn Sārit and Al Ḩawţah. It somewhat resembles the unfolded Lower Ordovician of South Oman (Morton, 1959; F. R. S. Henson, unpub. data, 1954–60) with which it is here tentatively correlated. Farther east-northeast from Mirbāt toward Ra's Naws, the Murbat Sandstone has wedged out and Cretaceous rocks directly overlie the basement peneplain (Wetzel and Morton, unpub. data, 1948–50; Beydoun, 1964).

In Oman igneous basement rocks crop out only in the vicinity of Ra's al Ḩadd (Lees, 1928; Morton, 1959), but pre-Ordovician sedimentary rocks crop out along the Al Ḩuqf-Ḩawshī swell (Morton, 1959). These include basal sands probably derived from silicic igneous or older quartzite sources without a high-grade metamorphic component. Overlying the sands are evaporitic platy limestones and dolomites containing stromatoliths, followed by a second sequence of clastics and an upper sequence of platy limestones and dolomites. This series compares closely in lithology and succession with the nonmetamorphic basement of southwest Ḩaḑramawt, namely the Ghabar Group, although the beds in Oman are thicker, devoid of pyroclastic components and are only locally folded. They are cut by quartz veins and mafic dikes which also occur in the basement of Dhufar, but so far are unknown in the overlying Ordovician of Oman.

These pre-Ordovician rocks of Oman have been assigned provisionally to the Lower Cambrian on the grounds that their evaporitic upper part may represent the beginning of a cycle completed in the "Hormuz Salt Series" (Middle and Upper Cambrian) which exists down the regional dip to the west (Morton, 1959). The salt series is missing at the outcrop where thick Lower Ordovician to Upper Cambrian clastics transgress over the eroded Lower Cambrian(?). However, the assumed continuity of the latter with the Hormuz salt is strongly supported by direct evidence in deep borings and by the discovery of *Linguella* cf. L. *nicholsoni* in salt pseudomorphs at the base of, and in apparent continuity with, the Lower Ordovician, which suggest transition downward to evaporitic Upper Cambrian which may occur in basinal environments (Henson, unpub. data, 1954–60; Beydoun, 1964).

The debris brought up by the Hormuz salt plugs in Oman and adjacent areas (O'Brien, 1957) includes platy limestone and dolomite with rare stromatoliths, clastic rocks, gypsum, tuffs, and intrusive and extrusive silicic and mafic igneous rocks in various combinations. No volcanics have been found in later Paleozoic sedimentary formations of the Cambrian salt-dome areas.

It is suggested that in south Oman intra-Cambrian epeirogenic movements occurred after deposition of the Lower Cambrian(?) dolomite and limestone and prior to the Ordovician transgression, upwarping the Al Ḩuqf-Ḩawshī swell and probably partly isolating basins to the west and north in which the Hormuz salt was deposited (Henson, unpub. data, 1954–60). These same movements, increasing in intensity to the west, may have been responsible for the folding of the highest basement rocks of Dhufar and the E.A.P. A phase of igneous extrusion on a small scale followed in south Oman (Morton, 1959; Henson, unpub. data, 1954–60).

In western Arabia (Al Ḩijāz), Karpoff (1957, 1960) recognized a "Wadi Medina Series" which includes lava, tuff, schist, quartzite, gneiss, conglomerate, and migmatite, overlain unconformably by a "Wadi Fatima

Series." This latter series has a basal conglomerate and includes sandstone, shale, lava, tuff, and laminated limestone with stromatoliths. It is tempting to correlate it with the Ghabar and Garish groups of the E.A.P., although algal remains have not yet been found in the latter area.

Brown and Jackson (1960) recognized the Wadi Fatima Series, ranking it as a formation, and correlated with it their Abla Formation which crops out near Najrān near the northeast border of Yemen. Their Fatima and Abla Formations rest unconformably on an older Murdama Formation (possibly equivalent to the Medina Series of Karpoff) and on a calc-alkaline granite series. They are overlain by the "Shammar rhyolite and andesite flows and tuffs, and tuffaceous sediments," and are intruded by the "Eastern Granite." The Fatima Abla, and Shammar Formations and Eastern Granite Group are given an age range of about 600–640 million years, based on the rubidium-strontium ratio in biotite from two samples from the Eastern Granite (Brown and Jackson, 1960).

Geukens (1960) grouped the majority of the basement rocks of Yemen into the "Medina Series" and remarked that the metamorphic rocks are intensely folded and generally strike north-south; during this period important granite bodies were emplaced. He recognized an unconformity between the Precambrian Medina Series and a less intensely folded "Fatima Series" preserved only in north Yemen and consisting of conglomerate and metamorphosed arkose passing into quartzite. The folds in general trend east. This Yemen Fatima Series marks a transgressive phase over the peneplaned top of the Medina Series. Geukens regarded its age also as Precambrian.

The upper Shammer unit of west Saudi Arabia is vestigial or missing in the E.A.P. Henson (unpub. data, 1954–60), however, believed that its presence before peneplanation is suggested by the abundance of dikes penetrating the upper basement formations (Gharish Group and others).

In Somalia, the Inda Ad Series as described by Mason and Warden (1956) rests unconformably on the basement complex. The basal part contains sandstone and a conglomerate with pebbles of the basement complex; the series is only dynamically metamorphosed, but sedimentary structure is well preserved. Above the conglomerate is a series of mudstones with siltstone and limestone bands, overlain by variegated mudstone and graywacke, in turn overlain by sandstone, grit, and conglomerate which are intraformational. The Inda Ad thus bears close overall similarity to the Ghabar Group of the E.A.P. (p. H9). A series of pelitic (phyllite, schist and metamorphosed limestone) and associated volcanic rocks occurs in the Erigavo district; locally these differ only slightly from the cleaved mudstones of the Inda Ad, but they have been regionally metamorphosed—chlorite to hornblende facies (Mason and Warden, 1956). These metamorphic rocks are unlike the basement complex beneath the Inda Ad and bear general resemblance to the Gharish Group of the E.A.P., which is considered equivalent to the Ghabar Group (p. H9).

Greenwood (1961) questioned Mason and Warden's evidence for a younger Inda Ad resting unconformably on the basement complex and regarded their basal conglomerate as one of the interformational ones. Considering the other evidence available, he suggested that the rocks of the Inda Ad grade westward into the basement complex, the gradation from little-altered sedimentary strata in the east to the complex of metamorphic and igneous rocks in the west being brought about by intensification of metamorphism and igneous activity, the nature of which is regional. This proposed relationship does not invoke an unconformity. He further stated that if it is assumed (a) that the Inda Ad and basement complex of Somaliland are two expressions of a continuous series and (b) that the Inda Ad is Lower Cambrian—by correlation with the E.A.P. Ghabar Group and the Oman sedimentary rocks—then at least part of the basement complex must be of the same age, and this would be somewhat startling. He admitted that until more conclusive evidence is obtained alternative interpretations are possible.

So far isotope-age dating has contributed only slightly and indirectly toward a solution to these problems. Apart from the figures quoted by Brown and Jackson (1960) for west Saudi Arabia, a sample of muscovite-bearing pegmatite from the Gharish Group of the E.A.P. has been analyzed by D. York at Oxford University (unpub. data, 1960). This sample from the Wādī Gharīsh area at lat 14°08′ N., long 48°12′ E. indicates an age of 590±50 million years (potassium-argon method). The pegmatite is younger than its host rocks, but it is thought to have been associated with the orogenic or post-orogenic magmatism which probably accompanied, and certainly followed, the folding and metamorphism (p. H13). Metamorphism probably occurred in stages but in the course of a major orogenic cycle.

Another sample of muscovite from a pegmatite collected in the W.A.P. (area north of Aden) by Heybroek has been analyzed for Schürmann, and indicates an age of 545 million years (potassium-argon method) (Schürmann, written commun., 1961).

The only other dates so far available are from the younger granites, determined by N. J. Snelling (see p.

H14), which indicate that igneous activity took place in the lower Paleozoic.

An age of 590 million years for the Wādī Gharīsh pegmatite would indicate either (a) that the Gharish Group basement rocks of the E.A.P. are of late Precambrian age which would extend the age for the base of the Cambrian slightly upward, or (b) that the younger basement rocks are of Early Cambrian age. The problem must remain unanswered for the time being.

The prior review is perhaps too full of assumptions to prove anything. Nevertheless, it shows that there is some reason for considering a younger age than Precambrian for some basement rocks in parts of Arabia. The fact that their surface is peneplaned should not be the criterion for assigning them automatically to the Precambrian.

Until further isotope-age determinations for the E.A.P. basement rocks are made, little more can be said of the age of the basement rocks of that area.

ECONOMIC ASPECTS

Surprisingly few occurrences of economic minerals have been discovered in the basement areas of the E.A.P. What has been discovered does not appear to be of commercial value, being mainly limited to occurrence of iron in dikes or mineralized veins in areas of difficult access or too far from seaports. Some scattered occurrences of other minerals, including traces of galena, some mica (here of no commercial value), and small garnets are of no economic significance. It must be pointed out, however, that no systematic mineral survey of the area has been made. Such a survey may yield some results, but they will probably be limited, to judge by the overall picture so far known.

MESOZOIC ERA

JURASSIC SYSTEM

The oldest sedimentary rocks directly overlying basement are of Jurassic age. They are exposed in the coastal mountain belt of southwest Ḥaḍramawt west of long. 48°38′ E. They reappear eastward in Al Mahrah at Ra's Sharwayn and probably at Al Masīlah, although in the latter locality no diagnostic fauna is present in the part assigned herein to the Jurassic.

Two types of Jurassic rocks are recognized in the E.A.P. The first is the complete sequence exposed in the coastal areas, which is an open-sea sedimentation sequence. The second, incompletely exposed, occurs in the inland saltdome areas; its lower part is an evaporitic sequence deposited in restricted basins or seas, and its upper part is an open-sea sedimentation sequence.

The Jurassic of the E.A.P. and the adjacent W.A.P., on the basis of abundant faunal evidence, is mainly Upper Jurassic in age. The basal part, a sequence of clastics without any fossils, is believed to be Middle Jurassic to possible Early Jurassic in age.

The formations which make up the Jurassic of the area are as follows:

Age	Group	Coastal areas (see pl. 2)	Salt-dome areas (see pl. 3)	
Callovian to Tithonian	Amran Group	Naifa Formation	Naifa Formation	
		Mabdi Formation	Sabatain Formation	'Ayad-M'qah Member Layadim Member Shabwa Member
		Shuqra Formation	Unexposed	
Middle to Lower(?) Jurassic		Kohlan Formation	Unexposed	
		—Unconformity: Peneplanation—	—Unexposed—	
		Basement (volcanic and metasedimentary rocks and granite)	Unexposed	

KOHLAN FORMATION

The Kohlan Formation constitutes the basal unit of the Jurassic succession in the area. The name Kohlan was first applied (Lamare and others, 1930) for a similar succession exposed in Yemen in the Kuḥlān area northwest of Ṣan‘ā’, where it consists of marls with sandstone and conglomerate layers that contain basement fragments succeeded by sandstone and interbedded sandstone and sandy marl that contain plant impressions. The whole succession reaches a maximum thickness of about 200 m.

In the E.A.P. (and the W.A.P.) reference sections have been taken from all well-exposed sections. The formation consists of a sequence of arkosic sandstones with several conglomeratic horizons which have variable-sized pebbles of vein quartz and igneous and metamorphic rocks; interbedded green and purple bands of marl, siltstone, and shale occur at various levels. The formation unconformably overlies peneplaned basement rocks and is current bedded; the sandstones are generally soft and friable, though bands of indurated ferruginous blocky sandstone occur. The upper part grades into the overlying Shuqra Formation, generally passing upward from standstone, through silty marl to calcareous sandstone and sandy limestone. There is no evidence of any break between the two formations. The overlying Shuqra Formation, on the basis of fossil evidence, is Callovian to early Oxfordian in age.

Thus, the gradational contact between the Kohlan and the overlying Shuqra indicates continuity of sedimentation between the two, and suggests that at least for the upper part of the Kohlan the age is probably Middle Jurassic. The lower part may be partly Early Jurassic and even Triassic, though Triassic is more unlikely in view of the comparative thinness of the formation and the overall type of lithology, which do not suggest accumulation over too long a period of time. No fossils or plant remains have been found in any part of the Kohlan in the E.A.P.

The formation is present in all completely exposed Jurassic sections of the E.A.P. and it everywhere underlies the Shuqra with gradational contact between the two. Thicknesses measured range between 17 and 81 m, the average being about 55 m. These variations are due to irregularities in the peneplaned basement surface on which the Kohlan Formation has transgressed, and to the persistence of scattered local highs in the basement during deposition of the Kohlan. The basement surface often shows a weathered rotted reworked upper few meters on which the Kohlan rests, and it may be composed of volcanics, granite intrusives, or steeply tilted and truncated metasedimentary rocks. Weathered and reworked volcanics show bedding parallel with the overlying Kohlan; examples of tilting of the basement with the overlying Jurassic are fairly common.

The Kohlan Formation shows marked uniformity in overall lithology, as interbedded siltstone, marl, and shale layers are almost everywhere present within the sandstone; conglomeratic zones are ubiquitous. The Kohlan's color is generally light—white and pink. It weathers gray to light brown, and is easily distinguishable from similar clastic formations of Cretaceous age because of this. In one section at Jabal ʻAtūq, a very thin limestone occurs near the base of the Kohlan, interbedded with marl and siltstone within the sandstone.

AMRAN GROUP

The formations of Late Jurassic age have been grouped together under the name Amran Group (Callovian to Tithonian). The Amran Group in the E.A.P. and W.A.P. embraces all exposed formations of Jurassic age occurring above the Kohlan Formation.

The name Amran was first used (Lamare and others, 1930) to describe Jurassic deposits occurring above his Kohlan Series in Yemen. The type locality of Lamare's Amran Series is the ʻAmrān area of Yemen, northwest of Ṣanʻā'. Paleontology has been discussed by Basse (1930). Rathjens and Wissmann (in Wissman and others, 1942) also examined a similar section in the same general area, and Karrenberg (in Basse and others, 1955) sampled an incomplete section nearby.

The Amran Group in the E.A.P. varies appreciably in thickness in the coastal exposures. This is in part due to sedimentation, but it is also in part due to erosion. A maximum measured thickness for the group is 733 m, and a minimum preserved thickness of 35 m has also been measured.

In Ḩaḑramawt, exposures occur west of long. 48°38′ E. Generally speaking, in the area immediately west of this longitude, the thinnest part of the group occurs, thickening westward to the maximum at Jabal Madbī (lat 14°17′ N., long 48°04′ E.), then thinning again, but only slightly, westward into the W.A.P. East of long 48°38′ E. the group is absent, reappearing again in Al Masīlah (no faunal evidence) and at Ra's Sharwayn in coastal Al Mahrah. Eastward and northeastward from these localities it disappears, being absent in Dhufar and also in Socotra to the east-southeast.

In the coastal type of sequence, the group is a marine open-water succession of limestone and marl facies. The lower part is a neritic shallow-water limestone and marl facies (Shuqra Formation), followed by a more open-sea marly facies (Madbi Formation), grading into an argillaceous limestone facies which in turn grades into and terminates in a shallow-water marly sandy facies (Naifa Formation). Inland, in the salt-dome sections, the lower part of neritic limestone facies (Shuqra Formation) is not exposed, but it is presumed to be present below the evaporites, which are the lowest beds exposed. The evaporates were deposited in restricted basins or seas and make up the Sabatain Formation which is correlated with the more open sea Madbi Formation as a lateral variant (see p. H20). Overlying both the Sabatain Formation and the Madbi Formation is the Naifa Formation, indicating the spread of open-sea conditions inland and the end of restricted deposition. The Naifa Formation is present in all Jurassic coastal and salt-dome sections in the E.A.P. that have not undergone sufficient erosion to remove it.

In its uppermost part the Amran Group is possibly lowermost Cretaceous (Berriasian) (M. Chatton, unpub. data, 1948–59) in the western part of the coastal area of Ḩaḑramawt, but this possibility is limited to a few sections where macrofaunal evidence is poor and suggests affinites with Berriasian.

A marked unconformity with little or no angularity at the top of the Amran Group, but which may occur at various levels, indicates a period of emergence and plantation prior to the Cretaceous transgression proper.

COASTAL SECTIONS

Shuqra Formation

This Shuqra Formation is present in all Jurassic sections in Ḩaḑramawt, in the W.A.P., and in the Ra's Sharwayn section of Al Mahrah. In Ḩaḑramawt it is between 60 and 80 m thick, though as little as 39 m has been measured as a full succession not reduced by erosion in the eastern most exposures of Ḥaḍramawt.

The name Shuqra Limestone was first used by Heybroek (in Hudson, 1954) for the sequence of limestone sampled by him near Shuqrah in the W.A.P. This section was later sampled by R. W. Wetzel and D. M. Morton (unpub. data, 1948–50) where some 98 m of well-bedded limestone, abundantly fossiliferous and including some rubbly and marly zones overlie 20 m of sandstone. The top of the limestone is not seen as it is overlain by a sub-Recent lava flow. Farther to the north in the W.A.P. a more complete section of Upper Jurassic (Amran Group) is exposed.

In southwest Ḥaḍramawt, Upper Jurassic reference sections are well exposed and the Shuqra Formation is divisible into the following units in many places:

1. A basal interval of well-bedded neritic limestone, generally sandy at the base and sometimes at higher levels, detrital and commonly oolitic and containing interbedded rubbly marls; fossiliferous.
2. A 7- to 10-m interval of very fossiliferous rubbly yellowish marl.
3. Sequence of well-bedded limestone as in unit 1.
4. A terminal 5- to 10-m interval of fossiliferous rubbly marl as in unit 2.

The top interval may be absent in some sections in southwest Ḥaḍramawt. Where this happens, the overlying Madbi Formation rests directly on unit 3, indicating either a disconformity or a lateral extension upward of the limestone of unit 3 to replace the marl of unit 4.

At Ra's Sharwayn, the Shuqra is about 56 m thick and consists of 36 m of fossiliferous limestone and marl bands and an upper 20 m of fossiliferous marl. Apart from this locality the formation is not exposed elsewhere in Al Mahrah.

In the field there is an apparently conformable contact with the overlying Madbi Formation, but the absence of the uppermost rubbly marls of the Shuqra in some sections would seem to indicate a local disconformity.

The rich faunal assemblage has already been partly described by Hudson (1954) from the collections from Jabal al 'Urays near Shuqrah in the W.A.P. and from Ra's Sharwayn in Al Mahrah. In the assemblage from these sections and from the sections in southwest Ḥaḍramawt, the following fauna occur (Hudson, 1954; unpub. data from the following: Hudson, 1948–56; Gosling, 1956; Cox, 1949–56; Chatton, 1948–59; Elliott, 1951–59; and Spath, 1955–57):

Rhynochonella hadramautensis Stefanini, *R.* aff. *R. moriere* Dav., *R. hudlestone* Roll., *Somalirhynchia africana* Weir, *S. wetzeli* Hudson, *S. tumida* Muir-Wood var., *S. bihendulensis*, *S. africana* var. *smellei* Weir, *S.* cf. *S. somlica* (Dacque), *S. bihenensis*, *S. africana* var. *jordanica*, *Terebratula bisuffarcinata* Schlotheim, *T. subsella* s.l., cf. "*T*" *subsella* Leymerie, cf. *T. zeiteni* de Loriol, "*T*" *aulites* Stefanini, "*T*" cf. *T. suprajurensis*, *Daghanirhynchia hadramautensis* (Stefanini)., *D.* cf. *R.* cf. *morieri* Stefanini, *D. subversabilies*, *D. daghaniensis* var. *platiloba*, *D. daghaniensis* var. *elongata*, *D. daghaniensis*, *D. macfadyeni*, *D. kabietensis*, cf. *D. farquharsoni* Muir-Wood, "*D*" *platiloba* Muir-Wood, "*Burmirhynchia*" *gregori* Weir, *Somalithyris bihendulensis* Muri-Wood, cf. *S. macfadyeni* Muir-Wood, *Chaltonithyris bihenensis* Weir, *Cererithyris somaliensis* Weir, *Lophrothyris senilis* Muir-Wood, cf. *L. Ptyctothyris daghaniansis* Muir-Wood, *Striithyris somaliensis* Muir-Wood, *Trigoithyris eruduwensis*, *Sphaeroidothyris? browni*, *Zeillerina latifrons* (Krumbeck), *Eocallista krenkeli* Cox, *Ceromyopsis arbica* Cox, *C. striata* d'Orbigny, *C. eccentrica*, *C. somaliensis* Weir, *Pholadomya aubryi* Douville, *P. lirata* (J. de C. Sowerby), *P. protei* Defrance, *P.* (*Homomya*) *inornata* J. de C. Sowerby, *Lima* (*Plagiostoma*) *harronsis* Dacque, *Lopha solitaria* (J. de C. Sowerby), *L. gregarea* (J. Sowerby), *L. costata* (J. de C. Sowerby), *Mytilus* (*Modiolus*) *imbricatus* (J. Sowerby), *Nerinea somaliensis* Weir, *Aulacomyella* cf. *A. similis* (Munster), *Astarte* (*Coelastarte*) *scytalis* Holdaus, *Paralleledon egertonianus* Stoliczka var. *crebricostatus* Stefanini, *Gryphaea balli* (Stefanini), *Exogyra fourtaui* Stefanini, *E.* cf. *E. nana* (J. de C. Sowerby), *Mactromya aequalis* Agassiz, *Ceretomya wimmisensis* (Gillieron), *Musculus somaliensis* Cox, *Eligmus aualites* (Stefanini) *E. Weiri* Cox, *Grammatodon* (*Indogrammatodon*) *egertonianus* (Stoliczka), *Stylina macfadyeni* Thomas, *Amphiastrea gibberosa*, (Gregory), *Astrocoenia newtoni* Gregory, *A. Bernensis* Koby, *A.* cf. *A. Hypodiadema facfadyeni* Currie, *Belemnopsis tanganensis* (Futterer), *Sutneria* aff. *galar* (Oppel), *Shuqraia zuffardiae* (Wells), *S. heybroeki* Hudson, *S. arabica* Hudson, *S.* cf. *S. Stromathopora douvielli* Dehorne, "*Stromatopora*" *harrarensis* Wells, "*S*" *kurtchensis* Wells, *Milleporidium somaliense* Zuffardi-Comerci, *Pseudocyclamina* cf. *P. sequana* Mohler, *Nautiloculina colithics* Mohler, *Trocholina palastiniensis* Henson, *Valvulinella jurassica* Henson, *Pfenderina* sp., *Salpingoporella annulata* Carozzi, *Cylindroporella J. I.*, and others.

This fauna establishes a Callovian and Argovian (Oxfordian) age for the Shuqra, though the uppermost part probably ranges into the Sequanian.

Madbi Formation

The Mabdi Formation immediately overlies the Shuqra Formation and occurs in all sections of the Jurassic wherever it has not been removed by erosion in southwest Ḩaḑramawt west of long. 48°38′ E. The type section is chosen from Jabal Madbī. Generally, the formation is thinnest in the eastern part of southwest Ḩaḑramawt where thickness of some 60–100 m are known, and it thickens westward to an observed maximum in the Gharīsh-Madbī area (maximum at Wādī Gharīsh, 290 m). Westward from there thicknesses range from 105 to 250 m, depending probably on the influence of scattered local highs that may have persisted for a while during sedimentation. The formation extends into the W.A.P.

In southwest Ḩaḑramawt the Madbi consists of a series of marls, gray to dark gray and yellow, commonly shaly and in places silty, and locally gypsiferous; some sections contain thin gypsum beds. With the marls are interbedded thin bands of rubbly or marly limestone, in places detrital, and generally fossiliferous; bread-loaf-type concretions reaching half a meter in diameter are common at various levels, and the marls commonly are bituminous in their upper part.

In Al Mahrah the Madbi Formation is believed to be present only at the Ra's Sharwayn section (Beydoun, 1960, 1964) and is present there in a limestone facies with several marl zones capped by shale and marl; fossils are common, though nondiagnostic.

The lower and upper contacts of the Madbī Formation are apparently conformable in the field, though the lower contact with the Shuqra may possibly be locally disconformable (for example, Wādī Gharīsh section shows a hummocky surface at the top of limestone (unit 3) of the Shuqra (p. H19). The upper contact is conformable and locally gradational.

The formation is fossiliferous throughout its sequence in the Ḩaḑramawt sections and thin lumachelle bands consisting of fossil debris are common at various levels. Among the faunal assemblage the following are present (unpub. data from the following: Hudson, 1948–56; Cox, 1949–56; Arkell, 1956–58; and Smout, 1953–59): *Gryphaea balli?* (Stefanni), *Lopha marshi* (J. Sowerby), *L.* cf. *L. solitaria* (J. de C. Sowerby), *Exogyra fourtaui* Stefanini, *Ostrea* (Liostrea) *wagurensis* Cox, *O.* (Liostrea) cf. *O. moreana* Buvignier, *Astarte* (*Coelastarte*) *scytalis* Holdaus, *Modiolus imbricatus* (J. Sowerby), *Inoceramus* cf. *I. suprajurensis* Thurmann, *Posidonia somaliensis* Cox, *Proconulus ambalensis* (Weir), *Terebratula* cf. *T. terebratula*, *Daghanirhynchia macfadyeni*, *Somalirhynchia africana* cf. *S. jordanica*, "*T.*" *aualites*, *S. africana* cf. var. *smellei*, *Laevaptychus latus* (Parkinson), cf. *Ataxioceras desmoides* Wegele, *Idoceras* cf. *I. farquharsoni* Spath, *Perisphinctes mombassanua* Dacque, *P.* (*Pachyspinctes*) *robustus* Spath, *P.* (*Divisosphynctes*) cf. *P. inaequalis* (Spath), *Belemnopsis tangenensis* (Futterer), *Rhopalo teuthis somaliensis* Spath, *Valvulinella jurassica* Henson, *Paleotrix* (form X), and others. From these a Kimmeridgian age is indicated, probably Sequanian to upper Kimmeridgian (lower Tithonian), but the lower limit may go down into upper Argovian (Oxfordian).

The Madbi Formation is equivalent to the Sabatain Formation inland in the salt-dome areas. This is indicated by the following: (a) the position of the Naifa Formation conformably overlying the Madbi in the coastal-type Upper Jurassic and the Sabatain in the salt-dome-type Upper Jurassic; (b) the presence of gypsum, locally in thin primary beds within the Madbi—indicating the advent of evaporitic conditions in the coastal areas—though much more common inland; and (c) faunal evidence, albeit rather meager, found in the Sabatain Formation. Regional correlations from Yemen support this view.

Naifa Formation

The Naifa Formation immediately overlies the Madbi Formation of the coastal Upper Jurassic and the Sabatain Formation of the salt-dome areas, and forms the top unit of the Amran Group. Its contact with the Madbi is conformable and gradational in a number of sections, and its contact with the Sabatain, preserved only at the 'Iyādh salt dome, appears conformable in the field.

The Naifa Formation type section is near Al Ma'abir in Wādī Ḩajr. The formation can be divided into two parts, upper and lower. The lower part consists of a sequence of thin-bedded fine-grained to porcellaneous limestone, with common thin zones of platy dolomite, dolomitic shale, rubbly marly limestone, or marl. This sequence is present everywhere, generally all of it being preserved, and ranges in thickness from about 50 m in the eastern part (immediately west of long 48°38′ E.) to several times that thickness westward and to some extent northwestward. A maximum thickness for this lower part totaling 446 m was measured at Jabal Madbī, situated toward the center of the area of Jurassic outcrops of southwest Ḩaḑramawt. Westward toward W.A.P., thickness is considerable though generally appreciably less than at Jabal Madbī itself.

The upper part of the Naifa Formation consists of a squence of marl, generally gray and yellow but also pink, commonly shaly and in places gypsiferous or silty, and containing interbedded marly limestone, which is gray, rubbly to fissile, fine-grained, and locally shelly. Where the upper part is preserved, it is thicker in the east than it is in the rest of southwest Ḩaḑramawt. A maximum thickness of 78 m for this part was measured at the Al Maʻābir section. The upper part is generally missing in the west, being partially recorded in only two sections where just 14 m in each is preserved. It is absent in the salt-dome areas.

In certain localities some of the upper part of the underlying thin-bedded limestone is also missing. This is due to a period of erosion late in the terminal Jurassic, which followed a phase of block faulting.

The significant thickening of the lower part of the Naifa Formation from east to west and the presence of a thicker upper marly sequence in the east than in the west may partly be explained by a lateral variation in facies; the upper part of the thin-bedded limestone in the west is probably equivalent to part of the upper marly sequence.

In three of the western sections, but especially well developed at Jabal Madbī, the thin-bedded limestone sequence has several conglomeratic zones in its lower part; these are largely conglomeratic limestone consisting of pebbles of Jurassic and some basement rocks in a limestone matrix, in places containing sandy layers. The conglomeratic zones grade into thin-bedded limestone, which are in places associated with platy dolomites and in the upper part with fetid and oily coarse limestone; at the Wādī Gharīsh section fetid shales, aragonite, and some marls are also associated. The maximum thickness of this conglomeratic member is in the Jabal Madbī section; it is less thick at Wādī Gharīsh, and even thinner at Jabal Sakhā near the W.A.P. border. The conglomerates mark intraformational breaks within the Naifa Formation and are attributed to local erosion after slight intra-Jurassic uplift, though some may be due to penecontemporaneous slumping and reworking by currents in shallow-water conditions. In Wādī Gharīsh many of the pebbles are subangular and are more of a breccia than a conglomerate.

The presence of these intraformational breaks and the association of evaporitic beds with some of them at the start of the Naifa Formation sedimentation appear to indicate local erosion of a partial barrier erected during earlier intra-Jurassic movements. This isolated the inland salt-dome areas, giving rise to the Sabatain Formation there, while the equivalent Madbi "open sea" Formation was being deposited to the south. The erosion of this partial barrier during early Naifa deposition allowed this latter formation to extend inland over the salt-dome areas, and open-sea sedimentation then became general for both areas.

In southwest Ḩaḑramawt, the coastal sections in the eastern part are more fossiliferous than coastal sections to the west. The latter have undergone more recrystallization, and the macrofauna found in beds in these sections are indeterminable. In general, the macrofauna is fairly well preserved in the marly and rubbly parts of the sequence, while that in the limestone is recrystallized. The occurrence of fauna is sporadic and varies from section to section; in some, extremely fossiliferous zones with abundant amonites occur (for example, Naifa section in Wādī Ḩajr, also examined by Little, 1925).

From determinations on the fauna collected, the formation includes the following (unpub. data from the following: W. J. Arkell, 1956–58; L. F. Spath, 1955–57; R. G. S. Hudson, 1948–57; F. Gosling, 1956; M. Chatton, 1948–59; A. H. Smout, 1953–59; and E. K. Elliott, 1955–59) : *?Virgatosimoceras* sp., *Perisphinctes* (*Pachysphinctes*) *robustus* Spath, *P.* (*P*) cf. *P. granti* Spath, *P.* (*?Dichotomosphinctes*) cf. *P. krapfi* Dacque, *P.* (*?D*) cf. *P. eggeri* von Ammon, P. (*?Lithacoceras*) cf. *P. torquatiformis* Spath, *Planites* (*?Biplices*) sp. cf. *P. africanus* (Dacque), *P.* cf. *P. polygyratus* (Reinecke) of authors, *P.* cf. *P. anabreviceps* (Dacque), *Taramelliceras* cf. *T. trachynota* (Oppel), *Aspidoceras* cf. *A. longispinum* (Sowerby), *Ataxioceras* cf. *lictor* (Fontannes), *Discosphinctes* cf. *geron* (Zittel), *Physodoceras* (*Simaspidoceras*) aff. *P. argobae* (Dacque), *Laevaptychus latus* (Parkinson), *Lamellaptychus pleidensis* Trauth, *Belemnopsis tangensis* (Futterer), *Grammatodon* (*Indogrammatodon*) *egertonianus* (Stoliczka), *Proconulus arabiensis* (Newton), *Aulacomyella* cf. *A. farquharsoni* Cox, *Calpionella mollelloides*, *C. alpina* Lorenz, *Nannoconus* cf. *N. steinmanni*, *Pseudocyclammina* sp., *Macroporella gigantea* Carozzi, *M. Pygmaea* (Gumbel), and others. *Pseudocyclammina* sp. occurs principally in the western sections.

From the above faunal suite, a Tithonian age is indicated for the formation, but opinion varies as to whether it is between Lower and Middle or between lower and upper Tithonian. The presence of *Pseudocyclammina* sp. in a form similar to Lower Cretaceous forms from the Persian Gulf area led Chatton (unpub. data, 1948–59) to attribute a Tithonian to Berriasian age to the formation in Ḩaḑramawt, but the macrofossil evidence, lacking in the western sections, indicates that no Cretaceous is present.

In the salt-dome areas the Naifa Formation consists entirely of thin-bedded limestone with bands of platy or shaly dolomite and thin rubbly layers; some fauna has been found.

At Al Masīlah in Al Mahrah is a sequence of some 116 m of limestone and dolomite (base not seen) overlain by 48 m of marl and shale with limestone and sandy limestone containing *Cyclammina* sp. and indeterminate oysters and other pelecypods (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50); it most probably represents the Naifa Formation, and underlies a thin conglomerate which probably marks the Jurassic-Cretaceous unconformity. The conglomerate is followed by 99 m of undated strata overlain conformably by Lower Cretaceous beds.

At Ra's Sharwayn a 50-m sequence of dolomitic limestone undelies a brecciated limestone interval and is overlain by datable Lower Cretaceous. The brecciated limestone is taken as evidence of unconformity (Chatton, unpub. data, 1948–59; Beydoun, 1960, 1964), below which the 50-m dolomitic limestone sequence is taken as representing the Naifa Formation.

SALT-DOME SECTIONS

Sabatain Formation

The Sabatain is the lowest exposed formation of the Amran Group in the salt-dome areas of west and northwest Ḩaḑramawt (and the two adjoining salt domes at Al'Ayādīm (Layadim) in W.A.P. and Şāfir in Yemen. It is a restricted succession of evaporites with clastics; the basal part is everywhere salt followed conformably by a persistent interval of shales containing Late Jurassic fauna (*Anaethalion* and others), overlain conformably by gypsum that laterally grades into clastics. The Late Jurassic age is confirmed in the Şāfir dome in Yemen (Geukens, 1960). The Sabatain Formation is the lateral variant of the Madbi Formation in the south; facies differences between the two are due to separation during sedimentation by a partial or complete barrier that led to evaporitic conditions for the Sabatain and open-sea deposition of the Madbi to the south. This barrier (or barriers) was subsequently removed during early deposition of the overlying Naifa Formation (compare conglomerates in the lower Naifa Formation indicating intra-Jurassic erosion) and allowed the Naifa Formation to spread over the salt-dome areas (p. H20–H21).

Alternatively, the rise of evaporitic conditions may have been partly or additionally due to the occurence of submarine plateau conditions where stagnation with rapid evaporation prevailed in the absence of deep-water current circulation (Henson, in Fox, 1959).

In Ḩaḑramawt the Shuqra Formation is not exposed below the Sabatain in the salt-dome areas, but in Yemen both the Shuqra equivalent and the underlying Kholan are present, the former occurring below evaporitic beds. It is therefore strongly indicated that the Shuqra Formation lies below the Sabatain in Ḩaḑramawt.

The seven surface salt domes of the E.A.P. occur in three areas: (a) the Al Minţāq area in the Wādī Ḩajr basin, which is the most easterly and southerly occurrence of salt domes in Ḩaḑramawt (lat 14°32′ N.; long 48°02′ E.) and includes Al Minţāq, Jūbah, and Siyāl al Milḩ domes, (b) the 'Iyādh area where the Ḩayd al Milḩ ('Iyādh) dome occurs (lat 14°59′ N., long 46°49′ E.), and (c) the Shabwah area, the most northerly of the three areas, where the Shabwah, Milḩ Kharwah, and Milḩ Maq'ah (M'qah) domes occur (lat 15°22′ N. long 47°00′ E.). Some 70 km west-northwest of 'Iyādh, the Al 'Ayādīm dome of Bayḩān (W.A.P.) occurs in the sands of Ramlat as Sab'atayn, and about 60 km north of that, the Şāfir dome in Yemen occurs also in the sands of Ramlat as Sab'atayn. No other surface expression of Jurassic salt domes is known from these three territories or from the neighboring countries.

The formation is variably exposed in these salt domes (the base is not exposed) from 62 m at Milḩ Kharwah to a maximum of 280 m in the 'Iyādh dome. It is divisible into four members, two persisting in all the domes. The members occur as follows:

'Ayad Member intertonguing with M'qah Member
Layadim Member—persistent
Shabwa Member—persistent
Base not exposed

Shabwa Member.—The Shabwa is the basal unit and crops out in all salt domes examined; its base is not exposed and generally only the top 10–20 m is exposed. The unit consists of rock salt having layered structure, gray striations, and bituminous stains. In all domes the salt is conformably overlain by the Layadim Member. This and the fact that the dip of the beds in the Layadim Member is parallel to the dip of the salt layers have led to the postulation of a stratigraphic contact between the two and to the belief that the salt is depositional and not of piercement origin (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50; Beydoun, 1960, 1964).

Layadim Member.—The Layadim is predominantly a shale unit, consisting of variegated shales, thin bands of marl, shaly limestone, dolomitic limestone, and some gilsonite beds; the shales are commonly black and papery, in places sandy, micaceous, and generally bituminous or carbonaceous. Laterally, in some domes, the unit becomes predominantly marly, though locally shaly, and contains salt streaks.

Thickness of the unit varies, being about 63 m in the Shabwah dome, but in some domes (for example, Al Minţāq) as little as 7 m is present. The contact with the overlying unit (the 'Ayad or M'qah Member) is conformable. The Layadim Member occurs in all the domes in the same stratigraphic position and in the same attitude as the underlying Shabwa Member and overlying 'Ayad or M'qah Member. Thickness and facies variations do not appear to alter its overall characteristics or its position in the succession.

Only in the Shabwah dome was any determinable fauna found in this member (Wetzel and Morton, unpub. data, 1948–50). This included the fish *Anaethalion*, and abundant *Estheria* and *Spongistroma.* On the basis of this, an Upper Jurassic age has been assigned to the Layadim Member (Beydoun, 1960; F.R.S. Henson, unpub. data, 1954–60; R. G. S. Hudson, unpub. data, 1948–56).

'Ayad Member.—The 'Ayad Member is one of the two top units of the Sabatain Formation, the other being the M'qah Member which forms a lateral variant of the 'Ayad. The 'Ayad Member consists of a series of white to yellow bedded gypsum with some interbedded thin bands of fetid dolomite, argillaceous and bituminous limestone, and limestone with phacoids. These bands vary from section to section, being absent in some places. The 'Ayad overlies the Layadim Member confromably. Its thickness varies, the maximum of 230 m being at the 'Iyādh dome. In most of the other domes, the member is incompletely preserved or absent owing to erosion, and only at 'Iyādh is it in actual contact with the overlying Naifa Formation. There, overlying limestone beds of the Naifa Formation dip conformably with the underlying gypsum of the 'Ayad Member.

M'qah Member.—The M'qah Member occurs in the Milh Maq'ah dome, and it is partly represented in the Shabwah dome as a tongue in the 'Ayad Member. The M'qah Member at the type section is about 150 m thick and contains some plant remains. It consists of coarse greenish ripple-marked sandstones that alternate with colored micaceous shales. Beds of shaly limestone, dolomite, and marl occur at various levels; gypsum is present at the base and top of the unit and in bands at various levels within the clastic sequence. Some beds are fetid and bituminous.

The M'qah Member, by its conformable position above the Layadim Member shales at the Milḩ Maq'ah dome and the intertonguing of its clastics into the gypsum of the 'Ayad Member at Shabwah, is shown to be a lateral facies variant of the 'Ayad Member. The indication is that lagoonal conditions developed in the northern part of the evaporitic basin, and that evaporitic conditions returned from time to time. Examination of the clastics suggests that they were derived from the basement of the Ath Thanīyah area to the west-northwest, which was undergoing erosion and supplying material into the evaporitic lagoonal basin of the Sabatain Formation. These lagoonal conditions persisted into parts of Yemen (Geukens, 1960).

Naifa Formation

The Naifa Formation has already been partly described (p. H20–H21). It is a formation common to both the coastal and salt-dome areas of Upper Jurassic deposits, with almost identical facies in both, characterized by thin-bedded rather porcellaneous limestone. It has been found completely preserved at Al Minţāq dome where it is in depositional contact with the overlying Qishn Formation, the contact being marked by a thin conglomeratic sandstone. The sequence at Al Minţāq is 150 m thick and consists of thin-bedded limestone, bands of platy or shaly dolomite, and thin rubbly layers. Contact with the underlying 'Ayad Member of the Sabatain Formation is not exposed. At 'Iyādh 87 m of the formation is preserved and consists of thin-bedded fine-grained rather porcellanous limestones, as in the Al Minţāq section. The top beds have been removed by erosion; the contact with the underlying 'Ayad Member of the Sabatain Formation appears conformable. The Naifa Formation is absent in the other salt domes (except Jūbah), having been eroded.

Some fauna has been collected from deposits in the Al Minţāq dome. This fauna, on the whole, is poorly preserved, but includes the following (R. G. S. Hudson, unpub. data, 1948–56; A. H. Smout, unpub. data, 1953–59) : *Thecocyathus* cf. *T. pussilus*, *Perisphinctes* cf. *P. lincki*, Choffat, ?*Lithacoceras* aff. *stenocyclus* Schneid not Fontannes, *Katroliceras* sp.?, *Calpionella alpina* Lorenz, *C. elliptica*, *C. undelloides*, *Nannoconus*, *N. steinmanni?*, *Textularia* sp., *Haplophragmoides*, and *Oliogostegina* sp. The microfaunal assemblage indicates an Upper Tithonian age (Smout, unpub. data, 1953–59). At 'Iyādh one ammonite was found, determined as *Barriesella* sp., and it is of probable Tithonian age.

No Jurassic is known from Dhufar (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50; Beydoun, 1960, 1964). Recent work in the area by the Dhofar Cities Service Petroleum Corp., however, indicates that clastics occurring below datable Early Cretaceous are of Jurassic age. Their age is based on spore and pollen determination and on the finding of *Coskinolinopsis primaevus* Henson (indicating a Liassic age) in a thin limestone in the clastics (J. M. Meier, written commun., 1961). These clastics suggests that only a part of the Jurassic remains in Dhufar, or else that only a part was deposited, Dhufar having been emergent during most of the period. The Jurassic clastics may be equivalent to part of the Kohlan Formation of the E.A.P.

REGIONAL CORRELATION OF THE JURASSIC

Plate 5 shows the correlation of the Jurassic formations of the area with those of neighboring countries.

The Kohlan Formation correlates with the Kohlan Series of Yemen (Lamare and others, 1930; Lamare, 1936) though Lamare's Kohlan is much more marly in its lower part. Originally (Lamare and others, 1930) this formation was given a Middle to Early (?) Jurassic age, but later (Lamare, 1936), on the basis of plant remains of a somewhat undiagnostic character found near the top of the succession and assigned to the Lias with reservation, it was assigned a Triassic or Liassic age and was correlated with the Adigrat Sandstone of the Ethiopi-Somali region.

Geukens (1960) described a succession of clastics occurring in various parts of Yemen between the basement peneplain and datable Upper Jurassic calcareous deposits and grading up into the base of this suquence. These deposits represents the Kohlan Formation, generally considered by him to be of Jurassic age.

The Adigrat Sandstone in former British Somaliland shows a gradational upper contact with the overlying Upper Jurassic limestone without any evidence of break and is taken to be Jurassic in age (Mason and Warden, 1956; Beydoun, 1964).

The Amran Series of Yemen (Lamare and others, 1930; Lamare, 1936; Geukens, 1960) is correlated only with the Shuqra Formation of the Amran Group of the E.A.P. This correlation is based on a similar facies and almost the same age range (Lamare and others, 1930; Lamare, 1936; Basse and others, 1955; Geukens, 1960; Wissmann and others, 1942).

Conformably overlying the Amran Series proper in various parts of Yemen are "transition" or "passage" beds (Wissmann and others, 1942; Basse and others, 1955; Geukens, 1960), variably including gypsum, clays, marls, and bituminous shales of Kimmeridgian age; they are more evaporitic east-northeast of Ṣan'ā' (Al Ghars, Al Ḩarrah) but pinch out in places.

These transition beds of Yemen are therefore correlated with the Sabatain and Madbi Formations of the E.A.P. The Ramlat as Sab'atayn basin appears to have extended westward from the E.A.P. and parts of W.A.P., into Yemen to include Ṣāfir, and to the vicinity of Ṣan'ā' (Basse and others, 1955; Wissmann and others, 1942; Geukens, 1960). Outside this rather restricted basin in the rest of Yemen, open-sea deposits similar to the Madbi Formation of the E.A.P. were being deposited—(shales, marls, limestones, and sandstones in near-shore areas) (Geukens, 1960). The Ṣāfir succession is very similar to that of the Ramlat as Sab'atayn, with the M'qah Member facies in the upper part; spore and pollen determinations from shale beds give a late Jurassic age (Delcourt, in Geukens, 1960).

In Yemen there are no beds equivalent to those of the Naifa Formation of the E.A.P. This is significant in that it indicates that the south-to-north Naifa marine transgression which deposited limestone in the E.A.P. and the W.A.P. following Madbi and Sabatain Formation deposition, did not reach Yemen. The zone of maximum subsidence during the late Jurassic, which was in Yemen in Amran Series (Shuqra Formation) time, shifted toward Ḩaḑramawt by Madbi and Sabatain times.

Tentatively, E.A.P. (and W.A.P.) Kohlan Formation may be equivalent to the Marrat and Dhruma Formations of Saudi Arabia (Lower to Middle Jurassic) (Steineke and others, 1958), or even to the Minjur Formation. The Shuqra Formation is in part equivalent to the Tuwaiq Mountain Limestone and probably in part to the Hanifa and Jubaila (?) Formations. The Madbi and Sabatain Formations are tentatively correlated with the Riyadh Group (Hith and Arab Formations). The Naifa Formation would then be equated wtih the Sulaiy Limestone, the age of which is a subject of controversy.

Southward from the Aden Protectorate, the Jurassic of former British Somaliland correlates well with that of the E.A.P. and W.A.P. but there is no evaporitic facies within the Jurassic in Somaliland.

ECONOMIC ASPECTS

No oil has so far been discovered in the E.A.P., but indications of the presence of hydrocarbons are found in the rocks of Jurassic age. These include bituminous occurrences associated with salt (Shabwa Member of Sabatain Formation), bituminous shales (Layadim Member of Sabatain Formation, and Madbi Formation), and oily shales and limestone (Naifa Formation). None of the occurrence are striking, but compared to other areas where Jurassic oil has been found (eastern Saudi Arabia, Qaṭar), conditions of source, reservoir, and caprock exist in the E.A.P. which should be favorable for some accumulation of oil.

Other Jurassic mineral occurrences consist of rock salt which is quarried from the various salt domes in the interior for local consumption and limited export within southwest Arabia.

One or two limited occurrences of iron in mineralization zones along local faults in Jurassic rocks have been found in the Wāhidī State, but difficulty of access and limited extent make them noncommercial.

CRETACEOUS SYSTEM

The Cretaceous deposits of the E.A.P. vary in lithology, and thickness from west to east. Unconformities, disconformities, and pinchouts mark intra-Cretaceous movements, transgressions, and regressions or shallowing.

Cretaceous deposits are well exposed in the E.A.P. and occur along most of the length of the coastal belt, in the deeper gorges of the Southern Plateau, in the Wādī Ḩaḑramawt-Al Masīlah basin, in the cliff faces of the western parts of the Southern and Northern Plateaus, in a few of the deep western gorges of the Northern Plateau, as well as over part of the Western Plains as hillocks.

It is in southwest Ḩaḑramawt that the succession is generally completely exposed. West of long 48°38′ E. the Cretaceous rests unconformably on Jurassic, the contact being generally marked by a thin conglomerate; little or no angularity is observed. East of long 48°38′ E. in the Al Mukallā area, the Crestaceous rests unconformably on peneplaned basement. From that locality eastward to Al Masīlah the base of the Cretaceous sequence is not seen, but in Al Masīlah and at Ra's Sharwayn, exposures go down to the Upper Jurassic, and evidence of unconformable contact is present (p. H22).

In view of the lithological variations of the Cretaceous as a whole between the eastern and western parts of the E.A.P., it has been divided into two equivalent lithostratigraphic groups, (a) the Tawilah Group for the Western (Ḩaḑramawt) Province, and (b) the Mahra Group for the Eastern (Al Mahrah) Province.

The two are equivalent in total age range, the Tawilah being dominantly a clastic sequence with some limestone and marl tongues in the east, whereas the Mahra Group is a dominantly limestone and marl facies with sandstone tongues increasing to the west. The groups interfinger, and certain persistent lithological units are common to both. In addition, each group presents some variations from west to east; some of the formations merge and some become thicker.

The groups and main formation divisions are given in the following table.

Western Province (Ḩaḑramawt		Eastern Province Al Mahrah	
			Sharwain Formation
Tawilah	Mukalla Formation	Mahra	Mukalla Formation
	Not present		Fartaq Formation
Group	Harshiyat Formation	Group	Harshiyat Formation
	Qishn Formation		Qishn Formation
Unconformity		Disconformity	
Jurassic or basement			

TAWILAH GROUP

The name Tawilah Group is a readaptation of Lamare's "Taouilah Series" (Lamare and others, 1930; Lamare, 1936) of Yemen, which comprises there a succession of continental sandstones overlying datable Upper Jurassic strata.

The group as exposed in Ḩaḑramawt is a shallow-water to lagoonal-marine sequence that changes character from west to east (see following table). Although it is dominantly of clastic composition, the appearance of limestone, marl, and shale tongues, particularly eastward, enables subdivision into more distinct formations in that direction. Thus, it is thinnest in the Al Mukallā area, (calculated, 500 m) thickening west and northwest and also eastward to the zone of deeper subsidence and facies of the Mahra Group.

W.A.P.-E.A.P. border	Jabal Billūm area	Al Mukallā area	Age
Tawilah Group (clastics, no limestone tongues present)	Mukalla and Harshiyat Formations (Rays member still persistent)	Mukalla Formation Lusb Member Mukalla Formation	Senonian (probably Campanian and Maestrichtian
		Sufla Member Harshiyat Formation Rays Member Harshiyat Formation	Cenomanian, Turonian(?), and Albian
	Qishn Formation	Qishn Formation	Aptian and Barremian
Unconformity			
Jurassic or basement			

The age of the Tawilah Group is Cretaceous by virtue of its occurrence between datable Late Jurassic and datable Paleocene. On the faunal evidence present in the limestone and in some shale tongues, it is Berremian to Maestrichtian in age. This age most probably applies even to the westernmost part where no fauna has been found.

QISHN FORMATION

The Qishn Formation is the lowest formation of both the Tawilah and Mahra Groups. It varies laterally between the two provinces, being considerably thinner in the Western Province, with some clastics in its lower part.

The type section is at Ra's Sharwayn in Al Mahrah near Qishn (Eastern Province), where the formation consists primarily of limestone and some marl, and is more than 400 m thick. Westward into Ḩaḑramawt toward the shoreline, the upper thick-bedded limestone part with its characteristic fauna persists, although it is much thinner and is partly clastic.

The reference section for the Qishn of the Tawilah Group is at Jabal ar Rays near Al Mukallā. This section is the most typical for the formation in that province where the succession is 32 m thick. It consists of a basal conglomeratic shelly sandstone with bands of oolitic fossiliferous limestone overlain by an interval of marl, commonly shaly, and bands of sandy limestone; this interval is capped by about 17 m of massive to well-bedded limestone, in some places rubbly and other places recrystallized, that contains *Orbitolina* cf. *O. discoidea* (Gras) Henson and *Choffatella decipiens* Schlum, which indicate a Barremian and Aptian age.

In the Al Mukallā area the formation rests unconformably on peneplaned igneous basement, but farther west it rests unconformably on Upper Jurassic, generally without evident angularity. The upper contact is with the Harshiyat Formation and is apparently conformable. Near the E.A.P.-W.A.P. border the Qishn has either pinched out or passed laterally completely into clastics. In the intervening area between Al Mukallā and the western border, the formation is locally absent in some areas (Jabal Shaqb, Wādī Raymah, some 6 km respectively south and southwest of Jabal Shabb) probably as a result of persistent local uplift into Aptian times.

At Jabal Ghubār (near Burūm) 63 m mainly of sandstone and gypsiferous marls and siltstone and some conglomeratic layers is capped by the fossiliferous limestone carrying Orbitolinas. In this upper limestone at the Ath Thil'ah as Suflá (Tilla Sufla) section near Al Mukallā (Little, 1925; R. W. Wetzel and D. M. Morton, unpub. data, 1948–50), in addition to the Foraminifera, *Heteraster oblongus* has also been found (Wetzel and Morton, unpub. data, 1948–50; K. Joysey, unpub. data, 1948–60). At Al Minṭāq, the basal generally clastic part contains the charophytre *Clavator* sp., and at various other sections in the limestone part *Permocalulus inopinatus* and *Cylindroporella* sp. have been found (E. K. Elliott, unpub. data, 1955–59). The base is invariably marked by a thick conglomerate or sandstone with some pebbles generally locally derived from the underlying Jurassic or basement; this marks the advent of the Cretaceous sea. In the Jabal Billūm section, however, the Jurassic Qishn contact is marked by a sandy dolomitic limestone overlain by some marly limestone containing *Neiea atava* (Romer) and *Pholadomya* cf. *collumbi* Coquand (F. Gosling, unpub. data, 1956).

The Qishn may overlie various zones of Jurassic for very short lateral distances and illustrates the effect of terminal Jurassic movements followed by planation prior to the Cretaceous transgression.

HARSHIYAT FORMATION

The Harshiyat Formation is well exposed in most Cretaceous sections of Ḥaḍramawt and consists predominantly of a sequence of clastics, mainly sandstones with current bedding and conglomerate zones; interbedded marl, siltstone, and some shale form distinct intervals at various levels, and plant remains have been found in these. Present within this sequence of clastics are two well-defined limestone or dolomitic limestone intervals; the lower occurs within the lower sequence of clastics and forms the Rays Member, and the upper caps the upper sequence of clastics and forms the Sufla Member. Where these two limestone tongues persist, they are readily recognized, and the Sufla Member enables a boundary to be placed between the Harshiyat and the overlying and lithologically similar Mukalla Formation. However, some 50 km westward and southwestward from the Al Mukallā area, the Sufla Member pinches out and the Harshiyat and Mukalla Formations are no longer separable. The Rays Member persists for 20 or 30 km more to the west beyond this area before it too pinches out, and the whole succession of Harshiyat Formation becomes indistinguishable from the overlying Mukalla Formation. Eastward from Al Mukallā the Rays Member probably pinches out, but the Harshiyat Formation in its clastic facies continues into Al Mahrah, gradually changing character and passing laterally in its upper part into the limestone and marl facies forming the Fartaq Formation. In the Ra's Fartak area, it all has passed laterally into this limestone and marl facies, and the entire Harshiyat is there replaced by the Fartaq Formation.

The formation is best developed in the Al Mukallā area where it also appears to be thickest, being 295–315 m thick. To the west of Al Mukallā, the thickness is in the order of 200 m but this may be partly due to local faulting out, though depositional thinning as a result of probable persistent local uplift into the Albian may have also taken place. Abrupt lateral variation within the clastics occurs, so lateral correlation of marl or shale intervals is not possible.

The faunal assemblage found in the Sufla Member shows that the upper part of the Harshiyat is of Cenomanian age; the lower part rests conformably on the Barremian and Aptain Qishn Formation, and is thus considered to be Albian in age. The base of the Sufla Member in one section (Ath Thil'ah as Suflá) is glauconitic and may mark a local disconformity.[4]

Rays Member.—The Rays Member consists of gray to brown, bedded to semimassive, coarsely recrystallized, partly dolomitic, ferruginous limestone that weathers reddish brown and attains a maximum measured thickness of 9 m in its type section at Jabal ar Rays near Al Mukallā. Owing to recrystallization, no

[4] There appears to be some relation between concentrations of glauconite and stratigraphic breaks, but opinions vary on this.

recognizable fauna has been preserved other than possible crinoid fragments. The Rays Member thins westward and pinches out some 80 or 90 km west of Al Mukallā. Southwest from Al Mukallā it becomes very thin and sandy. At Jabal Shaqb and in Wādī Raymah it almost directly overlies peneplaned basement, separated from the latter by a thin sandstone layer or a conglomerate. This suggests the persistence of local highs in these localities up to and including the earlier part of the period of deposition of the Harshiyat Formation. Occurrence of the Rays above the base of the Harshiyat is variable and probably was dependent on the influence of such local highs preceding or continuing into Harshiyat deposition. At Ath Thil'ah as Suflá (near Al Mukallā) there is no trace of the Rays Member and it may have either laterally passed into a marl sequence or been faulted out.

Sufla Member.—The Sufla Member is marine limestone tongue occurring at the top of a clastic sequence, and is gray, crystalline, in part fine grained and in part coarse grained, massive, and generally abundantly fossiliferous. Its maximum thickness of 16 m occurs at the Ath Thil' ah as Suflá section near Al Mukallā where it contains the following fauna (unpub. data from the following: R. G. S. Hudson, 1948–56, L. R. Cox, 1949–56, M. Chatton, 1948–59, and K. Joysey, 1948–60): *Exogyra olisiponensis* Sharpe, *E. flabellata* Collignon, *Coenholectypus* cf. *C. larteti* Cotteau, *Holectypus larteti* Cotteau, and *Orbitolina* cf. *O. concava* (Lamark); this fauna indicates a Cenomanian age. The base at this section is slightly glauconitic. It thins and then tongues out westward, first becoming sandy and dolomitized in that direction. Eastward from Al Mukallā, it may persist and thicken into the Al Mahrah Province to form part of the Fartaq Formation.

MUKALLA FORMATION

The Mukalla Formation consists of a clastic sequence primarily of colored, friable, and current-bedded sandstone, with pebbly zones and subordinate marls and siltstones. At Ath Thil'ah as Suflá, a thin fossiliferous limestone bed capping a sequence of marls occurs with the clastics and forms the Lusb Member.

The formation is widespread in its occurrence in Ḫaḏramawt and can be seen wherever the Tertiary cover has been eroded. It persists eastward into Al Mahrah in much the same facies and also extends into Dhufar. In Ḫaḏramawt, it overlies the Harshiyat Formation apparently conformably. Where the Sufla Member of the Harshiyat is present, the division between the two formations is at the top of the Sufla; there is no indication of a break. Where the Sufla Member is absent, the Harshiyat and Mukalla Formations merge as one continuous sequence of clastics without possible division; this applies especially to the westernmost part of Ḫaḏramawt. Thus, the age of the Mukalla Formation in Ḫaḏramawt has to be assumed. Fossils from the Lusb Member (which in itself has only been found in the Ath Thil'ah as Suflá section) indicate that the formation is partly Campanian in age. On the basis of correlation with Al Mahrah, the formation there is considred post Turonian, that is, Senonian.

The upper part of the formation is also a sequence of clastics and appears to be conformable with the overlying Paleocene formation. On faunal evidence, however, the upper contact is disconformable. In one section at the top, a small remnant of datable Maestrichtian in a clastic facies with thin carbonate beds has been found underlying datable Paleocene without visible field evidence of a break (Jabal Ḏubbah and Jabal Shabb); and in one other section, derived and reworked Maestrichtian fauna have been found in the basal meter or so of the Paleocene strata (Ra's Muwaysah) (p. H31).

The uppermost part of the Mukalla Formation in Ḫaḏramawt is therefore, in some sections, Maestrichtian in age. It would appear that the limestone Sharwain Formation of Maestrichtian age found in eastern Al Mahrah passes westward through a limestone-marl facies and then laterally into Ḫaḏramawt as clastics, datable only in a few localities and reduced in thickness to a mere tongue. These Maestrichtian clastics form a continuous sequence with the Mukalla Formation of Ḫaḏramawt, and most probably are either partly or completely eroded farther west in Ḫaḏramawt or have pinched out.

Apart from the fauna in the Lusb Member and the remnant of Maestrichtian fauna in the topmost part of the Mukalla in a few localities, the rest of the formation has so far proved unfossiliferous. The top is taken at the contact of the highest clastics (with or without thin bands of limestone or dolomite) and at the base of the papery shale (with or without thin bands of limestone) (p. H34) (M. Chatton, unpub. data, 1948–59). The shales and thin limestone commonly contain a good Paleocene faunal assemblage. If the shale is absent, the contact is taken at the base of the datable Paleocene limestone immediately overlying the Mukalla clastic sequence.

The Mukalla Formation in the Al Mukallā area is 165 m thick at Jabal ar Rays; it thickens westward at Jabal Shabb to 271 m. Westward from the latter area, it is not divisible from the underlying Harshiyat (p. H26). Exposures to the north do not permit accurate estimates of thickness, but is appears that some thickening occurs in that direction also.

Lusb Member.—The Lusb Member is a very local member found only at Ath Thil'ah as Suflá (near Al Mukallā). It is approximately 50 m thick, the top 5 m consisting of nodular reddish-brown-weathering limestone containing *Liostrea thompsoni Peron*, *?Gryphea vesiscularis*, *?Penopea*, and *Hantkania sp.* (unpub. data from the following: Chatton, 1948–59; L. R. Cox, 1949–56; and R. G. S. Hudson, 1948–56). These indicate a Campanian (Senonian) age. The limestone is underlain by 45 m of yellow, green, and ocherous gypsiferous marls and obscure bands of marly limestone (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). To the west the limestone cap pinches out and the underlying marls probably pass into clastics and are not distinguishable.

MAHRA GROUP

The Mahra Group comprises the formations of Cretaceous age in a primarily limestone and marl facies exposed in Al Mahrah (Eastern) Province of the E.A.P.

The group varies in lithology from sandstone in the west to a predominantly carbonate succession in the east; it also thickens to the east. The age of the group is Barremian to Maestrichtian, based on comprehensive faunal evidence. The following table shows the facies.

Mahra Group (Barremian to Maestrichtian)

From west to east				
Al Masīlah area		Ra's Sharwayn area	Ra's Fartak area	Age
Sharwain Formation		Sharwain Formation	Sharwain Formation	Maestrichtain
Mukalla Formation		Mukalla Formation	Mukalla Formation	Senonian
Fartaq Formation (Turonian(?) and Cenomanian)	Maqrat Member Tihayr Member Dha Sohis Member	Absent	Fortaq Formation	Turonian(?) and Cenomanian to Albian
Harshiyat Formation (Cenomanian(?) to Albian)		-Unconformity-		
Qishn Formation		Qishn Formation	Qishn Formation, part exposed	Aptian and Barremian
Unconformity		Disconformity	Not exposed	
		Jurassic		

QISHN FORMATION

The Qishn Formation has been examined in Al Mahrah at Ra's Sharwayn (type section) and Al Masīlah where it is well exposed, and has been seen at Ra's Fartak where only 15 m of it is exposed (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50; Beydoun, 1964).

At Ra's Sharwayn the formation is 411 m thick and consists almost entirely of limestone with marl zones and bands, alternating in the upper half with rubbly marly limestone and some shale stringers. The limestone is partly shaly, partly oolitic, and partly shelly, and it locally contains chert nodules. The base of the whole succession is marked by some 5 m of brecciated limestone—taken as evidence of unconformity (M. Chatton, unpub. data, 1948–59; Beydoun, 1960)—resting on a sequence of limestone which though it is without diagnostic fossils, probably represents the uppermost part of the Jurassic (p. H22). The Qishn is fossiliferous, and contains *Choffatella decipiens* Schlumberger in its lower part down to the top of the basal brecciated limestone. *Orbitolina* cf *Odiscoidea* (Gras) Henson occurs in the upper part together with *Diplopodia hermonensis* de Loriol, *Toxaster dieneri* de Loriol, *Coenholectypus portentoneus*, and *Neithea* cf *Nsiriaca* Conrad (unpub. data, from the following: Chatton, 1948–59; K. Joysey, 1948–60; and L. R. Cox, 1949–56). Some oysters and rare corals occur at various levels. On this faunal evidence, the age is Barremian and Aptian. In this typical section, the formation is overlain unconformably by the Mukalla Formation of Senonian age, the middle Cretaceous being entirely absent, most probably owing to local emergence at the end of the Aptian or during Albian time.

In Al Masīlah, a succession of strata totaling 498 m is attributed by the author to the Qishn Formation; the basal 99 m contains nondiagnostic fauna and consists mainly of limestone and marly limestone, with several sandstone, marl, and shale zones in the lower part. The base of the interval is marked by a thin conglomerate and sandstone. This conglomerate overlies sandy Upper Jurassic beds (p. H22). (The advent of sandy limestone in the underlying beds is believed indicative of Late Jurassic shallowing and probable emergence.) The basal conglomerate would thus indicate the Jurassic-Cretaceous uncomformity, and the start of the Cretaceous transgression as seen clearly in Ḩaḑramawt (p. H26).

The succession above the basal 99 m can be divided into 189 m of marly limestone and limestone with two main shale intervals, beneath 210 m of alternating shale and marl and marly limestone. The lower part contains the lowest indication of Barremian age with the lowest occurence of *Choffatella decipiens* Schlumberger from the base, together with *Dictyoconus arabicus* and *Cheloniceras martini* (d'Orb.) higher up (Chatton, unpub. data, 1948–59; L. F. Spath, unpub. data, 1955–57). A 2-m-thick gypsum bed capping a shale interval occurs 76 m from the base. The upper part contains *Orbitolina* cf. *O. discoidea* (Gras) Henson and *Cheloniceras* aff. *cornuelianus* (Chatton, unpub. data, 1948–59; Spath, unpub. data, 1955–57); the base of this part is disturbed and this may mark a break between the Barremian and

Aptian. The top is overlain apparently conformably by the basal shale of the Harshiyat Formation.

HARSHIYAT FORMATION

The Harshiyat Formation in Al Mahrah is known only from the Al Masīlah area, being absent to the east owing to erosion (Ra's Sharwayn) or facies change (Ra's Fartak). In a section near Ṭihayr, 196 m of colored basal shale, partly marly and with bands of marl, containing *Orbitolina* cf. *O. discoidea* (Gras) Henson and *Knemisseras* cf. *K. attenuatum* Hyatt at the base, is succeeded by current-bedded colored sandstone, with marl and shale zones, that alternates with shale and shaly marl containing sandstone bands; fauna includes *Exogyra* sp., *echinoids*, *Orbitolina* cf. *O. concava* (Lamarck), and *pelecypods* (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). On the basis of this faunal evidence, an Albian to probable Cenomanian age is indicated. The contact with the underlying Qishn is conformable and the lithology shows a regressional phase. The overlying formation is the Fartaq Formation; the base of the Fartaq is here represented by the Cenomanian Dha Sohis Member, and the junction is apparently conformable.

A lateral passage of Harshiyat occurs from west to east, clastics as represented by the Sufla Member of the formation in Ḥaḍramawt (Tawilah Group) gradually being replaced by a limestone and marl succession to the east into Al Mahrah. At Al Masīlah this lateral passage is only half completed; at Ra's Fartak farther east the change is completed with the full development of the Fartaq Formation.

FARTAQ FORMATION

The Fartaq Formation overlies the Harshiyat in the western part of Al Mahrah (Al Masīlah) and the Qishn in the eastern part (Ra's Fartak). It is mainly a limestone-marl lateral equivalent of the Harshiyat Formation of Ḥaḍramawt, as illustrated by the following table.

Ḥaḍramawt (Western Province)	Al Mahrah (Eastern Province)	
Al Mukallā area	Al Masīlah	Ra's Fartak
Harshiyat Formation (Cenomanian to Albian)	Fartaq Formation (Probable Turonian and Cenomanian) Harshiyat Formation (Cenomanian and Albian)	Fartaq Formation (Probable Turonian to Albian)
Quishn Formation	Quishn Formation	Quishn Formation

The type section at Ra's Fartaq is 510 m thick (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50; Beydoun, 1960, 1964). The succession starts with a basal 6 m of shale with marly limestone bands and contains the *Knemiceras* aff. *K. attenuatum*– *K. compressum* group, *Toxaster dieneri* de Loriol, *Coenholectypus portentosus* Cotteau, and *Trochodiadema libanotica* de Loriol (L. F. Spath, unpub. data, 1955–57; K. Joysey, unpub. data, 1948–60). Contact with the underlying Qishn is conformable and is based on the slight change of facies from the deeper water Qishn to the shallower water Fartaq (M. Chatton unpub. data, 1948–59); the change is not easily observable in the field. Above the basal shale is 184 m of partly marly crystalline limestone, with some bands of marl; oolitic and silty layers occur. This sequence is fossiliferous, containing *Coenholectypus portentosus* Cotteau, *Diplopoda hermonensis* de Loriol, *Orthopsis* cf. *O. granularis* Cotteau, *Polyconites verneuili* Bayle, and *Orbitolina* cf. *O. discoidea* (Gras) Henson, passing upward into *Orbitolina* cf. *O. concava* (Lamarck) (Joysey, unpub. data, 1948–60; Chatton, unpub. data, 1948–59). The remainder of the succession, some 320 m thick, consists of two-thirds limestone and one-third marl in alterating intervals; the limestone contains marly bands and some shale streaks, and the marl contains marly limestone bands and is in part gypsiferous. The entire sequence is fossiliferous. *Praealveolina cretacea* (d'Archiac) appears fairly low down and persists to the top (Chatton, unpub. data, 1948–59). Among other fauna present are the following: *Eoradiolites liratus* Conrad, *Neithea* cf. *N. subatanus* Blankenhorn, *Exogyra flabellata* Goldfuss, *E. matherouiana*, *Coenholectypus serialis* Deshayes, *C.* cf. *C. excicus* Cotteau, *C. ? larteti*, *Heterodiadema libycum* (Desor), *Diplopodia variolare* Brongniart, *Hemiaster fournali* Desor, and *H. cubicus* (unpub. data from the following: R. G. S. Hudson, 1948–56; Joysey, 1948–60; and Chatton, 1948–59).

The faunal assemblage of the whole formation gives it an age range of Albian and Cenomanian to probable Turonian. The formation is apparently conformably overlain by the Mukalla Formation, but a disconformable contact is possible.

In the Al Masīlah area the formation is much thinner in occurrence and is equivalent only to the upper part of the Fartaq Formation of Ra's Fartak (p. H_m). The total thickness here is about 209 m, divisible into three distinct units which have been given member status as they are not recognizable individually farther east. Together these make up the Fartaq Formation of Al Masīlah. Their total age range on the basis of faunal evidence is Cenomanian to probable Turonian. From base to top, they are the Dha Sohis, Tihayr, and Maqrat Members.

Dha Sohis Member.—The Dha Sohis Member is some 40–48 m thick and consists of a lower marly, rubbly limestone, and thin shale, a middle shale unit, rather gypsiferous and capped by glauconitic marl, and an upper marly limestone unit with chert nodules at the top (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). A Cenomanian age is based on the presence of *Orbitolina* cf. *concava* (Lamarck), pelecypods, corals, and echinoids, including *Toxaster dieneri* de Loriol (Joysey, unpub. data, 1948–60). The member varies laterally, and near Maqrat in the Al Masīlah area it is composed entirely of a rather massive limestone of reef facies, containing rudists as well as *O.* cf. *O. concava* and other forms. The Dha Sohis overlies the Harshiyat Formation apparently conformably though the contact is somewhat obscured. It is believed to be equivalent to the Sufla Member of the Harshiyat Formation of Ḥaḍramawt (Tawilah Group).

Tihayr Member.—The Tihayr Member is about 70 m thick and consists primarily of a series of green and purple shales, in part gypsiferous, and containing some bands of marly limestone and an interval of colored sandstone near the top (Wetzel and Morton, unpub. data, 1948–50). *Exogyra flabellata* Goldfuss, *Heterodiadema libycum*, *Coenholectypus serialis*, and *Echinocorys* sp. (Hudson, unpub. data, 1948–56; Joysey, unpub. data, 1948–60) indicate a Cenomanian to possible Turonian age. It overlies the Dha Sohis Member conformably.

Maqrat Member.—The Maqrat Member conformably overlies the Tihayr Member and is apparently conformably overlain by the Mukalla Formation. It is about 100 m thick and consists of a limestone sequence; near the base this passes into dolomitic limestone, and in the upper part it becomes coarse, containing thin streaks of marl (Wetzel and Morton, unpub. data, 1948–50). Foraminifera and other fossils are present but are generally recrystallized. *Pyrina* cf. *P. petracoriensis* (Chatton, unpub. data, 1948–59) occurs at the base, and other fauna include *Praealveolina* sp., rudists, gastropods, and pelecypods. The age range of Cenomanian and probable Turonian is indicated from the above faunal assemblage.

Mukalla Formation

The Mukalla Formation is common to both the Tawilah and Mahra Groups of Ḥaḍramawt and Al Mahrah respectively; it is the only formation that persists in the two provinces without any real change in lithological character. The formation has already been adequately described (p. H27–H28) and it is sufficient here to merely outline some facts about its character in the Eastern (Al Mahrah) Province as part of the Mahra Group.

At Ra's Fartak the formation is 142 m thick, and apparently conformably overlies the Fartaq Formation there, though the contact is somewhat obscure. It consists of sandstone with bands of shale, silty marl, and siltstone, and sparse thin bands of fossiliferous limestone (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). At Ra's Sharwayn, it is only 96 m thick and unconformably overlies the Qishn Formation. It consists of a sequence of sandstone and some shale bands. At Al Masīlah, it is 112 m thick and again consists of sandstone with some marly layers and siltstone, and apparently conformably overlies the Maqrat Member of the Fartaq Formation (Wetzel and Morton, unpub. data, 1948–50; Beydoun, 1960). In all three section areas it is conformably overlain by the Maestrichtian Sharwain Formation.

The age of the Mukalla Formation is taken to be Senonian, though no diagnostic fauna has been found in it. However, by virtue of its occurrence between Cenomanian to probable Turonian, and Maestrichtian, a general Senonian age is indicated.

Sharwain Formation

The Sharwain Formation is the top formation of the Mahra Group and has been examined in three localities in Al Mahrah (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). It shows a passage westward from a limestone sequence, through a marl and limestone sequence, to a marl sequence. The type section is at Ra's Sharwayn.

In the east at Ra's Fartak a 48-m sequence of a slightly marly crystalline limestone with rudists in the lower part overlies the Mukalla Formation conformably and represents the Sharwain Formation of this area (Wetzel and Morton, unpub. data, 1948–50; M. Chatton, unpub. data, 1948–59; Beydoun, 1960, 1964). It is conformably overlain by a thick sequence of bedded to massive saccharoidal limestones of datable Paleocene age which belong to the Umm er Radhuma Formation. The Maestrichtian transgression in the Ra's Fartak area was continued in the Paleocene transgression without a noticeable regressional phase as found to the west.

At Ra's Sharwayn 66 m of Sharwain Formation is present. The sequence begins with a 26-m-thick succession of marl containing harder calcareous concretions and capped by shale; *Lepidorbitoides minor* (Schlumberger) and *Loftusia persica* Brady occur throughout (Chatton, unpub. data, 1948–59). Then comes a 13.5-m-thick succession of marl, calcareous and hard in the basal part, and containing *Lepidorbitoides socialis*

(Leymerie) and *Loftusia morgani* Douville (Chatton, unpub. data, 1948–59). The upper 26.5 m consists of limestone, marly at the base and crystalline upward, and containing *Omphalocyclus macroporus* (Lamarck), loftusias, and rudists (Chatton, unpub. data, 1948–59). The faunal assemblage indicates a Maestrichtian age. The succession is overlain by gray-white marl which is glauconitic at the base and was considered by Chatton to belong to the base of the Umm er Radhuma Formation.

At Al Masīlah the formation is represented by 30 m of marl with harder calcareous bands, shaly to gypsiferous in places, overlain by 5 m of shelly limestone. Loftusias are common throughout, and the contact with the underlying Mukalla Formation is apparently conformable and somewhat gradational upward from sandstone through sandy marl to the marl of the Sharwain. The contact with the overlying Umm er Radhuma is also apparently conformable. However, on consideration of the westward thinning in the Sharwain Formation in Al Mahrah and its passage into thin clastics in Ḩaḑramawt, the contact is probably disconformable, marking a slight break between the Maestrichtian and Paleocene transgressions.

In Ḩaḑramawt near Ash Shiḩr the clastics of the Mukalla Formation are overlain by approximately 4 m of fine clastics and a thin limestone bed containing *Omphalocyclus macroporus Glyphostomella* sp. and *Gyrodina*, directly overlain by datable Paleocene of the Umm er Radhuma (Chatton, unpub. data, 1948–59). Farther west at Jabal Shabb, west of Al Mukallā, the unfossiliferous clastics of the Mukalla Formation are capped by 5 m of additional clastics, mainly siltstone and shale with some marl, which contain *Haplophragmoides* sp. 4. These beds are overlain by 7 m of unfossiliferous argillaceous and dolomitic limestone and shale, which in turn is overlain by 3 m of dolomite, shale, clay, and glauconitic sandstone that contains *Omphalocyclus macroporus* (Lamarck), *Fissoelphidium operculiferum* (Smout), *Loftusia* sp., and rare *Rotalia* cf. *R. trochidiformis* (Lamarck). Datable Paleocene occurs 2 m above (Chatton, unpub. data, 1948–59). Thus, in this section, datable Maestrichitian in a clastic facies with carbonate bands totals some 15 m. At Ra's Muwaysah, a few kilometers to the south, reworked Maestrichtian fauna has been found at the contact of the Mukalla and the Umm er Radhuma (Paleocene) Formations, associated with the Paleocene fauna of the latter. In none of the many other Cretaceous-Paleocene contact sections examined in Ḩaḑramawt has any Maestrichtian fauna been found. The Sharwain Formation in Ḩaḑramawt is thus represented by a much restricted and reduced clastic sequence present only in the eastern part of coastal Ḩaḑramawt, and also is partly eroded; it was either never deposited or completely eroded away farther to the west.

DHUFAR

As a result of unpublished work by R. W. Wetzel and D. M. Morton in 1948–50 and visits to some Dhufar sections by the author (by courtesy of the Dhofar Cities Service Petroleum Corp.), a composite stratigraphic column of Cretaceous sedimentary rocks has been reconstructed from the scattered sections examined. From this it is seen that progressively younger Cretaceous rocks rest directly and unconformably on pre-Cretaceous beds from west to east, the progression indicating that a land surface existed which was first submerged in the west (Early Cretaceous times) and only later submerged in the east (Late Cretaceous times). The pre-Cretaceous land surface in the west at Al Ḩawţah and 'Ayn Sārit exposes peneplaned and folded Lower Paleozoic(?) and basement sedimentary rocks (?) (p. H12). Resting on this surface are mainly clastic Lower Cretaceous rocks (part Jurassic at the base). Near Mirbāt to the east, Murbat Formation clastics of probable Ordovician age (p. H13) discordantly underlie Lower(?) but most probably middle Cretaceous beds. The Murbat Formation wedges out eastward, and at Ra's Naws in the east, facing the Kuria Muria Islands, the old surface consists of peneplaned (granite) basement overlain by Upper Cretaceous sedimentary rocks.

The facies of Cretaceous sedimentary rocks in Dhufar appears similar to that of the Al Masīlah area of the Al Mahrah Province (E.A.P.), and the Cretaceous formations of Dhufar could thus be included in the Mahra Group. A Qishn Formation at the base is recognized, consisting of a marly sequence followed by limestone containing *Choffatella decipiens* and *Orbitolina* cf. *O. discoidea* (Barremian-Aptian). A Harshiyat Formation is also recognized. This rests on Murbat Formation in the Mirbāţ area, and consists of a lower clastic sequence of shale overlain by sandstone and terminating with marl containing *Orbitolina* cf. *O. concava* (Albian-Cenomanian). A reduced Fartaq Formation is recognized overlying the Harshiyat type marl and consisting of limestone with *Praealveolina cretacea* in its upper part (Cenomanian-probable Turonian). In some sections (mainly in the western part) the Fartaq Formation equivalent is overlain by limestone of Late Cretaceous age containing *Pseudotextularia* sp.; the limestone appears to be comformable over the Fartaq equivalent, though in some places an unconformity is reported and the limestone is reduced in thickness and contains Maestrichtian fossils. This limestone appears to represent an entirely carbonate Upper Cretaceous facies, unknown in the E.A.P. and apparently restricted to the western part of Dhufar. Finally, in the east (facing west of the Kuria Muria Islands) a thin limestone tongue containing Late Cretaceous (Senonian) fauna rests on a very thin Murbat (or basement) Formation(?) and is overlain conformably by a sequence of clastics. The clastics with their basal limestone tongue are the Mukalla Formation equivalent for Dhufar. Over these are Tertiary beds.

REGIONAL CORRELATION OF THE CRETACEOUS

Plate 5 shows the main correlations of Cretaceous units with neighboring countries.

In Socotra Island (administratively part of the E.A.P.) only part of the Cretaceous is present. Original geological work on Socotra and Samḫah (Semha) Island was done by Kossmat (1907). More recently, the present author made a geological reconnaissance on Socotra Island (1953–59); micropaleontological examination of the author's samples was done by A. H. Smout (unpub. data, 1953–59). As a result, a revision of the Cretaceous stratigraphic stages as indicated by Kossmat has been made and shows that only Albian and Turonian strata were deposited on Socotra and that these belong to the Al Masīlah area facies.

A basal clastic formation thinning from east to west consists of sandstone and marl and limestone beds that contain *Radiolites*, *Caprinidae*, *Modiola*, *Ostrea*, and *Orbitolina discoidea* var. *discoidea* (Smout, unpub. data, 1953–59); all occur mainly in the upper part. This is regarded as a Harshiyat Formation equivalent some 100 m thick, and it rests on peneplaned igneous basement (mainly granite). Its age would be Albian and Cenomanian. Overlying this formation conformably is a sequence of limestones, rudistic in the lower part, marly with interbedded marl and some sandstone at the base of the middle, and chalky in the upper part. Fauna includes *Radiolites*, sparse *Hippurites*, *Caprina*, *Orbitolina discoidea* var. *discoidea*, *Ostrea flabellata*, *Exogyra decussata* Goldfuss, *Orthopsis miliaris*, *O. perlata* Noetl., *Pseudodiadema marticensa*, *Pholadomya vignesis*, *Terebratula semiglobosa* var. *albensis*, *Orbitolina* cf. *O. lenticularis*, *Pseudocyclammina*, *Textularia*, and *Praealveolina* sp. (Smouth, unpub. data, 1953–59; Kossmat, 1907), all of Cenomanian and Turonian affinities. This sequence represents the Fartaq Formation equivalent of the Mahra Group. The top of the succession is overlain unconformably, though without any visible break in the field, by datable Paleocene limestone.

In Somalia (Hunt and others, 1956; Macfadyen, 1933; Mason and Warden, 1956; Somaliland Oil Exploration Co., Ltd., 1954; Beydoun, 1964) the Cretaceous shows a change of facies from east to west as it does in the E.A.P. from Al Mahrah to Ḥaḍramawt, the main area of former British Somaliland being covered by clastics (equal to "Nubian Sandstone") similar to those of the Tawilah Group of Ḥaḍramawt, but a special shale-clay facies within the sandstone sequence (Nubian) occurs locally (for example, Shabel and Durato beds) (Macfadyen, 1933).

In Yemen, Lamare (Lamare and others, 1930; Lamare, 1936) described a continental series of sandstone with conglomerate from the Ṣan'ā' region which he called the Taouilah Series. He assigned it a Cretaceous age, probably Cenomanian in its upper part. During the latter part of the Cretaceous, volcanic activity on a large scale took place in Yemen and volcanics rather than sediments were deposited during that time (trap series) (Lamare and others, 1930; Lamare, 1936; Geukens, 1960).

Geukens (1960) subdivided Lamare's Taouilah Series sandstone into a lower "Nubian" facies (continental to lagoonal in origin) which he called Taouilah Series and for which he retained the Cretaceous age; the upper series he called the Medj-Zir Series, this being a neritic succession containing marine fauna, on the basis of which a Paleocene or Eocene age is indicated. The Taouilah Series (Geukens, 1960) correlates with the Tawilah Group of the E.A.P. and W.A.P.

Correlation with Saudi Arabia is much more difficult, but on a total age range the Tawilah and Mahra Groups of the E.A.P. probably correspond to the Biyadh, Wasia, and Aruma Formations of Saudi Arabia (Steineke and others, 1958), though breaks between these formations are represented by continued sedimentation in the E.A.P. The Yamama and Buwaib Formations of Saudi Arabia are not represented in the E.A.P. and the Hauterivian (and at least part of the Berriasian) are missing at the Jurassic-Cretaceous unconformity in the E.A.P.

ECONOMIC ASPECTS

Little (1925) reported on the lignite occurrences in the Al Mukallā area. These are toward the top of the Mukalla Formation and, though fairly persistent and of good quality, are not of commercial value owing to the extreme difficulty of exploiting them. Little also reported on some limited occurrences of bauxite, which are also noncommercial.

Cretaceous sandstones of the Tawilah Group offer some good reservoirs for hydrocarbon accumulations that migrate from older rocks, but caprock is somewhat limited and deep erosion exposes much of these beds. No hydrocarbon indications are known from beds of the Tawilah Group. The formations of the Mahra Group in the carbonate facies may offer suitable conditions for the generation and accumulation of hydrocarbons, but it is not known how far inland this facies extends away from the broken coastal part.

The Cretaceous Tawilah Group formations generally are good aquifers, being reservoirs for all runoff in the rugged and faulted coastal part, particularly where the overlying Paleocene is badly broken. In the unfaulted north where the Cretaceous clastics are reached in drilling, and particularly in the west, regional water accumulations of good potability are found. This is particularly true in the Al' Abr-Zamakh-Minwakh area and in the northern plains.

CENOZOIC ERA

TERTIARY SYSTEM

Tertiary deposits are widespread in south Arabia and cover the greater part of the E.A.P. and Dhufar. Where erosion and faulting has cut through them to expose older rocks in the E.A.P., particularly in the south, the Tertiary beds have often been preserved in down-faulted blocks together with the older rocks.

The Tertiary Period commenced with the strongly transgressive Paleocene, so by the end of the Paleocene, mainly carbonate deposits were spread over the greater part of south Arabia (E.A.P., Dhufar, Oman), the Persian Gulf region, the Horn of Africa, and the island of Socotra. In most of the W.A.P. and Yemen, this period was primarily marked by large-scale volcanic activity. Marine Eocene deposits were then laid down over the Paleocene in the entire region (except Yemen and W.A.P.), to be followed by emergence in the upper Eocene.

During the Oligocene and Miocene in the E.A.P. and Dhufar, marine sediments were deposited over much smaller areas, mainly in coastal embayments in which they are still preserved.

The rest of the Tertiary Period involved no further major marine sedimentation; post-Miocene deposits consist of coastal beach terraces and reefs, river terraces, eolian and fluviatile deposits, and renewal of volcanic activity in the E.A.P., and W.A.P., which persisted into Recent times.

The Tertiary deposits of the E.A.P., and to a large extent of Dhufar, can be divided into three stages. The first stage brought about major marine deposition of a group of sediments that were primarily carbonate, but with evaporitic and clastic phases which are placed together under one group—the Hadhramut Group, divisible into several formations. The second stage is one of lesser marine deposition of a varied nature that occurred in embayments into an existing coastline, established as a result of general uplift. These heterogenous deposits have been grouped together as the Shihr Group, which, however, has not been divided into separate formations. In Dhufar, Oligocene and Miocene deposits, mainly chalky limestones, were also laid down near the present coast. During the third stage no noteworthy marine transgression occurred, and such marine sediments as were deposited are the results of oscillations in sea level over an established coastline. Accompanying eolian, fluviatile, and lacustrine deposition occurred over a land surface which was much the same as it is at the present time. Toward the close of the Tertiary Period, volcanic activity commenced in the coastal districts of the E.A.P. (and W.A.P.), and persisted till Recent times.

HADHRAMUT GROUP

The Hadramut Group includes all sedimentary strata of Tertiary age from the Paleocent to the middle Eocene, namely all deposits laid down after the end of the Maestrichtian (which generally involved a phase of regression and planation in the region (p. H30–H31) and before the upper Eocene emergence. The deposits are marine, in the main carbonate deposits, but they include shale, marl, and some evaporitic deposits of Eocene age.

The following table gives the formations of the Hadhramut Group. The appropriate ages given for each formation are those for the E.A.P. type and reference sections, but some transgressing of stages by formations occurs within and outside the E.A.P.

Emergence		Upper Eocene
Hadhramut Group	Habshiya Formation	Middle Eocene (Lutetian)
	Rus Formation	Lower Eocene
	Jeza' Formation	
	Umm er Radhuma Formation	Paleocene
	Disconformity	Planation
Cretaceous		

The Hadramut Group varies in overall thickness. Acurate estimates are not possible in most places because of the postmiddle Eocene unconformity and the general lack of exposure of the basal formations in an area of generally flat-lying rocks.

From measurements of individual formations in various parts of the territory, however, the thickest sections occur in the area of Al Masīlah and its tributaries in Al Mahrah, where all formations are well developed and preserved. This region marks the flanks and axial areas of a broad structural depression marked by the Ḩaḑramawt-Al Jiz' syncline. Thick but incomplete sections of the group crop out in the Ra's Fartak area in south Al Mahrah. The area appears to be more basinal. Thinning of the group appears to take place westward and northward from the coastal areas and from the synclinal area of the Ḩaḑramawt-Al Jiz' basin. This thinning and its relation to tectonic development are discussed later (p. H41).

UMM ER RADHUMA FORMATION

The Umm er Radhuma Formation is strongly transgressive in facies; it forms the basis of the Tertiary tableland of the E.A.P. and Dhufar and crops out in cliff faces wherever this tableland is deeply dissected or faulted.

The name Umm er Radhuma was first applied in Saudi Arabia where the type section for the formation occurs (Steineke and others, 1958). The age in Saudi Arabia is considered to be Paleocene and lower Eocene, and the thickness at the type section is about 230 m.

In the E.A.P. the Umm er Radhuma Formation consists mainly of limestone of Paleocene age, easily distinguishable from the overlying lower Eocene shale-limestone succession of the Jeza' Formation. However, in some parts of the territory, namely in southeast Al Mahrah (for example, Ra's Fartak and the Damqawt area) and in Dhufar, limestone sedimentation was continuous from Paleocene through early Eocene time, making it increasingly difficult in most places to divide the two formations; where they are indivisible the Umm er Radhuma includes Paleocene-lower Eocene.

The type reference section for the formation in the E.A.P. is at Say'ūn in Wādī Ḩaḑramawt where the formation was measured and sampled by R. W. Wetzel and D. M. Morton (unpub. data, 1948–50) and later by Beydoun and others (unpub. data, 1953–59). This section, which is typical of the formation in the E.A.P., shows the following characteristics from base to top: A basal dolomite some 1.5 to 2 m in thickness is overlain by (1) a 4-m basal interval consisting of (a) 2 m of ochre and gray papery shale containing scarce *Lockhartia* sp. and ostracodes followed by (b) 2 m of fine-grained nodular limestone containing the same fauna and also algae, (2) 9 m of marly limestones that are nodular weathering and exfoliating, become massive upward, and contain *Lockhartia haimei* Davies, *L. diversa* Smout, and *Daviesina khatiyahi* Smout (M. Chatton, unpub. data, 1948–59; A. H. Smout, unpub. data, 1953–59), and (3) a 43-m sequence of massive-weathering dark-brown and dark-gray limestone, fine to coarse grained, in parts marly, nodular in the upper part, and commonly containing calcite veins and chert vugs. Unit 3 is distinctive and in some sections it is very dolomitic and recrystallized, but regardless of this, it is invariably distinguished by its massiveness and dark color; it forms a distinctive cliff in the lower part of the formation. Fauna in this unit includes those already mentioned under unit 2, together with *Taberina daviesi* Henson, *Kathina selveri* Smout, *Valvulina triangularis* d'Orbigny, *Dictyoconus* sp., and shell debris. The rest of the type section consists of massive white and gray limestone, with dolomitic, chalky, calcarenitic, and shelly zones. It is nodular weathering and locally cavernous owing to scaly disintegration and exfoliation; scattered chert nodules occur. In the coastal districts the cavernous weathering is striking, accentuated by wind erosion and local slumping. The whole of this sequence is generally rich in microfauna which include: *Lockhartia conditi* (Nuttall), *L. tipperi* (Davies), *Sakesaria* cf. *S. cotteri* Davies, *Nonionella* cf. *N. jacksonensis* Cushman, *Globorotalia velascoensis* (Cushman), *Rotalia trochidiformis* (Lamarck), *Operculina sindensis* Davies, *O. patalensis* Davies, *O. salsa* Davies, *Assilina dandotica* Davies, *Aranikoti* Nuttall, *Nummulites wadiai* Davies, *N. thalicus* Davies, *N. globulus* Leymerie var. *indicus* Davies, *Furcoporella diplopora* Pia, and *Ovulites* sp. (unpub. data from the following: Chatton, 1948–59; Smout, 1953–59; and G. F. Elliott, 1955–59). On the basis of this faunal assemblage a Paleocene age is indicated.

In Ḩaḑramawt, the Umm er Radhuma Formation overlies Upper Cretaceous Mukalla Formation clastics. Although contact appears to be conformable in the field, it has proved on faunal consideration to be disconformable (p. H31).

The actual position of the contact between Paleocene Umm er Radhuma Formation and Upper Cretaceous Mukalla Formation in Ḩaḑramawt has been open to controversy. Some observers (Chatton, unpub. data, 1948–59) prefer to include in the Cretaceous the basal dolomite below the 4-m interval described in unit 1, and take it to be representative of Maestrichtian. They place the contact at the base of the overlying papery shales (base of unit 1), which often contain Paleocene Foraminifera. In some sections this shale is much thicker and may include thin limestone bands, or, as in the 'Amāqīn section, it may have sandstone layers above it, whereas in the other sections it is absent and limestone rests directly on clastics or on a thin dolomite. In such localities the base of the limestone is taken as the base of the Paleocene transgression and thus as the base of the Umm er Radhuma Formation. As this view seems to be supported in some places by faunal evidence, it is adopted here, although in the field differentiation between papery shale zones occurring at the top of the Mukalla Formation and those at the base of the Umm er Radhuma Formation is not easy. Neither is it easy to distinguish between thin dolomites and recrystallized limestones occurring in some sections in several bands over the critical contact zone. The papery shales at the top of the Mukalla Formation have been described by Chatton (unpub. data, 1948–59) from thin-section examination as deposits indicating a lagoonal to semievaporitic phase that marked a regressional period at the end of the Maestrichtian. On the other hand, the papery shales in the base of the Umm er Radhuma appear, on the basis of thin sections, to be transgressive deposits.

Variation in the thickness of the formation in the E.A.P. is associated with the growth and development of the biaxial Ḩaḑramawt arch and its Ḩaḑramawt-Al Jiz' syncline (pl. 6). The most marked thinning takes place, however, toward the line of the north axis of the biaxial arch, with the probable absence of basal Paleocene north of this line and the pinching out of the lower massive unit (described as unit 3) toward this line. All this suggests that the north axis may have been active as a barrier during early Paleocene time and later submerged in the middle Paleocene. (*Lacazina wichmanni* (Smout, unpub. data, 1953–59) is found at the base of the succession north of the axis.)

The Umm er Radhuma Formation is regarded as partly equivalent in age to the trap series of Yemen (Wissmann and others, 1942). In Ḩaḑramawt, it thins toward a Paleocene shoreline presumably somewhere in the W.A.P, and it thickens eastward into Al Mahrah; in the Ra's Fartak-Damqawt sector of eastern Al Mahrah and in Dhufar, the limestone facies continues upward well into lower Eocene, this part laterally replacing the Jeza' Formation.

Ra's Fartak is a good example of the upward extension of the limestone facies but is also a locality where a carbonate Jeza' Formation may still be recognized. Wetzel and Morton (unpub. data, 1948–50) measured 318 m of cliff-forming limestones and some dolomite cropping out massively, overlain by 177 m of limestone containing dolomite and scattered chert nodules and bands. These are overlain by marls of the Habshiya Formation of Lutetian age. Thus, between the top of the clastics of the Mukalla Formation and the marls of the Habshiya Formation is 495 m of continuous carbonate deposits. The sequence is on the whole fossiliferous, enabling age and formation divisions to be made within it. The basal 48 m represents the Sharwain Formation (p. H30). This unit differs from the overlying 154 m of massive yellow-white rather saccharoidal sequence of limestones that weathers brown and contains *Lockhartia condidi* Nuttal, *Daviensina khatiyahi* Smout, *Rotalia* sp., *Quinquiloculina* sp., and *Dictyoconus* sp. (Chatton, unpub. data, 1948–59). This assemblage gives the sequence a Paleocene age, and the succession represents the lower part of the Umm er Radhuma.

The rest of the massive cliff face, 116 m thick, is made up of much the same sequence of limestone but includes some dolomite and a basal marl bed in which the lowest occurrence of *Alveoline ovoidea* d'Orbigny is recorded together with *Sakesaria cotteri*. *Rotalia* sp. "A" occurs higher up with *Alveolina ovoidea* (Chatton, unpub. data, 1948–59; Wetzel and Morton, unpub. data, 1948–50). The assemblage indicates an early Eocene age but the succession still belongs to the Umm er Radhuma Formation. The top 177 m crops out on a gentler slope, the lower 86 m consisting of massive limestone and dolomitic limestone, with scattered chert nodules and *Alveolina ovoidea* d'Orbigny and *A. globosa* Leymerie (Chatton, unpub. data, 1948–59); the topmost 103 m consists of thin-bedded partly chalky limestone with thin shale partings and chert bands. The age of this 177-m sequence is early Eocene; the lower massive 86 m belong to the Umm er Radhuma Formation, whereas the upper thin-bedded 103 m represents the Jeza' Formation in a limestone facies (p. H36) (Beydoun, 1960, 1964). Thus, at Ra's Fartak is a continuous carbonate sequence ranging in age from Maestrichtian at the base through Paleocene to early Eocene.

JEZA' FORMATION

The Jeza' Formation is typically formed in western Al Mahrah and Ḩaḑramawt; there it overlies, and is easily distinguishable from, the Umm er Radhuma Formation and forms a typical mesalike landscape on top of the Umm er Radhuma tableland. It is not present in easternmost Al Mahrah or Dhufar.

The type section for the formation is in the Al Masīlah basin in western Al Mahrah. There in the Wādī Ḩibūn area, 133 m of Jeza' Formation consists of alternations of papery yellow and pink shale, some marl and thin bands of limestone, chalky to crystalline limestone (in places silicified and with bands of chert), and some bands of gypsum near the top. Fauna is abundant and includes dwarf echinoids, lamellibranchs, ostracodes, and the following Foraminifera: *Rotalia trochidiformis* Lamarck, *Lockhartia* cf. *L. cotteri* Davies and Pinfold, *Sakesaria tipperi* Davies, *S.* cf. *S. cotteri* Davies and Pinfold, *L. tipperi* Davies, *L.* aff. *L. haimei* Davies, *Nummulites* aff. *N. globulus* Leymar, var. *indicus* Davies, *Dictyoconus* aff. *D. indicus* Davies, and *Operculina* aff. *O. subsalsa* Davies (M. Chatton, unpub. data, 1948–59). The faunal assemblage indicates an early Eocene age.

The Jeza' overlies the Umm er Radhuma Formation conformably. In the southeastern sections of Al Mahrah, it is generally distinguished from the Umm er Radhuma by the appearance of marls (Ra's Sharwayn and Ra's ad Darjah), but where no marl is present (Ra's Fartak), only the thinner bedding and partly chalky facies of its limestone distinguish it from the Umm er Radhuma. At Damqawt and in Dhufar, however, these characteristics are lost, and there the Umm er Radhuma Formation includes the Jeza' Formation equivalent. The Jeza' is overlain in the type area and in western Al Mahrah and Ḩaḑramawt by the Rus Formation and the contact is conformable, in many sections also being gradational. Transition beds (included in the Rus for mapping) are present between the Jeza' and the Rus in several sections in north Ḩaḑramawt. In the Ra's Sharwayn-Ra's Fartak sector and somewhat northward from there, the Rus Formation is absent, and the Jeza' Formation (or equivalent) is overlain by the Habshiya Formation.

Although at the type section the Jeza' is of early Eocene age, the lower part of the formation may range in age to Paleocene. At Ra's Sharwayn Paleocene fossils are present in the basal few meters, and in northwest Ḩaḑramawt (Zamakh area) these forms persist for some way up.

Variations in thickness of the Jeza' Formation occur. The thickest sequence is probably in the southeast and in the Ḩaḑramawt-Al Jiz' synclinal area, with slight thinning westward and northward.

RUS FORMATION

The type locality for the Rus Formation is in Saudi Arabia (Steineke and others, 1958). In the E.A.P. the type reference section is in the Al Masīlah basin in western Al Mahrah. There in Wādī Ḩibūn a thickness of 138 m consists of bedded to massive gypsum and some bands of interbedded limestone that are chalky to gypsiferous or silicified in the lower part and gypsiferous chalk in the upper part; some marl and porous limestone bands as well as chert nodules also occur in this part. There are no fossils (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). The Rus Formation rests conformably on the Jeza' Formation, with slight gradation indicated by thin bands of gypsum in the top of the Jeza'; it is overlain conformably and also somewhat gradationally by the Habshiya Formation, gradation appearing with the advent of chalky beds in the top of the Rus.

The age of the formation, by virtue of its occurrence over datable lower Eocene Jeza' Formation and under middle Eocene Habshiya Formation, is considered to be early Eocene. The formation may, however, be somewhat diachronous over long distances (for example, it probably is in part Middle(?) Eocene in Dhufar).

The Rus Formation is developed over most of the E.A.P. except in the extreme southeast corner of Al Mahrah in the Ra's Fartak-Ra's Sharwayn area, where it was either never deposited or not developed as an evaporitic formation. This area probably remained well supplied by refreshing currents so that evaporitic conditions did not arise.

The Rus Formation appears best developed in the Wādī al Jiz' basin and in the eastern part of the Wādī Ḩaḑramawt basin where it is thickest. It is widespread over most of the Northern Plateau, but is preserved only in a local synclinal depression although in thick occurrences) on the eastern part of the Southern Plateau in Ḩaḑramawt and over most of the extension of the depression in Al Mahrah, as well as in the tectonic river valley of the Wādī Ḩajr basin and a part of Wādī Mayfa'ah. It crops out over a large area of northern Dhufar.

Over most of the territory the formation contains thick beds of gypsum or anhydrite with associated thin dolomite bands and chert, and the upper and lower parts commonly are transitional. The upper contact, however, is abrupt in many sections in Ḩaḑramawt, though it is still apparently conformable, suggesting a possible discontinuity between lower Eocene evaporites and the middle Eocene transgression. In north Ḩaḑramawt and north Al Mahrah, however, apparent local and lateral variations to chalky deposits, many gypsiferous, and to gypsiferous marls, are common, particularly in north Al Mahrah where the dwarf echinoid *Sismondia polymorpha* Duncan and Sladen (K. Joysey, unpub. data, 1948–60) of probable early Eocene age has been found in chalky deposits with embedded calcite geodes. This local and lateral variation from evaporites is consistent with behavior elsewhere—for example, Saudi Arabia, Qatar (Steineke and others, 1958; Sugden, 1966)—and is probably due to water replenishment or the influence of currents. In other parts of the northern territory local replacement of the gypsum by solution breccia occurs and is generally accompanied by formation of collapse structures. Near the edges of the depositional basin the Rus thins and then pinches out or passes laterally into lower and middle Eocene deposits of the Jeza' and Habshiya Formations.

HABSHIYA FORMATION

The type section for the Habshiya Formation is in the western part of the Wādī al Jiz' basin where 224 m was measured (R. W. Wetzel and D. M. Morton, unpub. data, 1948–50). The succession consists of gray-green, yellow, and pink papery shale and yellow chalky and gypsiferous marl alternating with limestone and chalky and dolomitic limestones; the shale and marl are dominant in the lower half. The whole succession is rich in fauna, including *Nummulites gizehensis* (Forskel), *N. discorbinus* (Schloth) var. *major* Rozlos, *N. staminlus* Nuttall, *N.* aff. *N. wadiai* Davies, *N. substacicus* Douville, *Dictyoconoides kohaticus* Davies, *Assilina spira* (de Roissy), *Alveolina elliptica* var. *nuttali* Davies, *Heterocella fragilis* (Defrance), *Thalmoporella* sp., and "*Gymnocodium nummuliticum*" Pfender (unpub. data from the following: M. Chatton, 1948–59; A. H. Smout, 1953–59; G. F. Elliott, 1955–59; K. Joysey, 1948–60). Abundant dwarf echinoids are associated with the microfauna, represented by *Echinocyamus nummuliticus* Duncan and Sladen, *E. subcaudatus* (Desmoulins), and *Sismondia marginalis* (Desmoulins) (Joysey, unpub. data, 1948–60); these have been collected from the formation in other localities in the territory. Other echinoid fauna is common in the upper part at the type section and at other sections in the E.A.P. (such as Jabal Ḩabshīyah) and include *Echinolampus ovalis* B. de St. Vincent, *E. discoidea* d'Archiac, *E. fraasi* de Loriol, *Schizaster africanus* de Loriol, *S. vicinalis* Agassiz and Desor, *Duspatangus formosus* de Loriol, *Opissaster derasmoi* Checchia-Rispoli, *O. digonus* d'Archiac, *Linthia somaliensis* Currie, and *Migliorinia migiurtina* Checchia-Rispoli (Joysey, unpub. data, 1948–60). This faunal assemblage gives a Lutetian (middle Eocene) age to the formation.

The formation is thick in the northern part of the territory, forming the capping rocks of the crestal area of the North Ḩaḑramawt arch from about long. 49°30′ E. and eastward into Dhufar; the belt progressively broadens eastward from its western extremity at Jabal Ḩabshīyah. In the Wādī al Jiz' basin and up onto that part of the Southern Plateau to the south, the formation is again present, but it does not occur westward on the Southern Plateau and is only preserved in a few localities in southwest Ḩaḑramawt.

The formation overlies the Rus Formation in most of the E.A.P. Its contact with the Rus is conformable, though in several localities there is a clean-cut change from evaporites to shales and marls, indicating a possible time break in those localities between evaporitic deposits and Lutetian transgressive deposits. In many sections, however, the Rus becomes transitional at the top (p. H36). In southeastern Al Mahrah, where no Rus is present, the Habshiya overlies the Jeza' or Umm er Radhuma Formation.

Over most of the E.A.P., the Habshiya Formation has much the same lithology as in the type area, but in southwest Ḩaḑramawt where it is present in the Wādī Ḩajr basin in small outcrops—Qurūn Raḑmah (Ruḑamah)—the advent of sand in sandy limestone and of siltstone and silty shale within the formation indicates nearness to a shoreline probably somewhere nearer to the W.A.P. border area. At Damqawt, near the Dhufar border on the coast, a thick sequence of *Alveolina*-bearing limestone (Wetzel and Morton, unpub. data, 1948–50) probably comprises almost wholly Habshiya Formation equivalent, and in Dhufar the Habshiya is equivalent to two formations of middle Eocene age, namely the Andhur and Qara Formations; the Qara was partly referred to by Fox (1947) to be late Eocene. The Andhur Formation consists of alternating limestones, dolomites, and marls with abundant Lutetian fauna; it is overlain by variable limestone of the Qara Formation which also contains a rich Lutetian fauna (Wetzel and Morton, unpub. data, 1948–50). The Andhur may, however, actually pass in part into the Qara, the two being probably partly synchronous.

SHIHR GROUP

The Shihr Group comprises a transgressive sequence of sedimentary strata of varied lithology occurring in scattered generally scree-covered outcrops that form part of a depositional sequence laid down in coastal embayments after the emergence of the E.A.P. territory in the terminal Eocene. Into these embayments and morphotectonic depressions marine ingressions made their way, while at the same time a recently risen landmass was undergoing erosion and rivers were transporting a variety of material into this sea.

Outcrops are discontinuous, of varying thickness, and covered by scree and raised beaches, and deposits are heterogeneous; moreover the work done on these deposits was insufficient for dividing them into formations.

The strata making up the group consist of conglomerate, sandstone, marl, gypsum, reef limestone, chalky limestone, shale, and some dolomitic limestone, occurring singly or in combinations of several of the types mentioned. This variation in lithology was dependent on the proximity to emerged land surfaces undergoing erosion, on proximity to lagoons and river mouths, on presence in restricted or semirestricted basins, on contact with open shallow sea and favorable currents, or on distance from the coast and quiet-water conditions. Despite this diversity of lithology it is apparent from the study of the various sections that the strata belong to one group embracing one major episode. This group is mainly of clastics, the polygenetic conglomerate and sandstone laterally passing into marls or shales away from the source of material and toward the more open sea; at times the open sea became restricted, or lagoonal conditions resulted in the deposition of evaporites. Where oscillations occurred, exaporites are interbedded with clastics. Reef developments occurred from early in this phase of sedimentation wherever conditions were suitable, and continued to develop with intermittent subsidence and reworking (for examples, Buwaysh near Al Mukallā) until probably late in the Miocene.

In two sections described here a good fauna has been found, but in most places the succession is barren. The reefs have a good fauna of Foraminifera, corals, algae, and some echinoids, and some of the chalky limestones have yielded good foraminiferal assemblages. Oligocene and Miocene macrofauna have been found, but the foraminiferal assemblage is Aquitanian and Burdigalian in age. The Aquitanian is regarded by some paleontologists as being lowest Miocene overlain by the Burdigalian; others regard it as uppermost Oligocene and regard it as uppermost Oligocene and regard the Burdigalian as lowest Miocene. Gignoux (1950) pointed out that on the basis of mammalian fauna the Aquitanian must be regarded as uppermost Oligocene. In this account the Aquitanian is tentatively considered as transitional between the Oligocene and Miocene. The presence at the Buwaysh section of some Oligocene (s.l.) echinoids, *Schizaster vicinalis* Agassiz and Desor (upper Eocene and lower Oligocene range, R. G. S. Hudson, unpub. data, 1948–56), in association with Aquitanian-Burdigalian Foraminifera confirms at least an Oligocene age for the lower part, and Miocene (Burdigalian) for the rest, though a younger age including Pliocene for some of the conglomerates is probable.

At Jabal Ḍabḍab some 25 km west of Ash Shiḥr, a succession of interbedded coarse clastics and gypsum with bands of marl is capped by a chalky limestone containing a good microfaunal assemblage which includes the following: *Lepidocyolina* cf. *L. vaughani* Cushman, *L. sumatrensis*? (Brady), *L. tournoueri* Lemoine and R. Duville, *L. yurnaguenensis* Cushman, *Miogypsina* sp., *Operculinoides tournoueri* (de la Harpe), *Operculina complanata* Defrance, *O. complanata* Defrance var. *heterostegina* Silvest., *Amphistegina* cf. *A. nissi*, *Gypsina globulus* (Reuss), *G. vesicularis* (Parker and Jones), *Globigerina bulloides* d'Orbigny, *Eponides* sp., *Cycloclypeous eidae*, *Nephrolepidina sumatrensis*, *N. marginata* (M. Chatton, unpub. data, 1948–59; A. H. Smout, unpub. data 1953–59) and the algae Lithothammium in a top dolomitized limestone planed down to form a terrace. The age range of this fauna places the beds in the upper Aquitanian and Burdigalian. At Buwaysh, east of Al Mukallā, clastics are apparently overlain by foraminiferal and coral limestone with alternating thin sand and sandy marl. Fauna includes *Schizaster vicinalis* Agassiz and Desor in the lower part of the limestone, *Operculina complanata* Defrance, *Eulepidina ephippioides* (Jones and Chapman) *S. S.*, *Nephrolepidina marginata* (Michelotti), *Miogypsina* sp., *M.* cf. *M. globularis*, *Globigerina bulloides* d'Orbigny, *Pararotalia* cf. *P. mexicana* (Nuttall), *Amphistegina* cf. *A. lessoni* d'Orbigny, *Cibicides* sp., *Operculinoides* sp., *Astrocoenia* sp., *Chlamys pallium*, *Leptomussa* sp., *Favia* spp. and algae (Hudson, unpub. data, 1948–56; Smout, unpub. data, 1953–59). The fauna is Oligocene (s.l.) to Aquitanian and Burdigalian.

At Jabal Maṯhanah in the Wādī al Ghabar area some 50 km west-southwest of Al Mukallā, the succession is mainly conglomerate with interbedded sandstone and some gypsiferous sandy marl in the lower part. North of Ra's Fartak in Al Mahrah, some 150 m of Shihr Group beds is preserved and consists of a series of orange marls with gypsum, conglomerate, and thin beds of dolomitic limestones.

In the Karīf Shawrān volcano near Bi'r ʽAlī, some limestone ejecta belong to the Shihr Group and contain fauna as follows: *Taberina Malabarica* (Carter), *Meandropsina anahensis*? Henson, *Borealis melo* (Fichtel and Moll), echinoid debris, corals, and gastropods (Smout, unpub. data 1953–59). The foraminiferal assemblage indicates a Burdigalian age.

The Shihr Group can rest on any of the older formations depending on morphology and erosion at the time of deposition. Its conglomerates contain pebbles and cobbles of all older rocks exposed near the areas of deposition. It has been seen to rest on Habshiya Formation, on Jeza' Formation, on Rus Formation, on Tawilah Group, and on basement. Its contact with the sedimentary strata below is unconformable, but not everywhere with angularity. It is not overlain by any younger formations but various levels of it have been planed and covered with raised beach or river-terrace material.

In Dhufar a marine Oligocene sequence ranging in age from early to late Oligocene is thickly developed in the coastal area near Salālah and farther east at Ra's ash Shuwaymīyah on the Oman border. The facies is one of chalk and chalky limestone; the basal part contains shale and marl with chalky limestone, and *Nummulites fischteli* Mechelotti-*intermedius* d'Archiac is common; the rest of the succession contains *Lepidocyclina* and *Eulipidina* fauna and echinoids (Beydoun, 1964; Chatton, unpub. data, 1948–59). Miocene reef-type limestone and associated shale with *Ostrea* and *Pecten* overlie the Oligocene chalk and chalky limestone. Some observers in Dhufar postulate an unconformity between these and the Oligocene, and others include them as part of an Oligocene and Miocene cycle, while separating an overlying younger series of virtually horizontal limestone conglomerates as belonging to the Pliocene and Pleistocene (Dhofar Cities Service geologists, written commun., 1959). Although the limestone conglomerates are similar to those of the Shihr Group conglomerates of the E.A.P., their horizontal nature as compared to the tilted and disturbed nature of the Shihr Group conglomerates makes correlation between them dubious. Thus the Dhufar Oligocene (Miocene?) deposits differ from those of the E.A.P., except probably in parts of western Dhufar.

POST-MIOCENE DEPOSITS

Post-Miocene deposits fall largely outside the scope of this account and have been adequately described by Little (1925), Caton-Thompson (1938), Caton-Thompson and Gardner (1939), Wissmann (Wissmann, 1932; Wissmann and others, 1942), R. W. Wetzel and D. M. Morton (unpub. data, 1948–50), and others. However, a brief summary of these observations plus others made by the present work is not out of place in completing the stratigraphic description of the E.A.P. This summary also applies in general to Dhufar.

Raised beaches.—The following levels of raised beaches in the Al Mukallā area appear to be persistent terraces: 6–10, 25, 50, 60, and 75–80 m. In addition, a 100–120-m terrace is suspected. The 6–10-m terrace is the most recent and occurs in scattered localities along the coast, commonly as a wave-cut platform with abundant loose corals. The 25-, 50-, 60-, and 75–80-m terraces affected Shihr Group deposits by planing their tops, the last planing also occurring near Burūm and at Ra's al Mukallā, Umm er Radhuma Formation. The 100–120-m terrace and a suspected terrace at 150 m are indicated on Al Mukallā hill where Miocene(?) and younger corals are found plastered on Umm er Radhuma Formation on the side of the hill.

Caton-Thompson (1938) found paleolithic implements associated with 32- and 14-m terraces. Wetzel and Morton (unpub. data, 1948–50) observed "fossil" dunes backing the shoreline of a 15-m terrace.

Some fauna has been collected from the lower terraces at various localities and determined as follows: *Lopha turbinata* (Lamarck), *Chlamys* cf. *C. porphyres* Chemnitz, *Conus* cf. *C. Litteratus* Linne, *Cyprea* cf. *C. carneola* Linne, *Altectryona cucullata* (Lamarck), *Platygyra lamellina*, *Stylopora pistillata*, *Fungia* aff. *F. pleistocenia*, *F.* aff. *F. zuffardiae*, *Favia* sp., *Cyphastrea* sp., *Goniastrea* sp., *Stylophora* sp., *Platygyra* sp., *Monastrea* sp., *Montipora* sp., *Acropora* sp., *Solenastrea* sp., *Oulophyllia* sp., and *Leptoria* sp. (F. Gosling, unpub. data, 1956; R. G. S. Hudson, unpub. data, 1948–56). The above fauna is "usually considered to be Pleistocene, but faunally cannot be distinguished from Pliocene or Recent forms," according to Hudson.

River terraces and lacustrine deposits.—A number of river-terrace levels can generally be seen above the present-day drainage levels of the bigger widyān and overlying various older rocks from the basement upward. In lower Wādī Ḫajr at least three such levels are seen, one being about 150 m above present wādī level; similar levels are found in Wādī al Ghabar and elsewhere, and are marked by coarse conglomerate with finer layers. These terraces reflect regional oscillations.

Wetzel and Morton (unpub. data, 1948–50) noted the widespread occurrence of a 30–35 m terrace in the E.A.P. Eolian deposits and silts in Wādī Ḫaḏramawt and Al Masīlah are emboîté in this terrace and are known to overlie gravels in some areas.

Lacustrine deposits are associated with river terraces in the middle Wādī Ḫajr basin between Ṣidārah and Jawl Bā Ḫaywah (Jawl Ba Hawah). These deposits consist of sandy chalky marl and limestone, with *Chara* stems and gastropods, horizontally or subhorizontally bedded and laterally passing eastward into, and interfingering with, thick limestone conglomerates at Al Qaʿīmah village near Jawl Bā Ḫaywah. The age is probably Pliocene. Other lacustrine deposits occur in the north.

Gravel plains and alluvium deposits.—The formation of gravel plains already described (p. H4–H5) is due to action of both water and wind, and the plain surfaces may have been initiated in a pluvial period or periods in Pliocene or Pleistocene times. River silt is present in many localities now marked by hardly more than very flat broad drainage and within the sand-dune tracts of the territory.

Alluvial deposits, other than river terraces already discussed, include coarse gravel, sand, and silt in drainage channels, and conglomerates formed in widyān beds by recementation of pebbles due to arid desiccation.

Eolian deposits.—Loess and fluvioeolian deposits are fairly extensive, particularly in the Wādī Ḫaḏramawt basin; they also occur in smaller widyān of the plateaus and the coast. Three species of loess snails have been found (Wissmann and others, 1942) in these deposits; two of the species are widely distributed.

Terraces formed by these deposits are invariably cut by subsequent drainage and often exposed to their base where they are seen to rest on older river terraces. They mark a pronounced dry phase of Tyrrhenian(?) age, followed by rejuvenation of drainage. Sand dunes have already been discussed earlier (p. H4–H5).

Young eruptives.—Wissman (Wissmann, 1932; Wissmann and others, 1942), Lamare (Lamare and others, 1930; Lamare, 1936), and others have described and discussed the young eruptive rocks of southwest Arabia in detail. The present account briefly mentions these rocks as observed in the E.A.P. They form part of the Aden Volcanic Series.

The westernmost area of eruptive activity in the E.A.P. is in the Balḩāf-Bi'r 'Alī region where several craters, including many cinder cones, occur, and the region is covered by volcanic deposits including basalt flows, tuff, and ash. The fresh tuff cone of Karīf Shawrān near Bi'r 'Alī is a crater lake; the volcano was an explosive one that brought up a variety of older sedimentary rocks and an assortment of igneous rocks including granite and dunite. The main activity was restricted to the coastal strip and the neighboring part of the sea (close to the zone of strongest(?) faulting). Some activity took place inland, and basaltic flows associated with fissuring occur in limited outcrops in the Wādī Ḩajr basin, piercing through Eocene sedimentary rocks, and on the side of Jabal Shabb piercing through Cretaceous. No further trace of eruptive activity is seen until the Qusay'ir-Say-ḩūt area in the east, where flows and cones occur along the coast and variable extents of lava flows pierce through Tertiary sedimentary rocks along fault or fissure lines on the plateau and in Al Masilah. No other evidence of volcanism is known from anywhere else in the E.A.P., and there is none in Dhufar.

These volcanics form part of a Pliocene, Pleistocene, and Recent phase of eruptions which occurred in the Gulf of Aden-Red Sea region. Volcanic activity in southwest Arabia commenced as early as the Late Cretaceous in Yemen (Lamare and others, 1930; Lamare, 1936) and parts of the W.A.P., and in Paleocene and Eocene times in most parts of the W.A.P. This activity continued intermittently in southwest Arabia until Recent times. The E.A.P. activity belongs to the later phase.

Wetzel and Morton (unpub. data, 1948–50) reported the thickness of flows in the Quṣay'ir-Sayḩūt strip to be from 10 to 60 m. In Al Masīlah they recognized two flows; the older is emboîté in Pliocene conglomerate (generally overlies the 30–35 m terrace) and the younger covers the 12–16 m terrace in the widyān. The recognition of two phases agrees with Wissman, Rathjens, and Kossmat (1942), who reported a first phase ascribed to the late Pliocene and a second phase of younger Pleistocene age.

REGIONAL CORRELATIONS OF THE TERTIARY

The main correlations of E.A.P. formations with neighboring areas are shown on plate 5.

The Eocene sedimentary rocks of the E.A.P. were originally referred to as Oliogene and Miocene (Little, 1925; Wissmann, 1932; Wissmann and others, 1942) but their very rich faunal assemblage shows them to be early and middle Eocene (p. H35–H36).

In former British Somaliland, the Auradu Limestone, Allahkajid Series, Gypsum-Anhydrite Series, and Karkar Series are the counterparts of the Umm er Radhuma, Jeza', Rus, and Habshiya Formations of the E.A.P. both in lithology and in approximately the age range of each formation (Macfadyen, 1933; Hunt and others, 1956; Somaliland Oil Exploration Co., Ltd., 1954); a Paleocene age for at least part of the Auradu has been proved. The lower Daban Series of Somaliland appears to be a near-shoreline equivalent of the Karkar Series and reflects similar near-shore conditions as seen in the Habshiya Formation in Ḩaḑramawt near Jizwil (Qurun Haḑmah) (p. H37). Strata equivalent to the Shihr Group are found in the middle and upper Daban Series and the Dubar Series. The Daban Series is middle Eocene to Miocene in age, without a break between the lower and middle Daban, and the latter is in part late Eocene in age (Macfadyen, 1933). This age would indicate that, for at least part of the Daban basin, subsidence and sedimentation were probably continuous from the middle Eocene to at least the Oligocene, and thus suggests a late Eocene initiation of the Gulf of Aden (p. H43). The presence of upper Eocene is not known elsewhere in the general area of the Gulf of Aden and south Arabia except in the Al Buraymī district. Somaliland Oil Exploration Co., Ltd. (1954), on the other hand, considered the middle Daban as Oligocene transgressive on middle Eocene Daban.

In Socotra (Beydoun, unpub. data, 1953–59) the Umm er Radhuma Formation has much the same facies as occurs in the Ra's Fartak to Damqawt area of Al Mahrah (and in Dhufar), and ranges in age from Paleocene to early Eocene (A. H. Smout, unpub. data, 1953–59). There are no Rus or Habshiya Formation equivalents, a break having occurred between lower Eocene and Oligocene. A succession of marine chalky limestone and marl with chert and flint, and containing abundant microfauna, can be found preserved in structural depressions (Beydoun, unpub. data, 1953–59). Fauna collected includes the following: *Operculina complanta* (Defrance) var. *granulosa* Leymerie, *Globigerina bulloides* d'Orbigny, *G.* cf. *G. sacculifera* Brady, *Lepidocyclina dilatata* (Michelotti), *L. tournoueri* Lemoine and R. Douville, *Archaias* cf. *A. aduncus* (Fichtel and Moll), *Gypsina globularis* (Reuss), *Nummulites germanicus* (Bornemann), *Haplophragmium slingeri* Thomas, and *Austrotrillina* sp. (Smout, unpub. data, 1953–59). This assemblage indicates an Oligocene age. The facies indicates deeper open-sea conditions, with Socotra (and Dhufar) occupying an easterly and more basinward position in the path of the transgressing sea. The Oligocene deposits lie disconformably on Umm er Radhuma Formation but without evident unconformity in the field. No deposits of the Shihr Group have been seen (Beydoun, 1964).

In Qaṯar (Sugden, 1966), eastern Saudi Arabia (Steineke and others, 1958), and the Trucial Coast (M. Chatton, unpub. data, 1948–59), the Umm er Radhuma, Rus, and Dammam Formations are the equivalents of the Hadhramut Group of the E.A.P. Facies in the Umm er Radhuma there is similar to that of the Umm er Radhuma of eastern Al Mahrah, but variations occur in the facies of the Rus and Dammam Formations compared with their equivalent Rus and Habshiya Formations of the E.A.P.

In the Oman desert (Morton, 1959), the Umm er Radhuma Formation occurs in the same manner as it does in most of the E.A.P., but the lower Eocene Jeza' and Rus equivalents consist of chalky marl and limestone, gypsiferous shale, dolomite, and dolomitic marl. The middle Eocene is most variable, being a massive nummulitic limestone facies in the north and yellow marl and rubbly limestone facies to the south (Morton, 1959), similar to the Habshiya Formation of the E.A.P.

A thick sequence of marine Oligocene, consisting of limestones and chalky limestones, occurs with a break between it and the Miocene. The Miocene consists of a lower part of limestone, chalk, and marl, and an upper part, largely detrital and evaporitic, which is correlated with the lower Fars of Qaṯar and the Trucial Coast (Morton, 1959).

In Yemen the Tertiary period was characterized by considerable volcanic activity but calcareous fine sands were deposited locally by a limited Paleocene-Eocene transgression (Geukens, 1960). In the W.A.P. volcanic activity predominated and Paleocene and Eocene deposits like those of the E.A.P. are confined to the easternmost part.

ECONOMIC ASPECTS

Lime preparation from burning Umm er Radhuma limestone is a small-scale local industry. If cheap fuels for the kilns can be found, this industry could be developed for export outside the E.A.P. The kilns are wood fired, but wood, being generally scarce, has to be collected from increasingly greater distances. The wood is also required for charcoal manufacturing, another small-scale local industry.

Gypsum-anhydrite of the Rus Formation occurs in large quantities, particularly in the north, but no exploitation of this product has been undertaken, one reason being difficulty of working because of distance from the sea. World demand is met from other sources where conditions of working are easier.

Celestite has been found in bands more than half an inch thick within the Jeza' Formation on the Southern Plateau. No survey to assess the extent and importance of these bands has been made, but from the amount seen an assessment survey is probably justified and may prove promising.

Tertiary ground water is regional in the northern part of the E.A.P. and Dhufar (north flank of the North Ḫaḏramawt arch). Rus, Jeza', and Umm er Radhuma water has been found in good quantities in northern E.A.P. by drilling to an apparently regional water table. Similar conditions have been met in Dhufar. Salt contents are variable, but the water is generally potable. Umm er Radhuma water in these areas is generally under pressure and flows to the surface with varying ease depending on the hydrostatic head; on the whole, it is sulfurous but reasonably potable when allowed to stand.

In the more mountainous parts of the territory, springs occur at the base of the Umm er Radhuma or within the younger formations overlying impervious layers.

STRUCTURE

The E.A.P. and Dhufar are in the southern part of Arabia bordering the Gulf of Aden and the Arabian Sea. To the west are the W.A.P. and Yemen, both of which lie in the southwest corner of Arabia where the Red Sea, Gulf of Aden, and Ethiopian rift valleys meet in the region of what has been called the Afar triangle.

The E.A.P. and Dhufar thus fall outside the Afar triangle and the E.A.P. is bordered only by the Gulf of Aden rift. The area belongs to what has recently been referred to as the Ḫaḏramawt Plateau structural province (Aramco geologists), a description which, however, oversimplifies the structure.

The dominating topographical and structural feature of the area (E.A.P. and Dhufar) is the very gentle Ḫaḏramawt arch (s.l.) that spans the whole territory. It has two subparallel culminations in the North and South Ḫaḏramawt arches, separated by a broad gentle syncline. The structure is expressed in the morphology which developed mainly in the Tertiary.

The Tertiary structure is therefore described and discussed first, with an interpretation of the structural development. The next and final section gives a summary of structural history from the basement to the Tertiary as it is understood from the work so far carried out, and some comparison with the Somali side of the Gulf of Aden is given.

TERTIARY AND RECENT STRUCTURE

No local folding or faulting movements are known to have occurred during the early (Paleocene) stage of the Tertiary subsidence in the E.A.P., but in Paleocene and middle Eocene times the first indications are obtained in the stratigraphy (p. H35–H38) of the progressive development of the biaxial Ḫaḏramawt arch. This feature attained its present form approximately at the end of the Eocene, though faulting in the later Tertiary gave it its final collapsed south flanks (pl. 6).

The main arch, roughly equivalent to Wissmann's "Sudarabische Randschwelle" (Wissmann and others, 1942) (south Arabian marginal swell), has an intervening gentle syncline dividing it into the North and South Ḩaḑramawt arches respectively, together forming the highlands of the E.A.P. The axes of the two arches and the intervening Ḩaḑramawt-Al Jizʻ syncline trend west-southwest in Ḩaḑramawt, gradually swinging from west to east in Al Mahrah.

The North arch extends eastward into Dhufar through the Al Qamar and Al Qarāʻ ranges; in the west it flattens out and is lost in the plain east of the Yemen border. The length is some 600 km or more. The axial zone is expressed by Eocene strata and marked by the highest ground of the Northern Plateau, which also approximately defines the watershed. The flanks dip very gently to the north and south, the overall dip being about 1°, though steeper dips exist locally. The axis pitches in the Mirbāţ area of Dhufar where the feature is cut off by coastal faulting, but the Kuria Muria Islands may mark an extension of its basement core.

The median synclinal area is at present followed roughly by the lines of Wādī Ḩaḑramawt-Wadī al Jizʻ, the axis being slightly south of the Wādī Ḩaḑramawt line (p. H6). The syncline pitches eastward into the structural depression of Al Qamar Bay; westward it flattens out and is lost in the Shabwah area. Flank dips are very gentle, averaging about 1°.

The South arch has an observed length of some 350 km. In the east it plunges in the Ra's Sharwayn area where it is intersected by the coast; in the west a zone of faults trending west-northwest cuts across its axial line and its structural identity is obscured toward the W.A.P. border. Its northern flank is very gentle with dips of about 1°; but unlike the south flank of the North arch, the south flank of the South arch has collapsed as a result of subsequent large-scale faulting, doubtless associated with rifting in the Gulf of Aden. Owing to this faulting the arch is now bounded to the south along most of its course by a broken scarp rather than by a south-dipping flank, but the original flank is clearly seen in its eastern profiles in spite of step faulting.

Origin of the arch through warping (as distinct from faulting) is further indicated in evidence of its progressive development in the early Tertiary, when the facies and thickness distribution of contemporaneous sedimentary rocks were affected by it. Thus in any given profile in the eastern part, thick sections of Paleocene-Eocene strata are found on the two flanks of the South arch. These conditions suggest that the Gulf of Aden region also developed as a structural depression during the Paleocene transgression while the beginning of a very gentle uplift was proceeding over the axial zone of the South arch.

Uplift of the North arch was probably a little more pronounced. Thickness measurements and studies in the western region of the North arch suggest that during the early part of the Paleocene transgression, the North arch was somewhat active, forming a northerly temporary or submerged barrier in the Paleocene sea along which thinning and pinching out or facies change of the lower unit of the Umm er Radhuma Formation occurred. Soon after, however, probably in the middle Paleocene, the sea overcame this and spread over the whole north (p. H34).

In the early Eocene, thickness variations again reflect progressive development of the Ḩaḑramawt arch (s.l.), and the maximum development of evaporites (Rus Formation) occurred in the intervening gentle synclinal trough of the Ḩaḑramawt-Al Jizʻ line, again with greater thicknesses in the east than in the west. The evaporites are absent in the Ra's Sharwayn-Ra's Fartak coastal area, presumably owing to the pitch of the axis toward open-sea conditions.

During the middle Eocene, the Habshiya Formation of southwest Ḩaḑramawt thinned and became sandy toward a shoreline at about long 48°30′ E. (p. H37), suggesting that geanticlinal uplift with an eastward pitch was continuing.

Progressive development of the Ḩaḑramawt arch (s.l.) as a geanticlinal warping led to final emergence in the upper Eocene; geophysical surveys indicate that the north flank continues to dip continuously under Tertiary cover toward the Rubʻ al Khālī in Saudi Arabia.

This interpretation of the Ḩaḑramawt Plateau structure differs from that of Wissman, Rathjens, and Kossmat (1942), who ascribed the steeper south dip to flexuring and associated normal faulting at depth. Normal faults passing, with decrease of throw, into flexures are frequently observed in rift zones, but none have been observed passing into flexures of the scale of the Ḩaḑramawt arch. The visible south flank of the simpler eastern part of the arch is broken largely by normal strike faults, but the strata in most blocks dip south toward the downthrown side, indicating that a south-dipping flank existed before the faulting (Wissman and others, 1942) (pl. 6). In the more complicated western sector where there are intersecting fault systems, the south flank is no longer recognizable as such.

It might be assumed that the whole flexure developed through draping of sedimentary strata over a basement stepped down toward the Gulf of Aden rift by numerous small normal faults. However, such normal faulting would imply a tensional lengthening of the crust (in horizontal projection) to which a draped sedimentary cover would have to adapt itself by actual stretching to a degree which seems hardly credible, especially in massive limestones under little load. There seems no reason to suppose that the assumed buried faulting failed to rupture this cover, whereas later faults have done so. Moreover, basement rocks where exposed along the south flank do not show any step faults that diminish upwards into the sedimentary cover.

The linear continuity of the North and South Ḩaḑramawt arches over very long distances is opposed to origins either in normal faulting or in uplift due to expanding magma at depth (for example, Somaliland Oil Exploration Co., Ltd., 1954) which would probably produce shapeless bulges. For these reasons F. R. S. Henson (unpub. data, 1954–60) regarded the compound Ḩaḑramawt arch as a plis de fond in the literal sense, due to regional compression which buckled the whole thickness of the crust. This view appears to be confirmed by the fact that the trend of the arch cuts across dominant basement trends, although generally the tendency is for later faults to follow old lines. It is probably analogous to the Judean and Jordan arches which rose on either side of the Dead Sea rift at about the same time. The Dead Sea rift is a major discontinuity (geosuture) in the total crust along which, according to Henson (unpub. data, 1954–60), compressed crustal segments on either side may have buckled up because the discontinuity, yielding itself to slight transcurrent movement, interrupted normal fold propagation.[5]

Since the Gulf of Aden may follow an old geosuture (Henson, unpub. data, 1954–60), it is interesting to speculate on the possibility that the Somaliland plateau may be a counterpart, structually, of the Ḩaḑramawt arch (s.l.) and that the present Gulf of Aden may have originated as a megasyncline between the two before it was broken down by rift faulting.

The stratigraphic record on the Somali side of the Gulf of Aden shows that in a part of north-central former British Somaliland, middle Eocene lower Daban in its type area is continuous with the overlying middle Daban of late Eocene and Oligocene age (Macfadyen, 1933). Since middle Daban equivalents are missing from the plateaus on either side of the Gulf of Aden, it is clear that at least part of this area was structurally depressed when the plateaus emerged, but the extent and trend of the depression are unknown (p. H40).

The Somaliland plateau itself trends west to east in two segments offset from each other meridianally, with a well-marked zone of intense post-Eocene "Red Sea" faulting between them (Somaliland Oil Exploration Co., Ltd., 1954). As in southwest Ḩaḑramawt, slump faulting and antithetic rotation of blocks below the main escarpment of the plateau leave doubt as to the original form of the uplifts along most of its northern margin. But in northeast former British Somaliland, as in southeast Ḩaḑramawt, indications of original geanticlinal warping are found in some profiles. The plateau itself has gentle undulations comparable with those mapped on the Ḩaḑramawt side of the Gulf of Aden (Somaliland Oil Exploration Co., Ltd., 1954).

These observations suggest that the development of the Somaliland plateau was similar to that of its counterpart in the E.A.P. and that the geanticlinal arches on both sides of the Gulf of Aden were due to regional compression acting normally or obliquely to the Gulf axis in the west and to the old lines of weakness on the Dhufar-Kuria Muria and Socotra trends in the east.

Reactivated geosutures are thought to determine these trends, but basement "grains" within the arches, which are attributed to buckling of the crust as a unit, are not necessarily parallel. In Dhufar, for example, the east trend of the arch bears no relation to the basement grains (north, northeast, and northwest trends) in the limited exposures at Mirbāţ, whereas in Ḩaḑramawt basement trends are highly variable; those trending east are exceptional. However, as much of the area now embraced by the arch is devoid of basement exposures, no conclusions are justified.

In former British Somaliland the main Red Sea[6] faulting occurred at the end of the middle Eocene (Somaliland Oil Exploration Co., Ltd., 1954). In southwest Ḩaḑramawt strong faulting on the same alinement occurred before Oligocene and Miocene marine ingressions and may well have been contemporaneous with the Red Sea faulting in Somaliland.

It should be noted, however, that the most numerous and prominent faults are not strictly on the Red Sea trend (northwest) in the E.A.P. but follow a west-northwest trend, and they may have some different significance. The west-northwest trend is reflected in the basement trend of part of Jabal Sawād Bā Quţmī (p. H45) and in the basement structure of the Bulhar-area of Somaliland; it may be in part a reactivated old trend. The west-northwest trending faults are particularly pronounced between the offset east and west sections of the Somaliland plateau (Somaliland Oil Exploration Co., Ltd., 1954) and at the western and

[5] These conditions have been reproduced in laboratory-scale experiments at the Iraq Petroleum Company Research Center in London.

[6] The Red Sea group includes northwest, west-northwest, and north-northwest fault trends; only the latter is the true Red Sea trend (Erythrean). Other trends are the "East African" trend which is oldest (north, north-northeast) and conforms to the Afro-Arabian fracture pattern; the "Gulf of Aden" trend which is youngest (east-northeast, east; the east trend corresponds to the "Somali" trend of Wissmann); and the "Aulalitic" trend (northeast) of Wissmann.

eastern "pitch" of the South Ḩaḑramawt arch. Some of these faults in the E.A.P. are very long and straight, and their trend can be followed in Yemen, cutting across basement structure.

The faulting in these areas, therefore, may have developed during the culmination of the geanticlinal warping as a form of adjustment to differential crustal shortening which varied along the geanticlinal axes; or the faults may have determined the pitch of the arches. Thus, it might be suspected that some transcurrent movement, in which the Gulf of Aden trend may also have been involved, was associated with the faulting. If this is correct, it would explain a number of local structures indicative of compression ("block jostling") which occur in southwest Ḩaḑramawt and which probably originated at the end of the Eocene. These are seemingly anomalous in an area of predominant vertical movements and are discussed in the following paragraphs.

At Ẕulm Bā Tha'lab in the Wādī Ḩajr area, a structure some 30 km long and 8 km wide trends west-southwest, plunges east and flattens out westward. The core consists of basement extrusives which underwent multidirectional cleavage before peneplanation; the peneplain itself is now arched into a smooth domal form which the overlying sedimentary rock (from Jurassic to Eocene) follow concordantly in successive scarps down the flanks, and form a closure in the east. Dips are as high as 15°–20°. Two faults parallel to the axis bound the structure on both flanks, the northern dying out before it interrupts the full flank succession, and the southern cutting out the Jurassic. In the west the igneous core and the surviving flank strata are eroded and lost under a cover of blown sand. The trend of the feature is parallel to that of the South Ḩaḑramawt arch.

In the Wādī Kilyah area of the Wādī Ḩajr basin, a small thrust fault involves Cretaceous and Jurassic beds in an area where normal block faults prevail. It cannot be asserted that this structure originated during the late Eocene movements, but this seems probable in view of other evidence that minor horizontal displacements occurred at this time.

The Ẕulm Bā Tha'lab dome is of more than local interest because it suggests a mode of origin of some foreland folds (Henson, unpub. data, 1954–60). Lees (1952) accepted basement participation in foreland folding, visualizing anticlinal cores consisting alternately of upthrust slices or of bulges in the basement. But it is difficult to explain how gentle bulges such as the Ẕulm Bā Tha'lab dome, very small in relation to the total thickness of basement, could develop on the upper basement surface. The Ẕulm Bā Tha'lab dome was first explained as the result of a diapiric (?) squeezing of the basement rocks between observed lateral faults, such movement being facilitated by intense cleavage. However, the smooth arching of the peneplain is evidence that does not support the theory of movement along multidirectional cleavage planes. Normal folding processes are ruled out by the massive nature of the basement material, in which there could be no adjustment along bedding planes; microshearing and mylonitization were not recognized. Plastic deformation could not normally be expected to occur in lightly loaded basement except under intense and locally applied stress. Such stress, however, should be revealed in flow structures, which have so far not been observed, and is incompatible with the preservation of cleavage planes.

In Yemen are certain anticlinal swells and fault folds and in the high plateau sparse diapiric folds with basement cores and Jurassic flanks (Lamare and others, 1930). One such example was attributed to squeezing up of the igneous core along two parallel faults (compare Ẕulm Bā Tha'lab). These phenomena were noted to be different from those characteristic of normally folded areas, not only by their lesser intensity, but also by their local occurrence as unalined sporadic features in the block-faulted areas. The authors concluded by admitting the existence of squeezing movements that were due to the interplay of resistant blocks (block jostling) and that corresponded to a phase of compression resulting in vertical and tangential block movements. Foreland folds developed in this way would be analogous to the "diapiric buckling-folds" of Henson (*in* Fairbridge and Badoux, 1960).

Apart from structures of this type, the western part of the E.A.P. and parts of southeast Yemen and northeast W.A.P. are characterized by the occurrence of salt domes (p. H22), the extrusion of which is of some tectonic significance. Stratigraphically the salt has been shown to be of Late Jurassic age (p. H22, H23–H24).

All the domes, except those of the Al Minţāq area, have had their overlying Cretaceous and Tertiary cover entirely removed, and they rise in flat-plain or sand-dune areas with only Pliocene and Recent deposits surrounding their Jurassic cores and rims. In the Al Minţāq area, however, the domes which lie in deep widyān have all arched up their Cretaceous and Tertiary overburden, the latter consisting mainly of some 250 m of massive limestone. There is no surviving evidence of the salt having burst through the massive Paleocene limestone cover, but the steep tilt outward of this limestone from the core indicates that it was strongly pushed up. The structures are in fact salt blisters rather than piercement plugs, and they are oval or elliptical in shape.

The extrusion of salt clearly occurred after the Paleocene, probably at the end of the Eocene, although total sedimentary load was hardly sufficient to account for it without additional stimulus to start the movement (Henson, in Fox, 1959). There is no evidence of earlier movements in the stratigraphy, in spite of the opportunities provided by the terminal Jurassic normal faulting. Normal faulting alone was not, therefore, sufficient to initiate diapirism of the salt.

The E.A.P. domes are present in areas of post-Paleocene (east, northwest, and west-northwest trends) cross faulting which may have cut trap doors in the limestone roof to provide escape routes; but some tangential stress, due perhaps to horizontal components of fault movement, must have operated to cause salt diapirism. It is difficult to determine in the field whether there were any transcurrent, in addition to vertical, movements, because the surrounding beds are either generally flat and uniform (Al Minṯāq area) or else absent. But the west-northwest-trending fault group is that which, for other reasons, has been assumed to be transcurrent. It is possible, therefore, that diapirism of salt and of basement rocks and the development of other compression structures in Ḩaḑramawt may be attributed to horizontal block movements associated with this faulting.

Geophysical surveys in the northern part of the E.A.P. provide evidence of other salt domes that have not broken through to the surface. These are thought to be Jurassic salt, and are probably still in the process of moving up under differential load pressure which becomes effective as soon as an incipient salt column has been established.

Although these various indications of local tangential compression and movement at the end of the Eocene are vague and inferential, they are consistent with the opinion expressed earlier that compression rather than tension was responsible for the development of the Ḩaḑramawt arch (s.l.), and it is possible that the minor compression structures recorded in Somaliland may have originated in related block-jostling movements.

During Oligocene and Miocene times subsidence and progressive marine ingressions from east to west occurred in the Gulf of Aden area. It was probably during this phase of relaxation from compressional uplift that major normal faulting, generally somewhat parallel to the axis of the folding (east-northeast and east trends), broke up the south flank of the Ḩaḑramawt arch (s.l.).

Proof of faulting at this time is lacking over most of the area affected where no rocks later than Eocene are exposed, but the coastal Oligocene and Miocene deposits have been tilted by fault movements that predate the Gulf of Aden faulting, *s.s.* These fractures have been attributed by Henson (unpub. data, 1954–60) to gravitational breaking down of the rising coastline and not to basement influences. This cannot be entirely true because some faults on these trends occur far north of the rift margins and must be due in part to some other cause, possibly to differential block movements associated with shallow fold-fault structures. Moreover, true east-northeast-trending "Adenean" faults (Henson, unpub. data, 1954–60) are present along the coast in the Mirbāṯ coast of Dhufar, although the North Ḩaḑramawt arch extension (the Kuria Muria trend) and the bathymetric contours swing to an east trend.

The same movements may be responsible for faults and gentle undulations parallel to the axes of the Ḩaḑramawt arch (s.l.) over the high plateau areas; in the Raydat al M'arrā area two rather flat folds some 50 km long, separated by a shallow syncline, occur north of the axial zone of the South Ḩaḑramawt arch and are expressed in lower Eocene beds; they occur en echelon, pitching eastward and flattening out westward.

Similar features occur in the Wādī al Jiz' basin on both side of the main Ḩaḑramawt-Al Jiz' synclinal axis, and are generally parallel in trend to that axis. In places they occur en echelon to each other, separated by flat synclines. Some have a small amount of closure, others are only noses. R. W. Wetzel and D. M. Morton (unpub. data, 1948–50) referred to them as fault structures. They are expressed in Eocene beds, though some involve Oligocene and Miocene deposits on their flanks, indicating their origin or reactivation in the late Tertiary

Along the axial zone of the North Ḩaḑramawt arch in the Jabal Ḩabshīyah area, eastward-plunging noses expressed in Eocene beds occur south of the main axis of the arch.

There are other similar widely separated features of small dimensions, especially in the Al Mahrah area of the Southern Plateau. All appear to have associated faulting parallel to their axial trend, and faults trending east-northeast and east occur either on the flanks or in synclinal zones, and are undoubtedly associated with the formation of these structures.

Despite the important Oligocene and Miocene faulting there is no evidence of any volcanism having resulted.

The main (axial) Gulf of Aden trend is east-northeast—that is, parallel to the dominant basement grain of south W.A.P. (Wissmann and others, 1942) and to some late Miocene(?) faults near the western part of the South Ḩaḑramawt arch, but oblique to the east trend of the arch and its step-fault system farther to the east.

Mapped faults on the east-northeast trend are fairly common, and long, straight stretches of coastline following this direction have clearly undergone relative elevation in Neogene to Recent times because Oligocene and Miocene deposits are involved in the uplift. There is little doubt that they mark important lines of profound Gulf of Aden faulting, *s.s.*, along which the land area rose far above the Gulf floor. The step faulting of the Ḩaḑramawt arch (s.l.) is excluded from this group.

Although definite evidence to support the separation in time of the two systems is lacking, it is noted that the Gulf of Aden coastal trend abruptly truncates the South Ḩaḑramawt arch and its faults in the Ra's Sharwayn-Ra's Fartak area, whereas east-northeast-trending faults occur across the North Ḩaḑramawt arch in Dhufar.

In the former area there are also groups of Red Sea faults (northwest trend) which are considered later than the east-trending system and hence must be distinguished from the west-northwest-trending faults of Eocene date.

These generalizations apply, of course, only to systematic faulting which is complicated in places by abundant erratic fracturing on a small scale, or by rejuvenation of old faults.

No folding can, with confidence, be attributed to the Neogene and Recent movements, but some chaotic pseudofolding due to solution collapse is observed on a considerable scale in those parts of the high plateau where the lower (middle) Eocene Rus Formation gypsum has been dissolved below its cover of middle Eocene shale, marl, and limestone (Habshiya Formation) and then the collapsed cover has been recemented as pseudobeds.

During Neogene to Recent times much volcanism was associated with coastal faulting in the Gulf of Aden; some basalts occur further inland.

STRUCTURAL HISTORY

The Aden Protectorate lies on the gentle southeastward slope of the peneplaned Afro-Arabian shield which declines toward the southern part of the Middle East basin. Some authors have concluded that this slope was divided by the Jurassic trans-Erythrean trough (Lamare and others, 1930; Lamare, 1936; Arkell, 1952) into the Arabo-Nubian and Arabo-Somali masses (Picard, 1937; Mitchell, 1959), between which development of the volcanic Sabea block (Lamare and others, 1930; Picard, 1937) began late in the Cretaceous.

The oldest rocks seen in the peneplaned basement complex of the E.A.P. consist of Precambrian metamorphic rocks in the west, and similar rocks are exposed in the Mirbāţ area of Dhufar. A slightly younger basal extrusive series, covered by metasedimentary rocks that grade into nonmetamorphosed rocks, and associated younger intrusive igneous bodies make up the rest of the basement of southwest Ḩaḑramawt (p. H9–H11). The dominant strike of original structure in the basement is north trending, with northwest, west-northwest, and east-northwest cross trends. Metamorphism increases from east to west in southwest Ḩaḑramawt into the Wāḩidī State, and toward the W.A.P., with the result that confusion is possible between older and younger basement sedimentary rocks. Complexity in strike of folds and faults also increases westward.

Some time after the deposition of the youngest basement sediments and after some igneous intrusions had taken place, a period of powerful movements occurred, isoclinally folding the sedimentary rocks (and probably the volcanics). This diastrophism was accompanied or followed by dynamothermal metamorphism, probably in stages, and a system of intense multidirectional cleavage was imposed on all rocks. Further intrusive activity continued for some time thereafter.

The exposed series of Ḩaḑramawt is assumed to rest on an older metamorphic series exposed in the W.A.P. and this in turn on a more massive basement which is not exposed and not involved in the close folding of the outcrops. It is suggested that the exposed basement sedimentary rocks of the E.A.P. occupy a complex faulted depression in which the higher incompetent strata were faulted and crumpled under their competent cover in a kind of passive adjustment to deep-seated and short-ranged block movements, compression being applied from the west. Repetition of stresses could account for secondary schistosity and for ultimate multidirectional cleavage, perhaps resulting from the operation of stress couples due to horizontal blockjostling. These stresses and the main compression need imply no great displacement or crustal shortening (F. R. S. Henson, unpub. data, 1954–60.)

Peneplanation or mature erosion of the basement followed. After peneplanation, subsidence occurred around the northern and eastern margins of the Arabo-Nubian mass, where Paleozoic, Mesozoic, and Tertiary seas advanced and retreated over its extremely gentle slope.

The earlier marine cycles left no record in southwest Arabia, however, but successive transgressions in Jurassic, Cretaceous, Paleocene, and middle Eocene times led to the deposition of mainly shallow-water sediments.

The age of the basement peneplain in the E.A.P. is pre-Jurassic and probably dates back originally to the Paleozoic. On this peneplain a Jurassic marine transgression advanced from the south or southeast, but soon in the Late Jurassic, movements began to occur which caused the erection of a partial barrier that isolated an evaporitic basin inland. The movements are thought to have been largely block faulting. Later in the Late Jurassic the sea overcame the partial barrier and spread some way inland.

At the end of the Jurassic and in the earliest Cretaceous, uplift movements were again in evidence. In Somaliland this uplift followed the Gulf of Aden trend (Somaliland Oil Exploration Co., Ltd., 1954; Henson, unpub. data, 1954–60) and approximately follows the present line of the Somali plateau scarp. In the E.A.P. direct evidence is lacking for the assumption of a similar parallel uplift. Some indirect evidence suggests that uplift may have occurred, but this is by no means certain, because on both sides of the Gulf of Aden uplifts from which the Jurassic was removed diversified the main lines of the paleogeography, which is moreover concealed over large areas by later cover. In the E.A.P. and Dhufar the cross uplifts on a northerly trend (for example, Al Mukallā high) divide the region into north-south swells and depressions recognizable in coastal exposures by stratigraphic variations and inland by geophysical surveys.

During the Cretaceous the post-Jurassic erosion surface was tilted gently down toward the east and the Cretaceous marine transgressions advanced up this gentle slope from the east. Movements on a small, probably local, scale occurred along old lines of uplift. The Ra's Sharwayn area was uplifted in the Albian, and at Al Mukallā local uplift also occurred then and persisted until the end of the Cretaceous; the uplifted block trended north. Blocks were uplifted elsewhere also, some persisting throughout the Cretaceous, but in general Cretaceous sedimentation gradually levelled off the floor. This process retarded and accelerated as the successive cycles regressed and transgressed in the Cretaceous, owing to gentle epeirogenetic movements.

In Ḫaḏramawt, regional hiatus between the Cretaceous and Paleocene has been discovered from stratigraphic and paleontological studies, but the Paleocene follows the Upper Cretaceous in outcrop without any visible break. Local exceptions are found in the overlap of Paleocene on Lower Cretaceous at Al Mukallā and even on basement in the Wādī al Ghabar area. A gentle eastward tilting of the land surface occurred at this time and up this slope the Paleocene transgression advanced from the east.

In the Paleocene further slight tectonic movements began. In the north of the territory elevation of the North Ḫaḏramawt arch probably commenced with the end of slight terminal Cretaceous uplift; for a while it formed a (submerged?) barrier to the advance of the Paleocene sea, but it was overcome soon after during the late(?) early Paleocene. Westward in the W.A.P. and Yemen the Paleocene sea thinned and pinched out against a shoreline made up of the volcanics that had commenced in part to be extruded as early as the Late Cretaceous.

Tertiary movements continued throughout the early Eocene and thickness and facies variations of the Eocene are related to the progressive development of the gentle geanticlinal Ḫaḏramawt arch (s.l.) (p. H14–H46) that spans the whole territory.

No upper Eocene deposits are known in the territory, or elsewhere in southwest Arabia, but they occur locally in Somalia; it was during late Eocene time that the Ḫaḏramawt arch (s.l.) attained its maximum development, with general emergence and erosion. The development of the Ḫaḏramawt (and Somali) arch is regarded as due to regional compression which buckled the whole thickness of the crust. Important block faulting and step faulting followed along the coastal belt, largely obscuring the south flank of the arch which, however, is clearly seen in relatively unbroken sections. The prevailing fault trends of the arch are evidently related to the fold strike. The faults appear to be predominantly of normal type, but some local compression structures were produced before or at the same time as the folding and and faulting history.

Thus at Ẕulm Bā Tha‘lab the basement peneplain with a cover of Jurassic to Eocene formations has been smoothly arched up and faulted, the uplift being on too large a scale to be explained by only vertical movement. At Wādī Kilyah a small flat thrust involves Jurassic and Cretaceous beds. In Yemen where such structures occur, including basement "diapirs," some tangential block movement in the basement is suspected (Lamare, and others, 1930).

The salt extrusions of the Shabwah-‘Iyādh–Al Minṭāq areas may have been stimulated by subsurface drag stresses of the same origin, the salt functioning as a gliding plane near basement level. The extrusions occurred after the Paleocene and made their way through the massive limestone cover, with no sign in the stratigraphy of earlier activity, in spite of opportunities provided by faulting at the end of the Jurassic. The domes occur in an area of post-Paleocene cross faulting which may have caused the fractures and breaks seen in the limestone roofs of the domes.

The emergence and upwarping of large areas in Arabia and in the Gulf of Aden region and the formation of the Ḫaḏramawt and Somali arches was followed by extensive Oligocene and Miocene "transgressions" which invaded inland into coastal depressions from a

Gulf of Aden already formed before late Tertiary rifting.

The emergence of Arabia then resumed and has continued until the present day, with coastal faulting, tilting of Oligocene and Miocene deposits, local Pliocene and Pleistocene marine ingressions, and basaltic extrusions. Recurrent uplift and oscillations of the land surface in the Pliocene and Recent completed the history.

These events occurred all around the margins of the Arabian Peninsula and were not confined to the rift valleys (Red Sea and Gulf of Aden). It is indeed difficult to judge how much of the rift faulting was due to graben subsidence and how much to regional uplift of the bordering land surfaces.

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