AUFSÄTZE

On Afro-Arabian Graben Tectonics

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With 15 figures

Zusammenfassung

Unser Studium, das sich auf die Region zwischen Kenya und der Levante beschränkte, ergab eine Entwicklung der afro-arabischen Gräben, welche nicht vor dem ausgehenden Oligozän oder untersten Miozän begann. In mehreren taphrogenen Phasen, besonders in den Übergangszeiten von Miozän zu Pliozän, Pliozän zu Pleistozän und im mittleren Pleistozän sinken die Gräben weiter ein. Wir haben keinerlei Beweise ehemaliger, großangelegter Grabenstrukturen im kristallinen Grundgebirge oder in den präoligozänen Deckschichten, die während des jüngeren Känozoikums wiederbelebt wurden und die Bildung der afro-arabischen Gräben ausgelöst hätten. Bedeutende Verwerfungen in den voroligozänen Deckschichten sind recht selten beobachtet worden. Wo sie auftreten, stimmt ihre tektonische Richtung kaum mit dem Hauptstreichen der känozoischen Gräben überein. Im besten Falle übten diese alten Verwerfungen einen Einfluß auf die Entwicklung von Kreuz- und Diagonalverwerfungen aus, die auch eine Rolle bei der Anlage der Subgräben, Grabensplays und sonstigen Abzweigungen der Hauptgräben spielen. Ebenso selten ist Parallelität des Streichens der metamorphen Formationen des Grundgebirges und seiner intrusiven Dykes mit den Hauptgrabenlinien festzustellen.

Die afro-arabischen Gräben entstanden auf einer untertertiären Peneplain von regionaler Ausdehnung, die sich weit über Gondwana erstreckte. Die Gräben zerschneiden unbekümmert tektonische Highs and Lows, wie etwa Schwellen und Becken — eine Erscheinung, die nicht mit der Theorie eines „niedergebrochenen Gewölbesteins als Folge vorhergegangener Aufbiegung“ zu vereinbaren ist. Der gelegentliche Eindruck eines Gewölbes mit axialem Graben ist rein morphologisch zu werten und ist das Ergebnis „isostatisch“ hochgehobener und gekippter Großhorste, die an die Hauptgräben geknüpft sind. Im übrigen sind die meisten Megahorste keine „Halbhorste“, sondern riesige Blockgebirge (Levant, Etbai, Ethiopia, Danakil, Yemen), deren beiderseitige Hauptflanken durch große Zerrverwerfungen von Tausenden von Metern Sprunghöhe begrenzt sind. Diese Haupthebungen verursachten besonders während des Plio-Pleistozäns eine starke Abtragung der Deckschichten von den höchstgehobenen Teilen der Grabenschultern und seines Hinterlandes. Die wenigen bekannten Aufschlüsse von Kreide und Eozän in der Küstengegend des Roten Meeres, die als Anzeichen eines früheren marinen Golfes und Vorläufer des Rift valleys gedeutet wurden, sind allem Anschein nach Reste solcher Deckschichten, die in den abgesunkenen Grabenschollen von der Erosion verschont blieben.

Die kartierten Randverwerfungen sind normale Abschiebungen von durchschnittlich 70° Neigung, die auch in den nachfolgenden taphrogenen Phasen

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fixierte „ortsgebundene" Grabenrahmen blieben. Im Grabeninnern folgt ihnen eine Vorbergezone von gekippten Schollen, die auch zweitrangige Horste und Gräben in sich bergen. In den überdimensionalen Gräben von Afar und Rotem Meer mögen diese sekundären Gräben und Horste sogar Ausmaße annehmen, die in Breite den ostlevantinischen Gräben gleichkommen können. Im axialen Teil von Afar, des Roten Meeres und des Gregory Rift Valley tritt als jüngstes, d. h. pleistozänes Strukturelement ein ausgesprochener Graben-im-Graben (rift-in-rift) auf. Weniger deutlich ist diese junge Struktur im Graben des Golfes von Aden entwickelt. Der Adengraben weicht auch in anderer Hinsicht vom Pattern des Roten Meeres ab, vor allem in seiner untermeerischen Topographie und den eigenartigen transversalen off-set-Verwerfungen — beides morphotektonische Züge, die an den mittelozeanischen Rücken des Indischen Ozeans erinnern.

Ein Vergleich der geophysikalischen, besonders der Schweremessungen, die in den einzelnen Großgräben ausgeführt wurden, zeigt sehr widersprechende Ergebnisse. Während die höheren positiven Bouguerwerte magmatisches schweres Material im Boden des zentralen Graben-im-Graben-Abschnittes vermuten lassen, herrscht im größeren Teil des Afar-Verwerfungstrichters und im gesamten Gregory rift valley ein ungewöhnlich großes Schweredefizit, das auf eine äußerst dicke Kruste hinweisen würde. Dies ist um so merkwürdiger, da sowohl die Gräben wie die Horste Äthiopiens und Kenyas von gewaltigen basaltischen Trap-Laven und sonstigem basischem vulkanischem Material überdeckt sind.

Die Hypothese einer — im entgegengesetzten Sinne des Uhrzeigers — stattgefundenen Drehung und Drift der arabischen Halbinsel (einschließlich ihres vermuteten Einflusses auf die orogene Entstehung des Zagros-Faltengürtels) stößt auf mancherlei Schwierigkeiten:

1. Da die taphrogene Zerstückelung nicht nur die interkontinentalen afro-arabischen Gräben, sondern auch große Teile des Mittelmeeres und Indischen Ozeans betrifft, müßte die angenommene Drehbewegung von 7° um ein Vielfaches größer sein.
2. Yemen und Äthiopien, d. h. Arabien und Afrika, waren im Miozän noch ein zusammenhängender Kontinent. Als im Pliozän Yemen und Äthiopien (Danakil) durch den neu entstandenen Grabensplay von Bab-el-Mandeb abgetrennt wurde, war der nördliche Sinai und das nördlichste Ägypten ein Landisthmus geworden, wie er heute noch besteht. In der Tat war der Rote-Meer-Graben schon am Ende des Miozäns, obgleich für eine kurze Zeit, in ein eingeschlossenes evaporitisches Inlandbecken umgewandelt worden.
3. Was den axialen Graben-im-Graben des Roten Meeres anbelangt, der besonders Anlaß zur Drifthypothese gab, würde sein pleistozänes Alter eine Abdriftbewegung von ungefähr einem halben Meter pro Jahr verlangen. Es gibt indessen im Küstengebiet des Roten Meeres keinerlei prähistorische, historische oder gegenwärtige Zeugen, die auf ein seitliches Auseinanderweichen, und schon gar nicht von so großem Ausmaße, hinweisen. Eine jährliche Abdrift von einem halben Meter übertrifft überdies die optimistischen Berechnungen und Vorstellungen der Anhänger von so großen Driftbewegungen, wie sie etwa zwischen Afrika und Südamerika postuliert werden. Endlich vermißt man bei der Behandlung von Drifthypothesen — und das gilt ebenso für die Fragen horizontaler Verschiebungen — ein näheres Eingehen auf die mechanische Beanspruchung, der die rigiden Krustenteile bei so intensivem Auseinandertreiben unterworfen sein mußten.

Abstract

This study of the Afro-Arabian gräben, which concentrates on the region between Kenya and the Levant reviews their evolution that begun not earlier than in the latest Oligocene or in the lower Miocene. The gräben continue to sink in several major downfaulting phases, especially during the transitional times of Miocene to Pliocene, of Pliocene to Pleistocene and in the Mid-Pleistocene. We have no proof of erstwhile major graben structures in the crystalline Precambrian basement or in the pre-Oligocene sedimentary cover revived during the young Cenozoics that could have redeemed the formation of the Afro-Arabian megagräben. Significant faults in the pre-Oligocene sedimentary cover are seldom observed. Where they occur, their tectonic direction scarcely runs parallel to the principal trend of the Cenozoic graben. At best these ancient faults may have had an impact on the development of cross — and diagonal faulting which played also a role in the disposition of the subgräben, graben-splays and other offshoots of the main gräben. Equally rarely has parallelism of trend between the basement metamorphics as well as their intrusive dykes and that of the main graben lineations been established.

The Afro-Arabian gräben originated in a lower Tertiary peneplain of regional dimension which had expanded over large part of Gondwana. The graben dissection thus took place regardless of former tectonic highs and lows such as swells and basins — a phenomenon that negates the theory of key-stone dropping as a result of preceding upwarping. The occasional impression of vaulting with the graben as its axis is purely of morphological significance; it is due to "isostatic" uplifting and tilting of the main horsts attached to the main graben. Besides, most megahorsts are not "halfhorsts" but huge blocks mountains (Levant, Etbai, Ethiopia, Danakil, Yemen) bordered on both flanks by major tensional faults with throws of thousands of meters. These major uplifts, which are especially noticed in the Plio-Pleistocene, caused, moreover, the removal of the sedimentary cover by erosion and denudation in the elevated parts of the graben shoulders and its hinterland. The few known outcrops of Cretaceous-Eocene in the coastal area of the Red Sea, believed to be indications of ancient marine gulfs and thus forerunners of the Rift valley are in all likelihood the relics of such coverbeds that were saved from erosion in the down dropped blocks of the graben.

The surveyed marginal faults are normal dip-slips of average 70° dip. These remained in the ensuing taphrogenic episodes the "localized" fixed graben frames. In the interior of the graben they are followed by a Vorberge zone consisting of tilted blocks that implicate also subsidiary horsts and gräben. In the superdimensional rifts of Afar and Red Sea, the subsidiary gräben and horsts of the Vorberge zone may approach a width comparable to that of the East Levant rift valleys. In the axial part of the Afar, Red Sea and Gregory Rift valley appears as youngest, that is, Pleistocene structural element a distinct graben-in-graben or rift-in-rift. This young structure is much less developed in the graben of the Gulf of Aden. The Aden graben differs also in other aspects from the pattern of the Red Sea, particularly in its submarine axial topography and in the peculiar transversal fault offsets, both morphotectonic features reminiscent of the Indian mid-oceanic ridges.

A comparison of geophysical, especially of gravity measurements, carried out in the various main gräben reveals very conflicting results. While higher positive Bouguer values led to the conjecture of heavy magmatic material in the bottom of the rift-in-rift of the Red Sea, in most of the Afar fault-funnel and in the entire Gregory Rift valley there prevails an unusual large gravity

deficiency that would point to an extremely thick crust. This is all the more remarkable as both rift valleys and horsts of Ethiopia and of Kenya are dominated by huge basaltic trap lavas and by other basic volcanic material.

The hypothesis of anticlockwise rotation and drifting of the Arabian peninsula (including its supposed impact on the orogenic origin of the Zagros fold belt) has many pitfalls.

1. As the taphrogenic destruction is not restricted to the intercontinental Afro-Arabian gräben, but extended far into the Mediterranen and into the Indian Ocean, any anticlockwise rotation of Arabia must exceed the 7° postulated movement.
2. Yemen and Ethiopia, that is Arabia and Africa, were in the Miocene still a continuous continent. When they became separated in the Pliocene by the Bab el Mandeb splay, northern Sinai and northernmost Egypt had been transformed into a landlocked isthmus that has remained a continental bridge to this day. In fact at the end of the Miocene the Red Sea graben had already been turned — though for a short period — into an enclosed evaporitic basin.
3. As regards the axial graben-in-graben of the Red Sea that especially prompted the assumption of a drift between Africa and Arabia, its Pleistocene age would demand a drifting rate of half a meter per year. There are, however, at the coastal area of the Red Sea no prehistoric, historic or recent witnesses of lateral stretching at the Red Sea and certainly not of such excess. The deduced annual drift of half a meter there, exceed even the most optimistic calculations and images hitherto made by the adherents of such large drifting as has been postulated to have taken place between Africa and South America.
4. Finally, in the studies on drifts — and this also applies to the question of horizontal fault displacement — there is wanting a proper discussion on the mechanical deformations to which the rigid crustal parts must have been subjected in the course of such intensive tearing apart motions.

Résumé

Cette étude sur les fosses de l'Afro-Arabie, qui se concentre sur la région s'étendant entre le Kenya et les pays du Levant, montre que leur évolution n'a pas commencé avant l'Oligocène le plus tardif ou le Miocène inférieur. Les fosses continuent à s'affaisser durant certaines phases majeures, en particulier pendant les époques de transition du Miocène au Pliocène, du Pliocène au Pleistocène, et également pendant le Pleistocène moyen. Nous n'avons aucune preuve de l'existence antérieure des structures des fosses principales dans le socle cristallin ou dans la couverture sédimentaire du pré-Oligocène, qui s'est réouverte pendant le Cénozoïque supérieur, et qui pouvait conduire à la formation des fosses de l'Afro-Arabie. On observe rarement d'importantes failles dans la couverture sédimentaire du pré-Oligocène. Là où elles existent, leurs directions tectoniques sont rarement parallèles au principal alignement des fosses cénozoïques. Au mieux, ces anciennes failles ont pu avoir une influence sur le développement transversal et diagonal de failles qui ont aussi joué un rôle dans la disposition du subgraben, graben splays et autres embranchements des fosses principales. Non moins rare, est le parallèlisme entre les lignes directives des formations métamorphiques et les dykes intérieures du socle et les lignes des grandes fosses.

Les fosses de l'Afro-Arabie ont leur origine dans les pénéplaines du Tertiaire

inférieure — pénéplaines d'une dimension régionale qui s'est étendue sur une grande partie du Gondwana. Les fosses se sont développées indépendemment d'anciens Highs et Lows tectoniques, comme par exemple les seuils et les basins régionaux — phénomène qui ne correspond pas à la théorie du « keystone dropping » comme résultat d'un précédent bombement. L'impression qu'on a parfois de l'existence d'une voûte avec un graben axial, est d'une signification purement morphologique; elle est en réalité causée par des soulèvements « isostatiques » et par des mouvements basculant des horsts principaux attachés aux fosses principales. Autrement dit, la plupart des mega-horsts ne sont pas des demi-horsts, mais d'énormes blocs montagneux (Levant, Etbai, Ethiopie, Danakil, Yémen) qui sont bordés sur leurs deux flancs par des failles d'extension avec des rejets sur des milliers de mètres. Cet important soulèvement, observé particulièrement au Plio-Pleistocène, a causé l'élimination de la couverture sédimentaire dans les sommets des horsts, par l'érosion et la dénudation. Les quelques rares affleurements connus du Crétacé-Eocène sur les côtes de la Mer Rouge sont supposés servir d'indications à l'existence d'anciens golfes marins et donc, précédant ce Rift valley, ils sont plus vraisemblement les témoins de la couverture sédimentaire sauvés de l'érosion et préservés dans les écroulements du graben.

Les failles marginales sont des failles normales avec des rejets d'en moyenne 70°. Durant les phases taphrogéniques, ces failles sont restées les cadres permanents des fosses principales. A l'intérieur du graben elles sont suivies par une zone de Vorberge qui consiste en blocs basculés impliquant aussi des horsts et grabens subsidiaires. Dans les dépressions faillées de l'Afar et de la Mer Rouge, ces fosses subsidiaires de la zone de Vorberge peuvent approcher une largeur comparable à celle du Rift valley de pays de l'est du Levant. Dans la partie axiale de la Mer Rouge, de l'Afar et du Gregory Rift valley, apparaît un distinct « graben-en-graben » ou rift-in-rift qui est le plus jeune élément structural de l'âge du Pleistocène. Cette jeune structure est beaucoup moins développée dans la fosse du Golfe d'Aden. Ce graben adénien est aussi différent du graben de la Mer Rouge par d'autres aspects, spécialement par sa topographie axiale sous-marine et par ses curieuses failles transversales; deux traits morphotectoniques qui nous rappellent les rides dorsales de l'Océan Indien.

Une comparaison de mesures géophysiques, et surtout de gravité, faites dans les différentes grandes fosses, a montré des résultats très contradictoires. Tandis que les valeurs de Bouguer sont très positives et conduisent à une conjecture sur l'existence d'une masse lourde et magmatique au fond du rift-in-rift de la Mer Rouge, dans la majeur partie du terrain de l'Afar et de tout le Gregory Rift, ces valeurs sont extrêmement négatives — et indiqueraient une croute très épaisse. Ce phénomène est des plus remarquables puisque les grandes fosses et horsts de l'Ethiopie et du Kenya sont toutes deux dominées par de vastes traps de laves et d'autres matériaux basiques-volcaniques.

L'hypothèse d'une rotation contre le sens des aiguilles d'une montre et d'une dérive de l'Arabie (comprenant une influence semblable sur l'origine orogénique des plissements du Zagros) présente maintes difficultés:

1. Puisque la destruction taphrogénique n'est pas limitée aux fosses intercontinentales de l'Afro-Arabie, mais s'étend plutôt jusqu'à la Méditerranée et l'Océan Indien, la rotation de l'Arabie doit dépasser le mouvement supposé de 7°.
2. Le Yémen et l'Ethiopie, c'est-à-dire, l'Arabie et l'Afrique, représentaient un continent non-interrompu pendant le Miocène. Lorsqu'ils se sont séparés par le splay de Bab el Mandeb, le nord du Sinai et l'extrême nord de

l'Egypte se sont transformés et sont devenus un isthme qui réunit jusqu'aujourd'hui les deux continents. En effet, à la fin du Miocène, le graben de la Mer Rouge était même déjà devenu — pour une courte période — un basin évaporitique assez fermé.

3. En ce qui concerne le graben-en-graben du centre de la Mer Rouge — sur lequel se base, tout particulièrement, l'hypothèse d'une dérive entre l'Afrique et l'Arabie — son appartenance à l'âge du Pleistocène exigerait une dérive d'un demi mètre par an. Toutefois on ne trouve, sur la côte de la Mer Rouge, aucune preuve préhistorique, historique ou récente d'un déplacement latéral — certainement pas d'une pareille envergure.

   Ce taux de dérive annuelle, dépassant même les calculs les plus optimistes faits jusqu'à présent par ceux qui soutiennent la théorie du « drifting », est supposé avoir eu lieu entre l'Afrique et l'Amérique du Sud.

4. Finalement, dans l'étude sur la dérive — et cela s'applique également à la question du décrochement horizontal — on sent l'absence d'une discussion sur la déformation mécanique des parties de la croute rigide qui sont subordonnées à des forces intensives de détachement.

Краткое содержание

Настоящее исследование посвящено изучению Афро-Аравийского грабена, расположенного между Кенией и Левантом. Эволюция грабена началась не ранее позднего Олигоцена или раннего Миоцена. Он продолжал опускаться в течение нескольких главных сбросовых фаз, особенно во время переходных эпох от миоцена к плиоцену, от плиоцена к плейстоцену и в среднем плейстоцене. У нас нет доказательств, подверждающих прежние главные структуры грабена в докембрийских кристаллических подстилающих породах или в доолигоценовых осадочных породах, возрожденных во время раннего кайнозоя, которые способствовали бы образованию Афро-Аравийского мегаграбена. В доолигоценовых осадочных породах редко наблюдаются значительные сбросы. Там где они встречаются, их тектоническая направленность отнюдь не параллельна основному направлению Кайнозойского грабена. В лучшем случае, эти древние сбросы могли содействовать развитию поперечно-диагонального сбрособразования, которое также сыграло определенную роль в расположении подграбена, откосов грабена и других ветвей главного грабена. Также редко наблюдается параллелизация пластов между метаморфическими породами фундамента и их интрузивными дайками и главным направлением грабена.

Афро-Аравийский грабен образовался в раннем третичном периоде в пенеплене регионального размера, распространившегося на большую часть Гондвана. Расчленение, вызванное грабеном произошло невзирая на предыдущие тектонические поднятия и опускания или бассейны, — явление отрицающее теорию, объясняющую образования грабена обрушением в замке сводового поднятия. Случайное впечатление свода с грабеном, в качестве его оси, имеет чаисто морфологическое значение. Оно вызвано ,,изостатическим'' поднятием и наклоном главных горстов, прикрепленных к главному грабену. Помимо того, многие мегагорсты являются не ,,полугорстами'' а огромными блоками гор (Левант, Этбай, Эфиопия, Данакил и Йемень), окруженные с двух сторон главными сбросами растяжения, которые опускаются на тысячи метров. Эти крупные поднятия, особенно заметные в плио-плейстоцене, вызвали, кроме того, снос осадочного покрова в результате эрозии и денудации возвышенной части грабена и его хинтерланда. Малоизвестные выходы пород мела-эоцена в приморском районе Красного моря являются указаниями на древние морские заливы и их предвестники в долине Рифта это остатки подобного покрытия, не подвергшиеся эрозии благодаря опустившимся блоком грабена.

Обследованные краевые сбросы являются сбросами смещения (в направлении падения) с падением в среднем на 70 °. В последующие тафрогенные эпизоды они продолжали оставаться неизменными границами грабена. Внутри последнего они сопровождаются зоной предгорья ,,Vorberge zone'' состоящей из наклонных блоков, включающих также дополнительные горсты и грабены. В огромных рифтах Афара и Красного моря, дополнительный грабен и горст предгорной зоны могут достигнуть ширины Восточно-Левантской долины рифта. В осевой части Афара, Красное море и долина Рифта Грегори являются самыми молодыми, т. е. плейстоценовым структурным элементом явно выраженного грабена внутри грабена или рифта внутри рифта. Это молодая структура гораздо менее выражена в грабене Аденского залива. Грабен Адена отличается также и в других аспектах от строения Красного моря, особенно в его подводной осевой топографии и своеобразных поперечных сбросах, напоминающих средне-океанские горные цепи Индийского Океана.

Корреляция геофизических, особенно гравиметрических измерений, проведенных в различных главных грабенах показывает крайне противоречивые результаты. Если высокие позитивные показатели Бугера позволяют судить о наличии тяжелого магматического материала на дне рифта внутри рифта Красного моря, то в большой части Афарской низменности и во всей долине Рифта Грегори наблюдается необычная большая гравиметрическая недостаточность, указывающая на исключительно толстую земную кору. Это тем более замечательно, что в обеих долинах рифта и горстах Эфиопии и Кении преобладают огромные базальтовые трап лавы и иной основной материал вулканического происхождения.

Гипотеза о дрейфе и вращении против часовой стрелки Аравийского полуострова (включая его предполагаемое влияние на орогеническое происхождение Загроской складки) вызывает много противоречий. (1) Поскольку тафрогеническое разрушение не ограничивается интерконтинентальным Афро-Аравийским грабеном и простирается далеко в Средиземное море и Индийский Океан, любое движение Аравийского полуострова должно быть больше постулированного 7° движения. (2) Йемен и Эфиопия, т. е. Аравийский полуостров, являлись непрырывным континентом еще в Миоцене. Когда они отделились в Плиоцене Баб-эль-Мандебским сбросом, северный Синай и крайний север Египта превратились в закрытый перешеек, который и по сей день продолжает оставаться континентальным мостом. В действительности, в конце Миоцена грабен Красного моря превратился, хотя и на короткий период, в совершенно закрытый эвапоритический бассейн. (3) Что касается осевого грабена-внутри-грабена Красного моря, особо подчеркивающего возможность существования дрейфа между Африкой и Аравийским полуостровом, то его плейстоценовый возраст потребовал бы, чтобы отношение дрейфа равнялось 0,5 метра в год. Однако, в приморской части Красного моря нет доисторических, исторических и современных доказательств протяжения Красного моря, особенно такого значения. Годовой дрейф в 0,5 метра превосходит даже самые оптимистические расчеты и изображения по сей день выдвигаемые сторонниками столь огромного дрифта, который предполагался между Африкой и Южной Америкой. (4) В заключени изучения дрифтов, — что относится также к вопросу о горизонтальном сбросовом смещении, былобы желательно провести надлежащую дискуссию на тему о механической деформации, которой подверглась жесткая часть коры в ходе столь интенсивного растяжения. (автор)

Introductory

The considerable extent of the theme impels the writer to confine the present study to the countries stretching between the Levant and Kenya (Fig. 1). This limitation was particularly called for because he had

the privilege of touring parts of Afar and the adjoining Ethiopian and Somali plateaux under the guidance of I. ARKIN and in the company of T. HAGEN. He is indebted, therefore, to the courtesy of His Excellency ASSEFA LEMMA the, Ethiopian Minister of Mines in Addis Ababa, to whom he wishes to express his gratitude for the facilities which he provided for the tour. He must also acknowledge with thanks Professor L. S. B. LEAKEY's special help in arranging for excursions in the Gregory Rift Valley under the guidance of Dr. I. WALSH of the Geological Survey and R. CLARKE of the Natural History Museum in Nairobi and a visit to the Olduvai layers in Tanzania through the offices of Mrs. LEAKEY. The observations on the spot, re-inforced by the available published material on the Red Sea and Aden Gulf, yield a substantial total, and the writer believes that a summing up of the research in this field is now opportune. He is especially obliged to the "Geologische Vereinigung" for its recommendation and invitation to present this paper on Afro-Arabian graben structures at its annual meeting on 23 February, 1969.

Discussion

Intercontinental gräben are block dissections of the crust caused by gravitative, vertical subsidence movements. Except for the insignificant miniature gräben, they evolve episodically in taphrogenic phases.

In the Afro-Arabian areas (Fig. 1), which are the immediate subject of this study, the graben downfaulting generally begins shortly before the Neogene (end of the Oligocene?), though most run simultaneously with it, and in numerous instances assume increased intensity in the Quaternary. Episodic faulting conforms to the graduated and progressive development of the structural pattern. As with the Rhinegraben (PICARD, 1968), the writer inclines to the view that in the case, too, of the extensive gräben of the Afro-Arabian system, a marked Vorberge-zone is noticeable alongside the framing marginal faults. This Vorberge structure, which consists of tilted blocks, subsidiary horsts and gräben, generally follows, in the central part of the graben interior, an axial trough that has evolved during the younger phases, namely, in the course of the fracture phases of the Quaternary. The faults of the Vorberge bordering that axial innermost graben segment can attain very considerable throws. But in the superdimensional graben depressions, the Vorberge zones may well incorporate further subsidiary gräben of appreciable dimensions (for example, in the Afar depression). Medium and smaller cross faults that may reach well into the graben interior here replace the border faults. The much larger, obtuse angled transversal faults that end in the main graben may expand into diagonal graben splays, which often reach extensive regional sizes. They thereby add to the structural complexity of the gigantic depressions of the Red Sea and the Afar triangle (main diameter-more than 350 km.).

Notwithstanding the individual traits, which can yet be differentiated through the rock diversity of the sedimentary and/or magmatic graben fillings, the Afro-Arabian gräben are a global tectonic phenomenon of

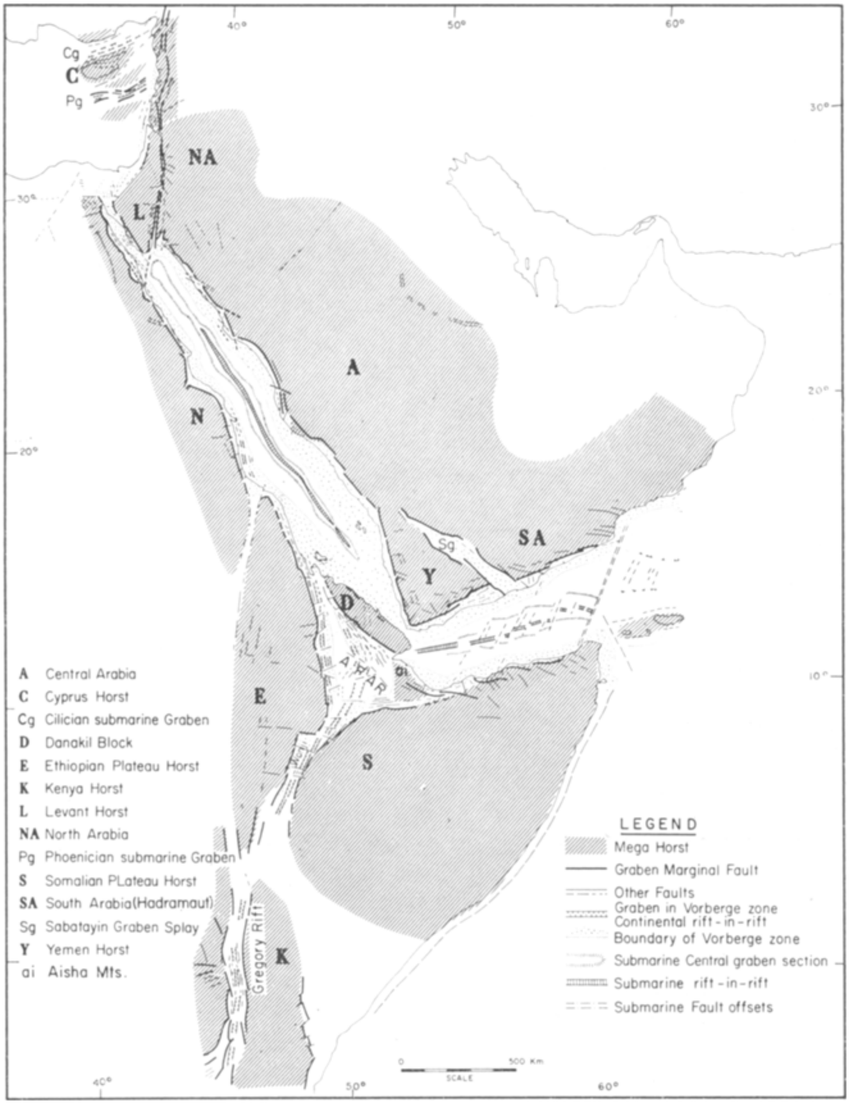


Fig. 1. Upper Cenozoic Taphrogenic pattern in the regions between the Northeastern Mediterranean and the Northwestern Indian Ocean.

the younger Cenozoics. As in the case of the European Rhenish system, so here too pre-rift Highs and Lows are cut, irrespective of whether they are regional swells and basins, or anti- and syneclises, up-and downwarps, syn-or anticlinal foreland folds. The gräben are thus in no case bound solely to upwarp vault zones, for example the Black Forest-Vosgues, the

Arabo-Nubian massif, the so-called Ethiopian and East-African swells. On the contrary, comparably in a way to the Rhinegraben (PICARD, 1968, p. 12), a close analysis establishes that the first downbreak of the Afro-Arabian gräben evolves on a flat and low relief of late Paleogene or sub-Miocene peneplains. Even the initial shield and plateau lavas flow over that low relief and precede the proper graben formation. That is why the gräben emerge after a continental, tectonic respite pause that had prevailed on the Gondwanian craton, and often also on its border areas. A pre-graben vault, such as the one visualised by ELI DE BEAUMONT in the Vosgue-Schwarzwald, and assumed to prevail also in the Arabo-Nubian massif, is little more than a morphological vision. What we confront in this massif are half-horsts that had been isostatically lifted and tilted in the wake of the episodic downfaulting of the graben. That impression vanishes as one gets to the genuine horsts surrounded by marginal faults on both flanks, as in the mega-blocks of the Levant, Etbai range, Yemen, Danakil, the Ethiopian high plateau and those of the East African craton (BROCK). The prerift upwarping theory, and the (GREGORY) keystone drop theory closely bound up with it, are, therefore, untenable even from a morphological point of view with respect to these regional blocks. One must, with BROCK (1953), equally rebut the idea (KRENKEL) of the uniform long swell originally running from Mozambique to as far as Ethiopia or even (as HOLMES believed) as far as the Arabo-Nubian massif, that was followed by graben downfaulting along their-length axis. In view of the current high topographical position of several mega-horsts that reach an altitude of up to 3000 metres, one would be more justified in speaking of block-mountains rather than of swells.

The attempts to trace these block mountains; as well as the large grabens that adjoin them, to old revived structures must prove abortive on closer examination (Fig. 2). The trend of Precambrian to Mesozoic dislocations and folds tallies only in exceptional cases with the directions of our young Cenozoic regional crustal faults. At the same time, we should not forget that, comparably to the experimental deformation ellipsoid (re-discussed in KUPFER, 1968), the strain ellipsoid of the earth must have recurrently reacted with kindred fissures upon compressional and tensional forms of the crustal epidermis (SONDER). Meridional, equatorial and oblique complementary fault directions recur in all rigid crustal parts, no matter whether we designate them (as in Central Europe) as Rhenish, Hercynian, Variscian, or (as in Afro-Arabia) East-African, Erythrean, Adenean, Aualitic, and so forth. All too little weight appears to be attached in this to the requisite mechanical deformation that should have occurred along the mobile fault planes, both vertically and horizontally, that recurrently moved over so many periods of our earth history. Such presumed permanent or episodic revivals at both dip-slip and strike-slip dislocations should have been manifested by enormous mylonitized friction zones.

Regional Survey

Red Sea and Levant

The upper Cenozoic Red Sea graben, 400 km. (maximum) wide and 2000 km. long, that separates Arabia from Africa, presents in its interior numerous bifurcations which are, in effect, little more than small offshoots of the graben (Suakin, Wadi Ifal for example). More striking and above all better investigated, are the northern splinters of the Red Sea graben, the Suez and Aqaba grabensplays. The (35 km. wide) Suez graben, which retains the so-called Erythrean direction (from NW to NNW) cuts the undulated Egyptian Galala and Western Sinai. We have no knowledge of its continuation under the continental and submarine young sediments of the Nile delta [1]). Much more narrow (a width of 10—15 km.) is the acute angled branching-off of the Aqaba Gulf and its graben-shaped continuation to as far as the Syrian-Turkish border. The sub-gräben of the Arava, the Dead Sea, the Jordan, the Orontes, the Kara Su which are variously designated and are more or less meridionally directed, are best grouped together into one group of an "East Levant Graben Zone" (PICARD, 1966). They dissect the Cenozoic anticlinorial uplifts and the synclinorial downwarps of the Negev, Jordan and Syria, including the foreland folds. The Sirhan depression, frequently assumed to be a graben, is apparently a major trough and, consequently, best fitted into the undulation system that stretches between the Jafr basin and the Rutba upwarp (BUREK). There still remains unresolved the question: To what extent does the Damascus depression owes its present tectonic situation to young taphrogenic movements?

The Neogene-Quaternary gräben of the Levant are however by no means restricted to the continent. They dismember the northeastern Mediterranean, for instance, the Phoenicia graben, the Cilicia graben, the Cyprus horst (PICARD, in press). Finally, mention should be made of the numerous smaller horsts and gräben that dissect the sedimentary cover of the Levant mega-horst into subsidiary blocks of diagonal to equatorial direction, such as Galilee, Lebanon, North Syria. Noteworthy too are the cuneiform miniature gräben wedged in the Precambrian crystalline basements of Sinai, of opposite Midian and of the Egyptian Etbai range, with fillings of sediments removed from the the adjoining horsts by erosion and denudation.

Ethiopia and Kenya

The split in mega blocks and graben splays is no less marked and forceful in the southern tip of the Red Sea graben. The Danakil block

[1]) It may be asked whether the Suez graben advances at all in the Mediterranean, or, like the Aden Gulf, is superseded by a graben trending more to an E—W direction. The second alternative should get support not only in the extraneous E—W fault lineament, that sets in on the structural line Cairo—Northern Sinai, but also in the parallel course of the Bouguer gravity anomaly lines (DE BRUYN).

here, as a separating barrier, (500 km. long; 100 km. wide; 2000 m. high) divides the Red Sea graben into two graben offshoots, namely the Dallol-Saltplain graben splay between the Danakil- and the Ethiopian blocks, and the Bab el-Mandeb graben splay between the Danakil and the Yemen blocks. The last-mentioned offshoot narrows down considerably as it reaches Bab el-Mandeb; its tectonic relation with the Aden Gulf graben is still not too clear or explicable. On the other hand, the Dallol-Saltplain graben, starting in the North at the Zulu Gulf, opens narrowly, then expands and becomes wider as it gets nearer to the so-called Wonji belt that terminates here. The Wonji belt is of East-African NNE orientation, and lies axiswise between the Ethiopian and the Somalian plateaux horsts. These two horsts form, with the Danakil horst, the gigantic funnel-shaped fault depression of Afar. It is most significant that all marginal main faults of the three major horsts are immediately followed by a Vorberge zone. That zone contains subsidiary gräben among the usual tilted step blocks. The subsidiary gräben are remarkable for their considerable width (10—15 km.), in keeping with the enormous dimensions of the Afar main graben. Like all other step blocks of the Vorberge, these run parallel to the main border faults; in other words, they trend between Erythrean NNW and meridional N—S, in Danakilean WNW, and between Adenean ENE and almost equatorial E—W directions. The East-African Wonji belt belongs to the Afar triangle only in its terminal sector. The largest part of it stretches southwards down to Kenya, and is detached by the 60—80 km. wide Gregory Rift Valley, whose direction is strictly towards N—S.

Aden Gulf: South Border Area:

An appreciable part of the Vorberge zone has been sunken down in the Indian ocean. This will be discussed later in our reference to the other suboceanic inner graben structures of the Aden Gulf. The major border faults on the continent appear to be detached en échelon.

The small "Aisha Horst" of Mohr (1967) situated to the South of the Gulf of Tajura (apparently the Ali Sabiet block of Azzaroli) is generally compared with the much larger Danakil horst north of this gulf; yet more precise data remain to be obtained before light is shed on these structure relations.

Southern Arabia (Yemen-Hadramaut):

Opposite the Danakil block stretches the major horst of Yemen. Like the horsts of the Ethiopian-Somalian plateaux and of the Danakil Alps, the Yemen horst, too, was built up of Precambrian basement rocks, Mesozoic cover sediments and Cenozoic volcanic material.

The graben splay of Bab el-Mandeb is distinguished by the meridional N—S direction of its western marginal fault, which borders the Yemen horst. The eastern border fault of the Yemen horst, however, resumes the Erythrean direction, and forms the rim of the sand-covered Ramlat-es-Sabatain depression. This eastern marginal fault extends to the North, as far as the Najran province of the Saudia-Yemen frontier district (GEUKENS), while to the South it continues its course either straight or en échelon as Ataq mainfault (GREENWOOD and BLEACKLEY). Moreover, the Ataq mainfault shaped the boundary between the crystalline Precambrian of East Yemen and the sedimentary Meso-Cenozoics of Hadramaut.

BEYDOUN's pictures show further NW—SE faults which traverse and cut through the south-western Hadramaut. Of these the important Ifdah fault is particularly noteworthy (according to GREENWOOD and BLEACKLEY). It embraces, jointly with East-Yemen's Ataq fault, the 80 km. wide Wadi Mayfa'ah drainage basin, which is also thickly covered by sandy alluvial. All these geological traits give the impression of an Erythrean- or Danakilean-directed graben splay, namely, a bifurcation of the Gulf of Aden graben composed of the fault depressions of Wadi Mayfa'ah and Ramlat-es-Sabatain, separating Yemen from Hadramaut. (The many internal smaller faults of the Sabatain graben splay have apparently contributed to the diapiric rising of the Jurassic salt deposits during the upper Cenozoic, namely, at the time of the formation of the graben).

In its tectonic situation, the South Arabian Yemen block recalls its North Arabian counterpart, the Levant horst. In both cases, acuteangled offshooting graben splays (Suez, East Levant, Bab el-Mandeb, Sabatain) and oceanic downfaultings (Mediterranean, Indian ocean) lead to the formation of a triangular crustal mosaic. Both horsts are marked by their additional subsidiary and miniature gräben. Like the post-Eocene undulations of North Arabia (El Jafr basin to Rutba upwarp), the Hadramaut borderland, too, with its anticlinorial waves of lower Cenozoic age, remains untouched by upper Cenozoic graben tectonics. BEYDOUN's meticulous mapping shows Adenean ENE oriented, en échelon shaped border faults, which follow an emphatic Vorberge block zone with typical endemic graben structures.

Pre-Rift Structural Tendencies

The Trend Disharmonies (Fig. 2):

The earlier regional structural maps (FURON, 1958, USSR, 1966), had already shown distinct disharmonies between the trend of the basement and the Paleo-Mesozoic-Paleogene cover and the trend of the young Mesozoic gräben; these disharmonies come even more markedly to the fore in the latest edition of international tectonics maps (CHOUBERT, 1968).

The folds and other bending forms of the Levant block are crossed by taphrogenic disturbance lines at the obtuse, and even at the right, angle. That contrast is particularly striking in the trend of the Precambrian basement of the Arabian demi-massif, where the Algonkian schists, especially the structural lineaments of the ophiolites, strike in a sharply angled direction towards the Erythrean graben. Even late Algonkian wrench faults (for example the Nadj fault), which traverse and pierce the low grade to non-metamorphic sediments of the youngest Precambrian, depart as much as from 20° to 30° from the direction of the marginal faults of the Red

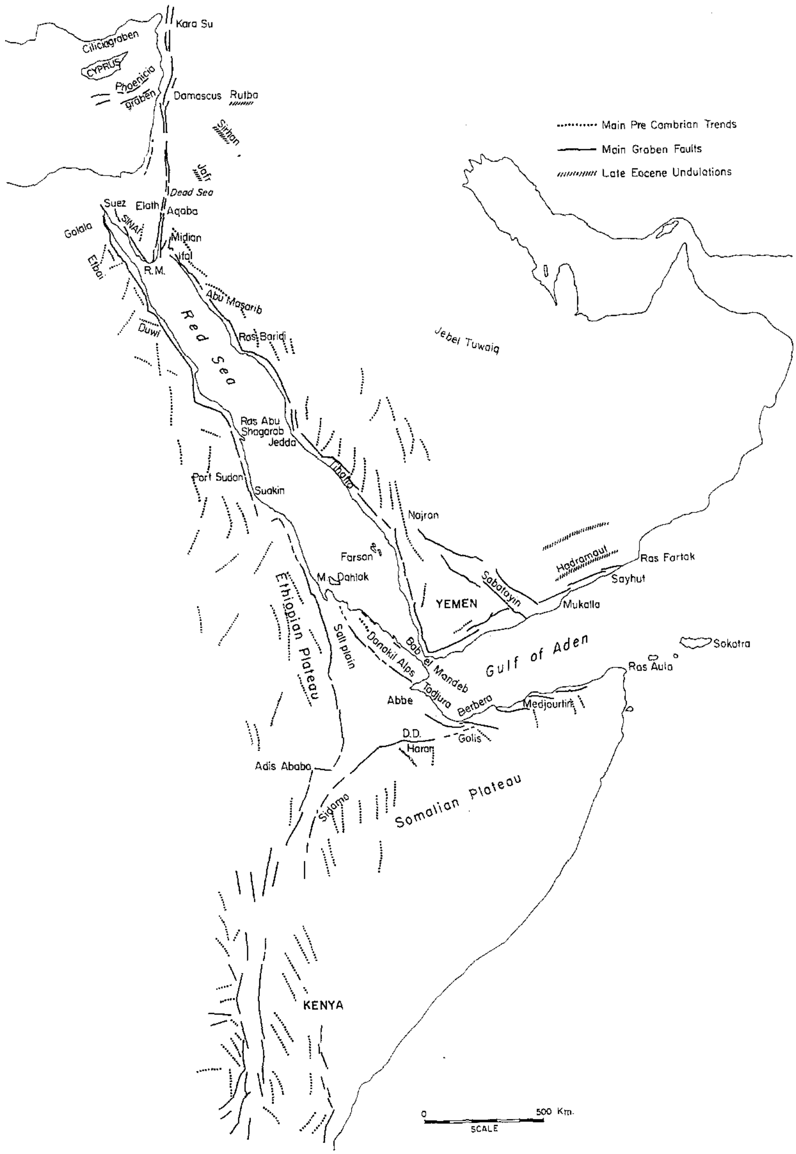


Fig. 2. Main Precambrian trends surrounding Afro-Arabian gräben regions. Sources: ARAMCO, 1963; CHOUBERT, 1968; FURON, 1958; MOHR, 1962; SCHÜRMANN, 1966; USSR, 1966. (Fig. 2. also indicates location-names refered in the text.)

Sea Graben. This geological fact thus supports the conclusion ob BROWN & JACKSON (1960, p. 77), when he said inter alia —

"The Arabian fault zone forming the eastern side of the Red Sea rift has no apparent connection with the ancient structural lines of the crystalline rocks . . ."

In the opposite semi-massif of Nubia, as well, the N—S trend of the Algonkian belt (PICARD, 1940) is in tectonic discord in relation to the Red Sea graben. DAINELLI's isohypses of the Precambrian surface of Ethiopia, and particularly the younger foliated schists of the basement (see MOHR, 1962, Figs. 2, 3), do not harmonise in their strike direction with the principal marginal disturbances of the Afar depression; or even run in a perpendicular direction towards them. Only in Northern Erythrea is there parallelism between the old lineament and the younger fault tectonics. The actual Wonji graben likewise cuts at an acute angle through the meridionally-oriented crystalline Sidamo complex. It is true that the northern Gregory Rift Valley runs somewhat 'casually' parallel to the trend of the crystalline socle; but that trend already departs in an oblique direction at the southern rift valley. In the Malawi (Nyassa) graben even the strike of the basement in the opposite graben flanks is thoroughly different. Indeed, there is perpendicularity even between basement trend and the graben direction of Lake Kiwu and the Upper Lake Tanganyika. In his discussion of the East African Rift Valley, Quennel reaches the conclusion that — "Faults rarely coincide with primary foliation".

The problem of Fault Rejuvenation:

In our reference to the wrench and normal faults of Saudi Arabia's Precambrian basement, we have already drawn attention to the fact that these faults had nothing in common with the direction of the border faults of the Red Sea. Where strike slips are assumed, as in the Abu Masarib fault (Abdel-GAWAD), they are connected with oblique subsidiary gräben or graben splays which contributed to the sinoidal, serrated translocation of the graben border faults. The survey made by the ARAMCO geologists, which covered that enormous, wholly exposed, territory, shows no definitive Precambrian faults which penetrated into the Paleozoic-Mesozoic sediment cover. Similar findings were reached on the latest observations in the Transjordan sedimentary cover of the Hisma region (BENDER) and the Elath region in the Sinaitic Negev (BENTOR). The NE—SW fault of Inner Arabia, largely covered by the sand dunes of the Great Nefud, do, it is true, dislocate the Paleo-Mesozoic layers, but they end at the basement outcrops. That fault may be of Cretaceous age, just like other assumed buried faults in the eastern flank of the Arabian shield (NAGIB, DUNNINGTON). Narrow, 2 km. wide, 200—300 km. long, arcuate gräben running from N—S to E—W (KARPOFF, 1956) are entrenched in the Jurassic-Cretaceous cuestas of the Jebel Tuwaiq. If the 300 m. throw observed by KARPOFF (p. 295) at Dhurma is consistent they should terminate in the sedimentary mantle, providing the gräben are wedge-shaped and not limited by straight vertical faults as drawn in ARAMCO's cross-sections.

In the Lebanon and the Negev, faults of late Jurassic age have been established. Their amount of throw and their regional extension is as yet unknown. DUBERTRET believes that such Jurassic faults are of wrench character, and were revived in most recent times as tensional Dead Sea-Jordan graben faults. In the view of the writer the necessary compressive forces of a Jurassic orogeny are wanting to establish such large scale horizontal displacements; nor are the mechanical manifestations of blasto-mylonitic friction zones documented. This applies also to VROMAN's (1961) E—W strike-slips, whose age is, however, not stated by him. Nor has a continuance of such Jurassic dislocations into the Cretaceous to Tertiary cover yet been established. The basic plateau volcanism in the Lebanon and the intensive dyke intrusions in the Negev are rather proof of tensional block dissections at the end of the Jurassic. In the wake of it, a taphro-epeirogenic uplifting occurred here, that was followed by sub-aerial erosion and pre-Neocomian peneplanation.

The problem of the Jordan-Dead Sea wrench faulting has been discussed elsewhere (PICARD, 1966, 1968, and in press). According to WETZEL and MORTON and, more recently, BENDER, thickness and facies differences, which have been adduced as proof of enormous horizontal displacements, are fully explicable in the light of old EN—SW oriented shore lines. This explanation does not, however, undermine the belief (BENDER, Fig. 22 b) that there were NW—SE directed marine ingression bays, which existed from Cambrian to as far as the Eocene. On the other hand, the writer is still in the dark as to why these diagonally directed ancient arms of the Tethys ocean should be taken as indicating subsidence tendency of such long duration along the current, yet meridionally directed Jordan graben. Nor are the recurrent trend of the Algonkian dykes in Midian, running parallel to the meridional strike of the Jordan-Arava gräben, (southernmost Transjordan), conclusive evidence of the predestined graben layout since Precambrian time. Other Algonkian formations, such as the Saramuj series (PICARD, 1941) in the Jordan valley are cut by young Algonkian dykes also in diagonal, even transversal, direction. One might similarly mention here the young Algonkian slates and greywacke schists of the Wadi Barqa (BENDER, p. 38, 46) which strike at an obtuse angle to this Levant graben section. (As in the rest of Arabia-Ethiopia, these weakly metamorphic sediments were peneplaned in eo-or infra Cambrian time.) But the most convincing example of trend disharmony between Precambrian basement dykes and young Cenozoic graben directions is found in SCHÜRMANN's (Fig. 16, p. 192) dike distribution map of Sinai and the Egyptian Eastern Desert, reproduced in our Fig. 3. There, nearly all dykes run perpendicularly or with obtuse angles to the strike of the Suez- and Aqaba graben. (See also SCHÜRMANN's Sheet IV, with marked trend disharmonies between basement foliation and Suez rift.)

BEYDOUN and AZZAROLI mention Jurassic block movements in the southern Arabian and Somali border areas, and also considered the possibility of reactivation during the Cenozoic downfaulting of the Aden

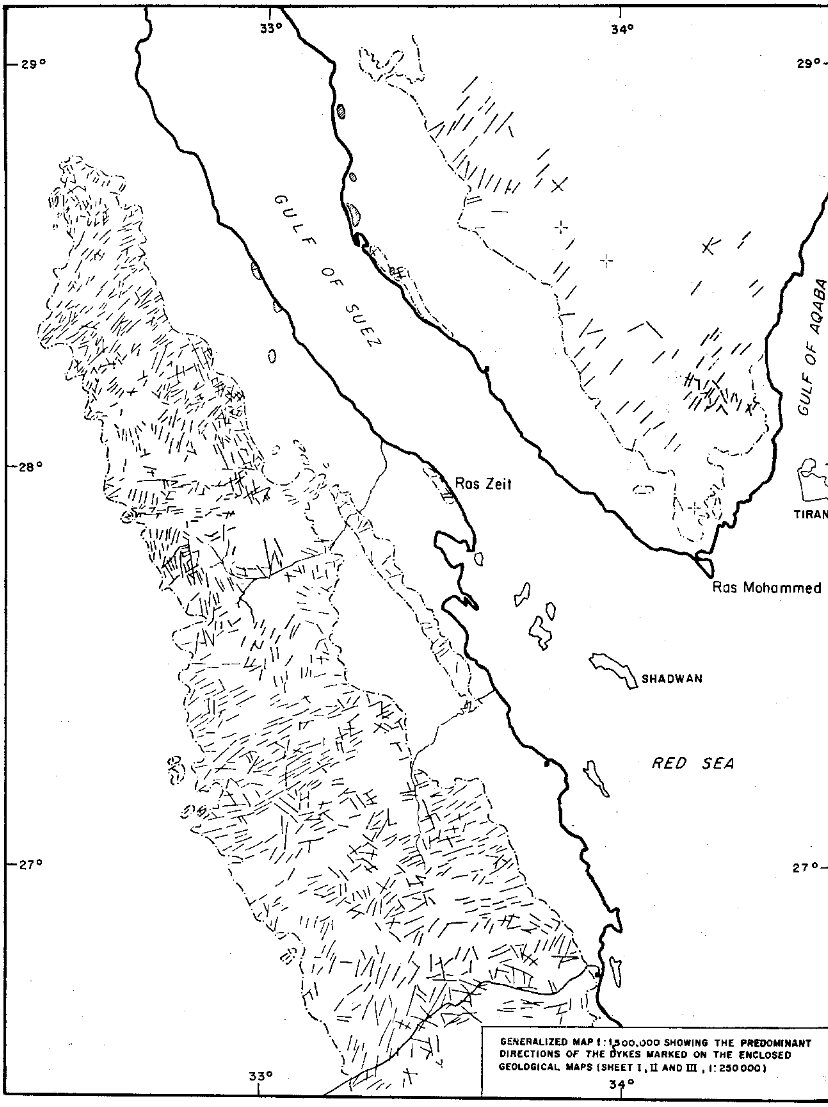


Fig. 3. Precambrian dykes in the Etbai Range and in the Sinai; from SCHÜRMANN, 1966 (Fig. 16)

graben. Nevertheless, AZZAROLI (1968) finds that assumption difficult to sustain in view of the different trend of the Jurassic sedimentary trough. According to GREENWOOD and BLEACKLEY, the graben faulting is "not controlled by basement faulting". To the best of our knowledge, no faults of definite Precambrian age have been established hitherto, or even mentioned, in Ethiopia. Nor do we know of such faults that moved again in the Mesozoic cover after the long Paleozoic interval of 200—300 million years. The origin of faults which cut through the Mesozoic (for example, Tigrai) or Eocene (for example, Somalia) sediments is closely linked with the Cenozoic taphrogeny.

As to Kenya, BAKER (1963, p. 18) stresses, with SHACKLETON, that "there is no evidence of . . . pre-Tertiary faulting".

Age of Rift Valley Formation

A key to the understanding of the geological development of the Gondwanian section of Afro-Arabia is provided, above all, by the peneplains or regional unconformities that stretch far across the continent. The more important of these for the present study are the infra-or eo-Cambrian land surfaces, and also the mid-Tertiary (late-Eocene to proto-Miocene) surfaces. They were caused not only by subaerial, but also by abrasive marine forces and, in turn, have produced some large formation gaps. Thus in South Arabia, Permian sediments lie directly on the pre-Cambrian basement formations. In Ethiopia this hiatus gets as far as the Triassic, while marine Mesozoic transgressions of the Indian ocean also contribute their share to the development of the discordance surface. As the writer could observe in Dira Dauwa, near Harar, even the fossil lateritic soils, which otherwise are intercalated between the peneplaned basement rocks and the sedimentary cover, were eliminated by the abrasive work of marine Mesozoic transgressions.

In North Arabia the shallow Tethys Sea already penetrates in the Paleozoic deep into the interior of the shield; in the result, sedimentary gaps of long duration are rarer there, except for the "Lipalian Interval". Such shorter intervals and unconformities are known to have taken place especially at the end of the Jurassic, Triassic and Eocene. Not a single rift valley, discussed here, started its downfaulting before the Miocene. The valleys evolved also on an undulated low relief that had developed in the course of the Lower Tertiary (principally Oligocene). In the course of the strong Neogene and Quarternary uplift subaerial erosion must have largely removed the Paleo-Mesozoic (and Eocene) sediments which once covered large portions of the Arabo-Nubian massif. Relics of these pre-Neogene formations can therefore be expected only in the downfaulted areas of the Red Sea graben or in the wedged-in miniature gräben of the mega-horsts (for example, Yemen, Sinai, Etbai). KARPOFF's (1956) as well as CARELLA's and SCARPA's (1962) discoveries of Cretaceous in the Vorberge zone of the Red Sea graben, near the uplifted crystalline basement of the Arabo-Nubian massif, may represent such relics. They are thus comparable to the Mesozoic Vorberge of the Rheingraben adjoining the crystalline (Hercynian) Black forest-Vosgues massif, the sedimentary cover of which has been equally downworn since the Tertiary graben faulting.

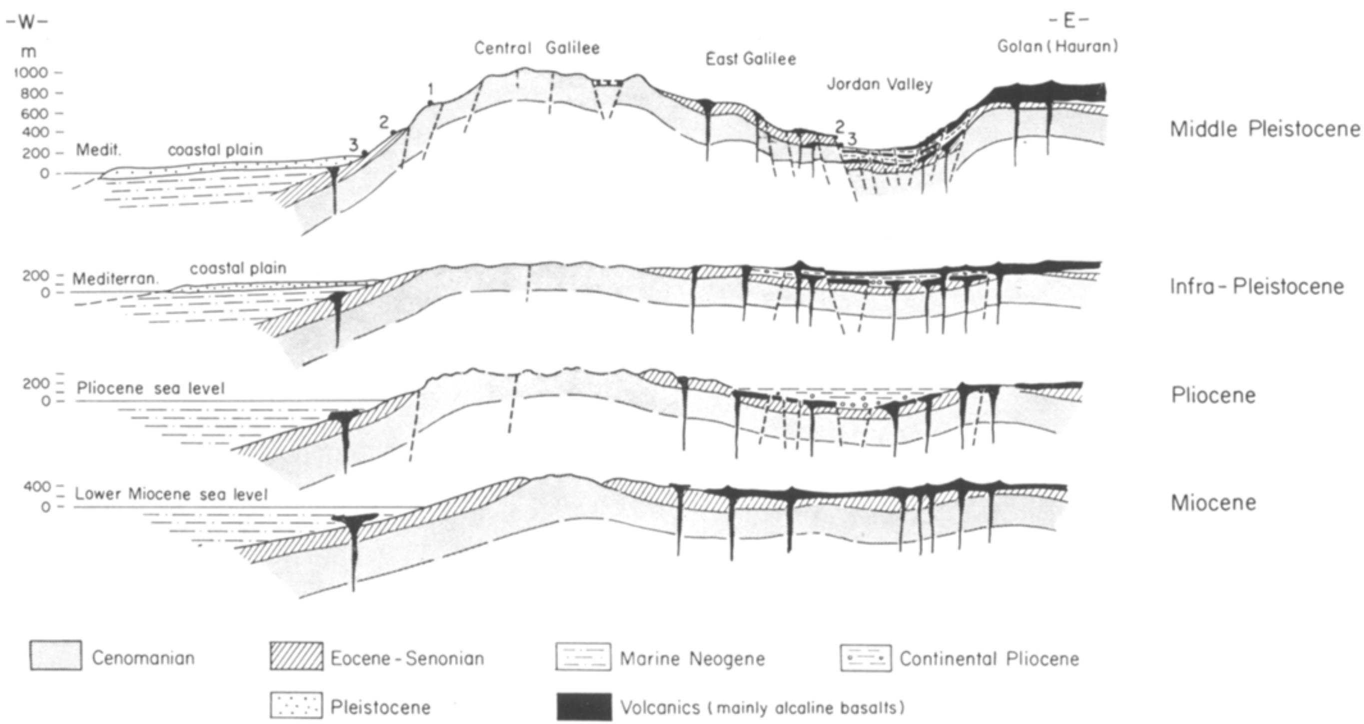
At all events, an assumed Mesozoic graben inception does not appear to the writer as to be the sole justification for the occurrences of pre-Neogene formations inside or at the border of the Red Sea through.

In the Levant, the extensive basalt traps which cover the Hauran and parts of southern Galilee have already (PICARD, 1932) been taken to be pre-existing land-surfaces. Graben downfaultings, had not evolved before the Vindobonian (PICARD, 1943), and were substantially directed diagonally (NE—SW, NW—SE). After a brief uplift followed by denudation (SCHULMAN, 1959), basalt plateau lavas-once again in the Pliocene-flooded upon a relatively low relief. Not till the proto-Pleistocene did the principal graben downbreak proceed[2]). It linked various Neogene inland basins with the newly formed, meridionally-directed, graben system of the Levant (Kara Su-Orontes-Jordan-Arava-Elath). In the Jordan Valley the Graben underwent further downsinking at the beginning of the middle Pleistocene. It was followed by volcanic eruptions that must have been active well into historic times, and whose lavas flowed over the graben shoulders, that had meanwhile been uplifted, down into the graben. Young-Pleistocene taphrogenic movements are insignificant. They are reflected in fine earthquake ruptures and minute strike-slip and dip-slip faults, probably traceable to endemic settling processes of blocks in the graben interior. The enclosed diagram (Fig. 4), which was shown at the Symposium of the International Hydrological Association in Athens (1962), gives a graphic conception of the graben evolution in northern Israel since the end-Miocene.

The structural development phase by phase of the East Levant graben is one of extraordinary affinity with that of the Gregory Rift Valley in Kenya, which will be discussed in the next chapter. SHACKLETON lays special stress on the regional importance of the sub-Miocene peneplain, and on its being covered by Miocene lavas upon which the initial downfaulting of the graben had subsequently taken place. BAKER, PULFREY and McCALL subscribed to that view and showed that the succeeding taphrogenic phases were also preceded by volcanic eruptions. Three important downfaulting episodes have been established by these authors in Kenya: mid-or end-Miocene, end-Pliocene, mid-Pleistocene.

According to MOHR's latest study on Ethiopia's principal gräben (1966, 1967), there again the Miocene trap series lie "with slight un-

[2]) The question whether there had already been in the Pliocene a uniform graben zone, stretching from the Gulf of Aqaba to North Syria, remains unresolved. There can be no doubt as to the existence there of Neogene basins. Thus, a marine Neogene graben splay of the Red Sea main graben is found in the southern Gulf of Aqaba, near Makhma (ARAMCO map, HEYBROEK). Semi-marine layers were described recently (BENDER) from the eastern border of the Arava valley; but they also occur on the western border of the Dead Sea, and have been known for some time from southern Galilee. Their presence there is easily explained as Neogene ingressions of transversally directed Mediterranean bays (for example, the Jezreel and the Beersheba inlets). *Ammonia (Streblus)* foraminifers together with other Pliocene faunas are attributed to the Pliocene (SHAHAR, REISS & GERRY). Their presence there may be ascribed to Neogene ingressions which entered via the Jezreel and Beersheba bays as far East as the present Jordan-Arava valley. In the circumstances, one may still adhere to an end-Pliocene age for the initial rupturing of the Jordan-Arava graben; in the event of an earlier dating one arrives at best at a' an early Pliocene age.



Fossil aquifer base-levels: 1 Miocene ?, 2 Pliocene, 3 Pleistocene

Fig. 4. Diagram illustrating the evolutionary stages from Miocene to Pleistocene in the Levant sector between Mediterranean, Galilee and the Hauran.

conformity upon Mesozoic rocks", and "on a generally low-lying peneplain". Originally of an altitude of 100 m., these were elevated in course of time to their present altitude of 3000 m. Nevertheless, MOHR adheres to the view of an original Oligocene upswell, upon which rifting and vulcanicity followed. According to him, swell-uplift and rifting phases fall principally into mid-Miocene, mid-Pliocene and mid-Pleistocene.

In Yemen, LAMARE had already identified sheet lavas as traceable to a pre-graben age. KARRENBERG is even more explicit when he says inter alia that — "At the beginning of the trap formation the uplift of the Arabian block had not yet started, and the Red Sea had not yet existed". GREENWOOD and BLEACKLEY place the first graben formation of the Aden Gulf in the Oligocene, or early Miocene, while according to AZZAROLI (1968) "the graben foundering started in Lower Miocene-Aquitanian" or in the Burdigalian (AZZAROLI, 1958), whereupon the principal faulting between mid-and upper Miocene followed. Moreover, he reached the conclusion that the gräben were first formed, and the marginal scarps subsequently faulted. In other words, he opposes the collapsed swell theory.

In the Eastern Desert of Egypt a strong "pre-Miocene relief" (HEYBROEK, 1965, p. 23) and a rather smooth land surface (el-Terabili, 1966, Fig. 2—6) preceded the downfaulting of the Neogene Red Sea-Suez graben and the responding uplifting of the "Red Sea Horst" or Etbai Range.

As to the age of the Red Sea-Suez graben and its downfaulting phases: Lower Miocene, Pliocene, Pleistocene, there is a consensus of agreement in the latest studies on the subject (BROWN, SESTINI, HEYBROEK, WHITEMAN). Summing up: following upon a peneplanation of the Afro-Arabian part of Gondwana, which developed principally in the Oligocene, there began a taphrogenic disruption of the crust that streched from the Mediterranean to as far as the Indian ocean. That dissection continues episodically up to the Quaternary.

Evolution of the Graben Pattern

Kenya

The following evolutionary and tectonic picture of the meridionally-directed, 60 km. wide Gregory Rift Valley is substantially based on the detailed mapping and the publications of Kenya's Geological Survey.

The initial marginal main faulting (Fig. 5) took place upon the Lower Miocene volcanic traps that rested on an undulated sub-Miocene peneplain, which had evolved before. With an original throw of 1200 m., that increased to 2800 m. in later fault phases, the marginal faults remained stable fault-frames throughout the succeeding graben sinking. Some smaller oblique faults became welded together with the marginal faults, but they never transverse it, even though they penetrate into the graben. The second principal downbreak occurred at the end-Pliocene or the proto-Pleistocene. It caused further significant faults of

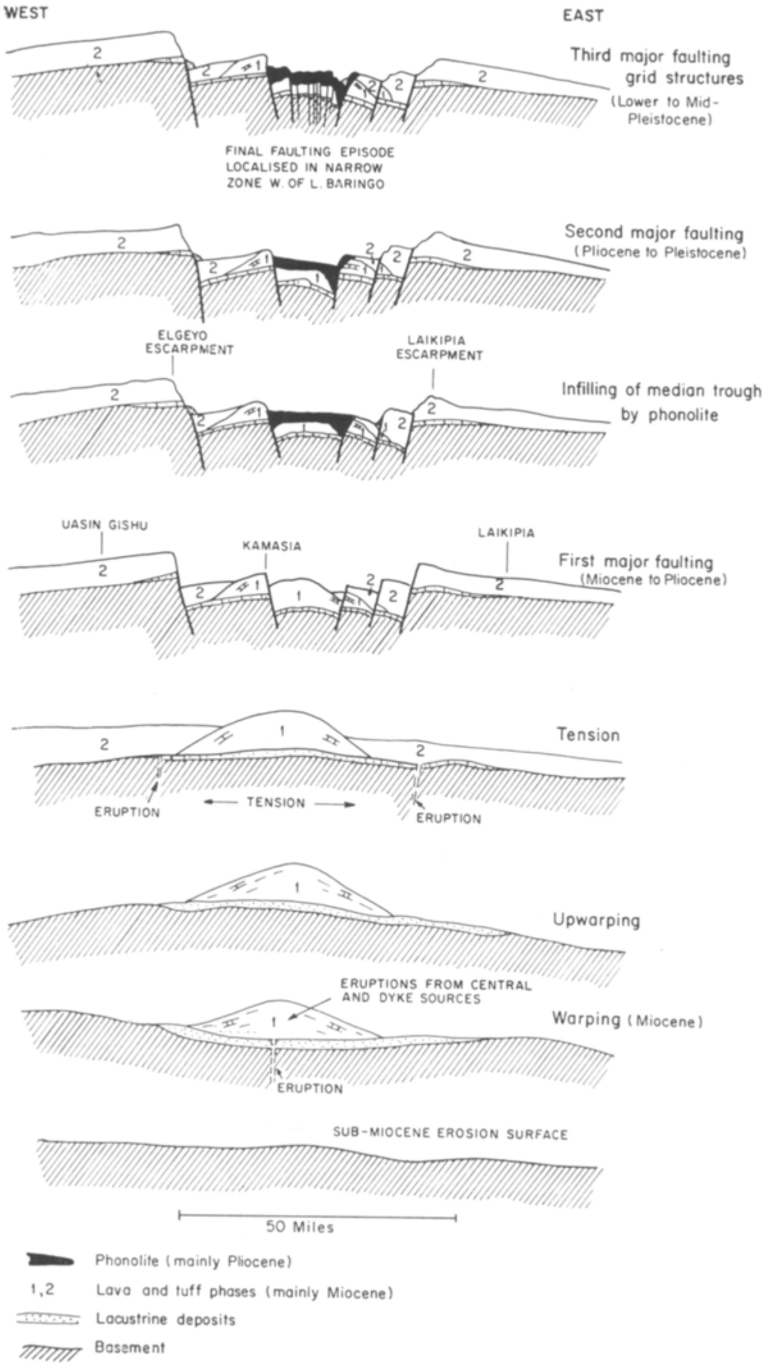


Fig. 5. Diagram illustrating the evolutionary stages from sub-Miocene to Pleistocene in the Lake Hannington sector of the Gregory Rift Valley of Kenya; from McCALL, 1967 (Fig. 14).

100 m. to 1000 m. throw, as well as many smaller oblique, rarely perpendicular, cross-faults, inside the rift valley. They prompted the formation of a Vorberge block system consisting of numerous tilted blocks of minor gräben and minor horsts, while the bigger faults led to secondary interior escarpments that developed especially in the ensuing graben movement at the axial Rift valley sector. Many accurate cross-faults in the Vorberge zone point to rotation, possibly also to slight horizontal displacement. In the case of the Marmanet-fault they might have been the effect to the recent earthquake there. Earthquakes are, however, rare in Kenya's Rift Valley, and their foci are deemed to be 'abnormally shallow' (McCALL). The third substantial sagging-in followed in the middle Pleistocene, and created a rift-in-rift feature in the innermost part of the graben. This is composed of a submeridionally-directed set of narrow, small, elongated block slices, each 100 m. to 1 km. wide, and of fault throws, most of which are of less than 100 m. (Fig. 6). This narrow-spaced system of parallel faults, that are only occasionally united by small cross-faults, has been termed "grid faulting". Apart from the rigid basaltic rock-fill, the inadequate free movement of the grid fault blocks within the rift-in-rift sector may well be the reason for the relative steep-angled hade of the faults, in striking contrast to the 60° to 70° dip of the Vorberge faults and of the main marginal faults. Interior movements during the upper Pleistocene-Holocene are expressed by tiny faults of a few metres throw and of quasi-vertical hades. They might also have been caused by ordinary settling processes of the soft, recent to sub-recent, sediments and volcanic tuffs. Other faults are, however, believed to be reactivated former faults.

Notwithstanding the thick and extensive pile of volcanic rocks which cover both the graben and the horst hinterland, extremely low Bouguer values of an average of minus 200 milligals have been recorded in the whole region. These gravity figures do not differ much from those registered on subrecent craters and their outpourings (for instance Menengai).

Ethiopia

The assumed continuation of the Gregory Rift Valley into the Lake Rudolf depression, or the branching off by en échelon shifting into MOHR's so-called Wonji belt — the Abyssinia fossa of Italian researchers —, is still matter for speculation, and much more exploration is needed before any conclusive findings are reached on this. The development of the NE trending Wonji graben is similar to that of the Gregory graben and, like it, is entrenched into volcanic series of enormous horizontal and vertical dimensions. They form the principal fillings of the Wonji graben and cover the huge adjoining Ethiopian and Somalian plateaux horsts. The Wonji belt (Fig. 1) assumes once again a marked axial rift-in-rift structure and, like the Gregory Valley, is rich in very young saline deposits. On its northern prolongation, the Wonji rift-in-rift feature enters upon the Afar depression.

The triangular Afar depression forms a fault funnel, whose diameters are of varying maxima, and range from 300 to 400 km. At the junction of the East African-Red Sea and Aden Gulf graben, the peculiar shape of the Afar depression is the result of three framing mega-horsts: Ethiopian plateau-, Somalian plateau- and Danakil horst (a small, but as

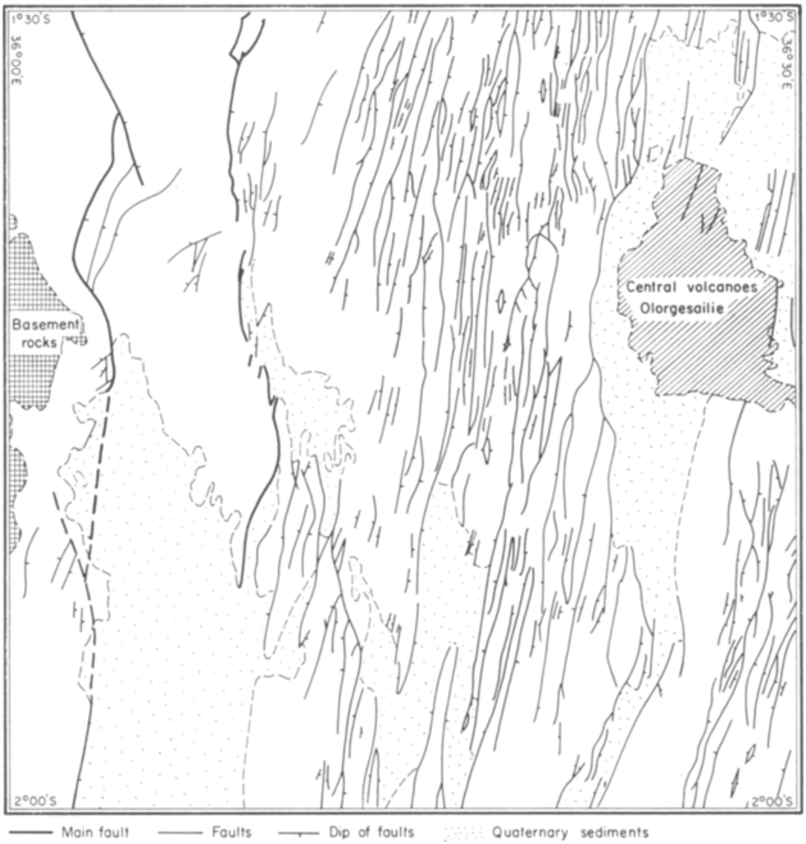


Abb. 6. Fault pattern illustrating the western marginal faults, the main Vorberge faults and the grid faults in the Gregory Rift Valley of Kenya; from BAKER, 1963 (Fig. 2).

yet little defined, horst, the Aisha block of MOHR or the Ali Sabiet block of AZZAROLI, has lately been added). Each of the three regional horsts and marginal faults have their parallel step-block system that has produced the Vorberge zone of the Afar funnel. These intersecting systems resulted in an intricate pattern of fault lines in the interior of the Afar funnel due to the varying strike directions, much depending on the trend of the main boundary faults. It became further complicated by the continuation of the rift-in-rift structure of the Wonji belt.

Fig. 7. Fault pattern at the eastern rim of the Ethiopian plateau, the Dallol-Salt-plain and the western rim of the Danakil Alps; courtesy of the Salzdetfurth Company, Hannover.

In preparing the following structural analysis and the design of the structural pattern map (Fig. 1), the writer was considerably guided by MOHR's recent publications (1964—1967). He also acknowledges his indebtedness to the Salzdetfurth Company, Hannover, for the use of the structural chart and the permission given him by Dr. H. MAYRHOFER, the Company's head of research, to reproduce part of it (Fig. 7).

In spite of that material and a few cursory observations in the field, it must be said that much more field mapping and cross-sectioning will have to be completed before full geological data are established on the taphrogenic structures of Afar; several findings, or at least theories, that have hitherto been current, depend all too much on airphoto interpretations.

The Salzdetfurth chart shows unmistakably the typical meandering pattern of the main marginal faults on the flanks of the Ethiopian horsts (the provinces of Tigrai and Erythrea), and of the Danakil horst that lies opposite to it. As in the Rhinegraben, so here too this zig-zag course is caused by rectangular cross faults, with presumably strike-slip tendency. The forceful headward erosion on its main escarpment conforms to the great uplift of the Ethiopian plateau, which is there expressed in the 6000 m. throw of the marginal fault. In numerous cases it renders difficult the precise determination of the main boundary fault line and of several cross faults. The same is true of the borders of the Somalian plateaux, which have been even less throroughly investigated.

The marginal fault is followed everywhere by the Vorberge zone. It is more or less the area between 'inner and outer rift margin' in Mohr's sketch map (1967). On the East-Ethiopian sub-meridional graben border, the Vorberge expand over a 50 km. wide strip. Along with the usual tilted blocks one comes across a number of subsidiary gräben and horsts that run parallel to the graben border; they are of alternating widths, from 10 km. ore more (for example, Guf-Guf, Maglala etc.). Their width dimensions are thus comparable to the sub-gräben of the East-Levant system. These subsidiary gräben of the Vorberge can be followed from the 'mouth' of the Afar funnel (end of the Wonji graben senso stricto) to as far the Red Sea (south of Massaua). In the lastmentioned region (Afar's northern tip), the Vorberge of East Ethiopia and Danakil get so close to one another that one is inclined to place even the Dallol graben there in the system of the Danakil Vorberge structures. (In its 10—15 km. width, its plug of rock salt, its topographical situation below sea level, and its (Pliocene?) Pleistocene age, the Dallol graben possesses many features common with the Dead Sea sub-graben). The centrally situated Dallol-graben that stretches across Lake Assala to as far as Lake Juliet as the so-called Saltplain depression, could, however, be regarded as a youngest axial rift-in-rift structure between the Vorberge belt of the Danakil Alps and that attaching the Ethiopian plateau horst. Like the rift-in-rift structure of the Wonji belt, the Dallol-Saltplain axis is marked by recent to subrecent volcanoes (Fig. 7).

The tilted blocks, subsidiary gräben and horsts of the Danakil Vorberge follow the NW—SE strike of the Danakil horst's meandering boundary fault as far as Lake Abbe. This Danakilean direction even predominates in the dislocations of the region stretching between Lake Abbe and the Gulf of Tadjura; others, according to Mohr (1966, 1967) are quasi-concentrically bent. Less strongly curved faults were indicated on structural pattern maps (MOHR, SALZDETFURTH) extending from Lake Juliet across Sardo to Lake Abbe.

In the Lake Abbe region the NW—SE Danakilean faults cross, or unite with, NE—SW rift-in-rift structures of the Wonji prolongation. MOHR (1967) extends this axial graben by turning it into the N—S direction over the Danakil horst to as far as the Red Sea. Nevertheless, an emphatic N—S transversal graben is lacking in the Danakil horst, while, as stated, volcanic eruption lines are equally available in the NW—SE oriented Saltplain graben. Moreover, young volcanoes are again extending from the Lake Abbe "junction" to the Gulf of Tadjura and the Djibouti area; there, in ENE Adenean direction.

According to MOHR (1967), the cross faults of the high plateau of Ethiopia continue far into the Afar graben (of the Wonji belt prolongation) in the North. Indeed he believes that they extend across the Saltplain depression and the Danakil Mountains, to as far as the Red Sea. But such cross faults, that cut uniformly through both megahorsts and the main graben, have not so far been proved on the spot; neither are they drawn on the Salzdetfurth chart. It is permissible to suspect that numerous boundary faults of the larger and smaller graben, assumed their meandering pattern through the shifting of the cross faults, and contributed to the mosaic-like configuration of the internal graben blocks, either without any movement or with only minor lateral movement. Larger transversal faults, which stretch from the graben hinterland of the Ethiopian plateau to the Afar depression, might, like the Ugoro and Maichew dislocations, be traced back to former Mesozoic lineaments. Yet for this, too, proofs in the field are still not forthcoming. The majority of the taphrogenic structures, which condition the Afar depression and their border escarpments, are of young Cenozoic age; the rift-in-rift structure of the Wonji belt prolongation and the axial Dallol Saltplain graben were primarily formed during the Quaternary. Over the Ethiopian plateau, the Danakil Alps and extensive parts of Afar, the inordinately low Bouguer values reach average minus 230 to minus 12 mgls. (GOUIN). These measurement data conform to the gravity results in Kenya. The volcanic sheet flows (2000 m. thick at Addis Ababa) and the volcanic eruption centres consequently remained without marked positive effect on the force of gravity in Ethiopia. Only in the Saltplain depression and in the Bab el-Mandeb splay of the Red Sea graben, was a small mass surplus (zero to 40 mgls.) registered.

Until now there has been no explanation of the cause of this considerable gravity deficiency. It might perhaps be attributed to the Mesozoic sediments, or to the mighty low grade-Metamorphic sediments of the Precambrian basement. Be this as it may, the gravity results of a large area of Afar and of the Wonji belt do not bespeak a heavy oceanic crust in close proximity to the surface. A geophysical comparison with the main trough of the Gulf of Aden and with the axial rift-in-rift of the Red Sea, that are marked by high surpluses, is, therefore, untenable.

Gulf of Aden and Borderlands (Somalia, Yemen, Hadramaut)

The writer has drawn upon the following studies in the structural analyses of these areas: for the Aden graben: LAUGHTON; for Somalia: DAINELLI, AZZAROLI and the oil companies reports discussed by BEYDOUN and LAUGHTON; for southern Arabia: BEYDOUN, GREENWOOD and BLEACKLEY, GEUKENS, as well as ARAMCO's geological map. In general outline the structural pattern has also been reproduced in the international regional geological and tectonic maps.

The taphrogenic chronology of the Gulf of Aden and its continental borders has affinity with that of Kenya and Ethiopia. Upon post-Eocene peneplains and shallow undulations such as the Hadramaut arch of BEYDOUN (1960) and the shallow Oligocene marine gulf and lowland of AZZAROLI (1958), there followed in the Lower Miocene (Burdigalian, according to AZZAROLI, 1958) the first important downbreak of the Aden graben. In the Pliocene, and even more so in the Pleistocene, there occured a further downfaulting of the graben that brought about an axial rift-in-rift feature in the submarine central trough. AZZAROLI (1958) arrives for the Aden rift at a 4000—5000 m. total throw.

The new ENE or Adenean trend was already noticeable in the direction of the boundary faults and Vorberge of the Somalian sector of Ethiopia (indicated in Fig. 1 by inferred line). The Adenean trend dominates the en échelon main faults of Somalia's coastal hinterland (Gobis, Medjourtin), of Hadramaut (Mukalla to Sayhut), and of those of Yemen's southern horst border. It is also noticed in numerous Vorberge blocks.

Cross-faulting ensued as well in Erythrean NW (including the Sabatain splay) as in Danakilean WNW direction. These crossfaults follow from the continental borderland to the coastal shore and probably continue in the shelf. The youngest cross lineation appears to be the NE directed submarine offsets, that virtually confine themselves to the area of the central trough and rarely touch the shelf, but never the continent.

Alien to the regular pattern, apparently, is the N—S directed fault, 50 km. long, in the Somalia Vorberge zone, east of Berbera, believed to be of Jurassic age and to have been rejuvenated during the young Tertiary movement (BEYDOUN). LAUGHTON has connected this meridional fault, as well as other cross faults of Erythrean direction, with those on the African coast, by way of an East drift of 2°. BEYDOUN and AZZAROLI do not subscribe to this, or any other, matching between South Arabian and Somalian coastal structures. GREGORY's cross section (reprinted in our Fig. 8), now almost seventy years old, continues to be valid for the purpose of demonstrating the Vorberge structure of the Guban depression of Somalia that adjoins the marginal faults of the Golis escarpment.

A net of rhombohedral, angular blocks and arcuate blocks "being antithetically rotated" (BEYDOUN, 1964, p. 99) is, again, characteristic of the Vorberge zone on the Somali side. Such a short Vorberge zone follows the marginal fault of the Medjourtin (Migiurtinia in AZZAROLI's paper 1958) escarpment as far as the coast, but probably extends below sea in the shelf area. Precise determination of position and of throw of the marginal faults is often rendered difficult because of headward erosion at the fault escarpment and of the disharmonic cover of the main fault by the "hanging" block-slices of the Vorberge zone.

Beydoun's cross-sections (our Fig. 9) of the South Arabian border areas do, however, give us a better insight into the structural phenomena of disharmonic faulting and endemic graben tectonics. The downdropped Vorberge blocks along the graben shoulder (for example, Madi Pass) consist as far as the coast (cross-section A. B. in Fig. 9) of tilted blocks and of subsidiary gräben, of which the width is comparable to those found in

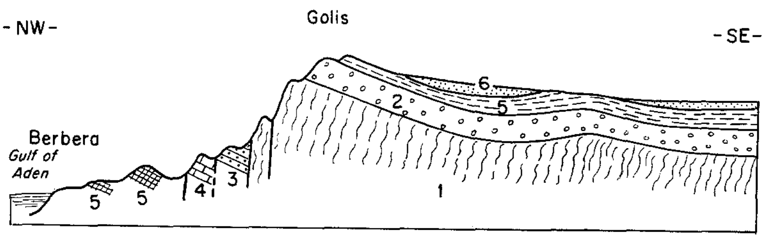


Fig. 8. Cross-section from the Golis plateau to the Somalian coast; from Gregory, 1921 (Fig. 43).

the subsidiary gräben of the Vorberge zone of western Ethiopia. Magmatic intrusive stocks, that were common on the Red Sea side of Yemen (Karrenberg), had, as massive buttresses, an endemic folding influence on the adjoining sedimentary blocks (Beydoun's "block-jostling"), a phenomenon that somewhat recalls saltdiapiric tectonics. The majority of the graben faults proceed in an Adenean direction. An impact of cross lineaments in Erythrean or Danakilean direction is more noticeable in the larger faults, such as those of Ataq and Iyadh that flank the Mayfa'ah depression (Sabatain splay). Erythrean oriented faulting is further known from the Yemen hinterland (Geukens) while in the coastal sector of the Gulf of Aden the Adenean direction prevails. The latter is represented by stepblock faulting with minor horsts and gräben, briefly mentioned by Greenwood and Bleackley (it is regretable that they failed to publish any cross section). Small gräben have been known for some time as features that are wedged in the plateau lavas of Eastern Yemen (Lamare, Geukens).

As to the submarine structures of the Aden Gulf graben, we depend in effect on the interpretation of the topographic sea bottom measurements. Laughton's profile (Fig. 2, p. 251), pattern map (Fig. 1, p. 151) and his classification into continental margin, main trough and central rough zone have been adopted for this purpose (see our Fig. 10).

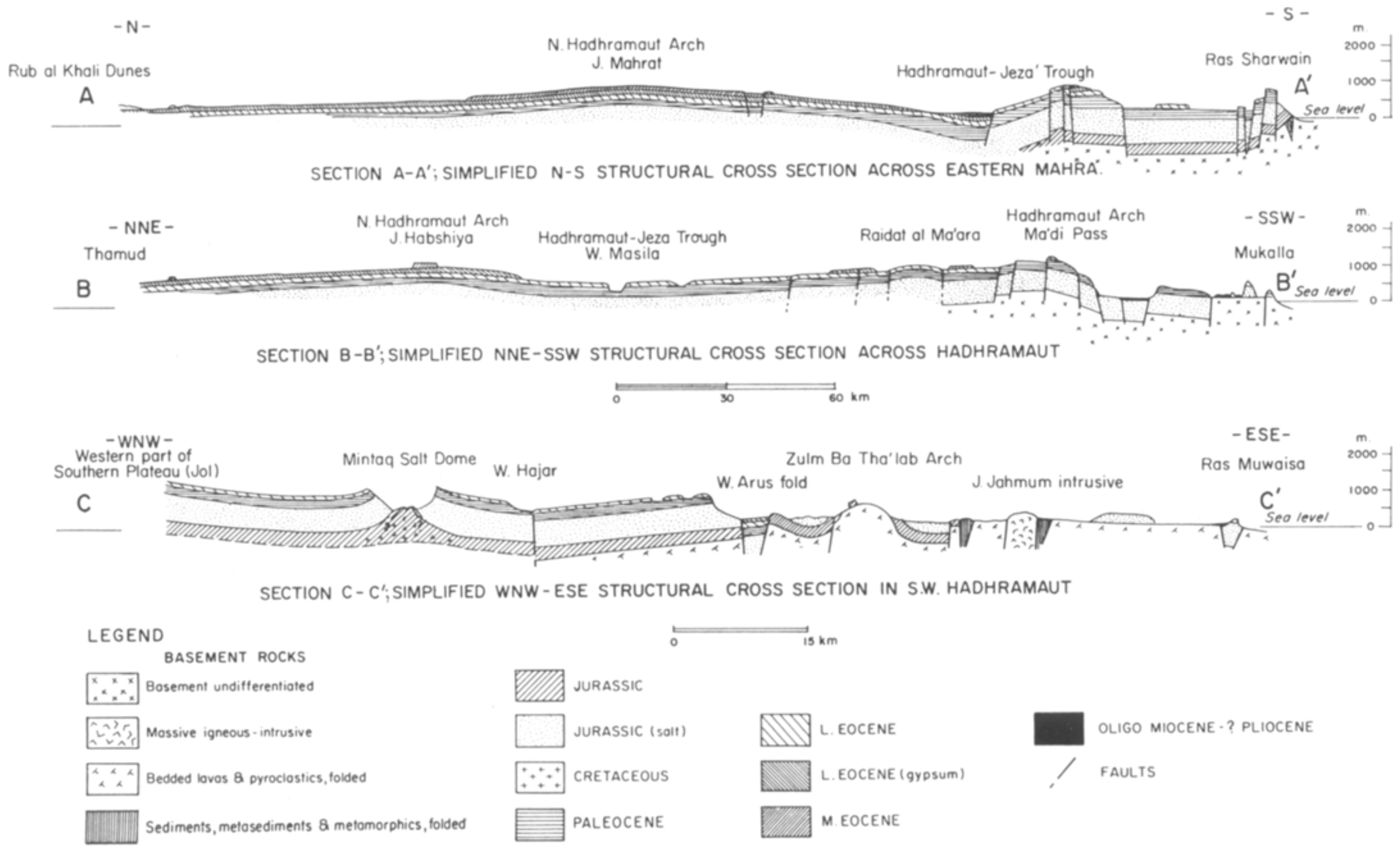


Fig. 9. Cross-sections from the Hadramaut hinterland to the Arabian coast; from BEYDOUN, 1960 (Plate 6).

Assuming that the varying divergences of the sea bottom relief are nothing but a tectonic expression of internal block segments, we have marked the latter by conjectural fault lines on LAUGHTON's profile (his Fig. 2. B.), and have transferred them to our Fig. 10. We are well aware of the hypothetical character of this reconstruction. According that conjectural reconstruction the Vorberge zone would be continuing itself in the submarine

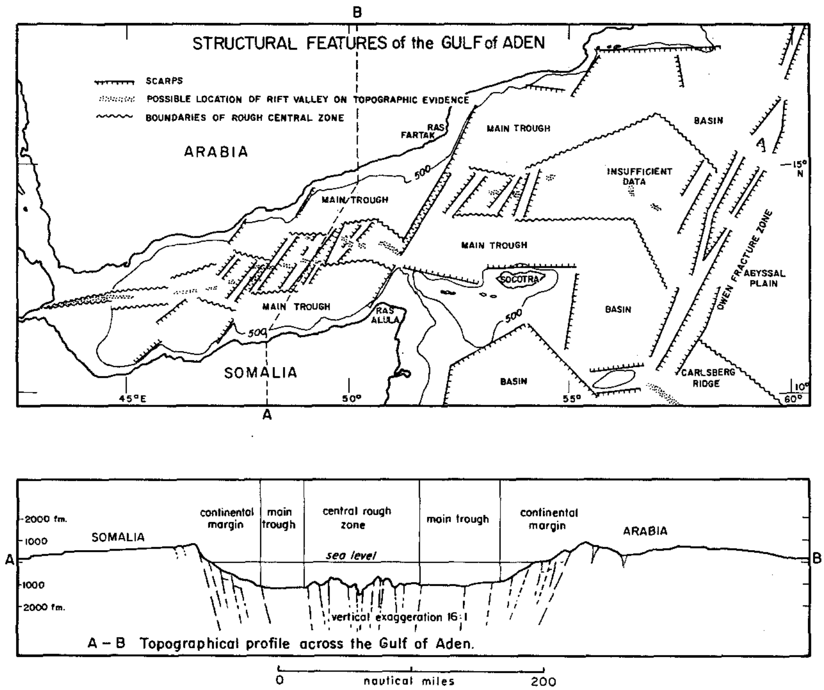


Fig. 10. Structural features and topographical profile of the Gulf of Aden; from LAUGHTON, 1966 (Figs., 1, 2). (Dashed lines in the topographical profile added by the writer to emphasize assumed block structures by conjectural fault lines.)

part of the "continental margin", and terminating at the sharp submarine escarpment, namely, before the maintrough. The highly dissected bottom relief of the 'central trough zone' would in that case be the younger tectonic feature of the graben; its small axial incision might perhaps conform to a rift-in-rift structure. LAUGTHON, like HEEZEN and THARP before him (1965), has compared 'the central trough zone' to the Mid-Oceanic Ridges of the Indian Ocean. The elevated, strongly dissected relief of the Mid Oceanic Ridges are in effect similar to the central bottom relief of the Aden graben. On the other hand, such morphological features are unknown in the interior of the intercontinental graben of Europe and Afro-Arabia, including the Red Sea (Fig. 15). The peculiar offsets of NNE aualitic direction, which traverse the 'central trough zone' were compared by LAUGHTON with oceanic transcurrent cross faults, or the transform faults. They traverse and dissect the ridge of the 'central trough zone' of the Aden graben in horsts and gräben which, like the Ras Aula-Ras Fartak trench, can attein a width of 15 km. Such transversal graben, linked with the so-called transform faults, have not been discovered in intercontinental gräben. Nor do they lend themselves to comparison with the cross faults, of apparent strike-slip tendency, of the Wonji belt and other cross-lineaments in Ethiopia. Nor are they known in the axial sector of the Red Sea graben, in which the presence of sub-crustal oceanic conditions has latterly been advanced as a favoured assumption. Such transcurrent cross-faults were originally marked in the sketch map of the Red Sea by HEEZEN and THARP (1965), but are already missing from the succeeding maps (1966). At all events, the offsets are not only the youngest (that is probably Mid-Upper Pleistocene) fault element but are, besides, confined to the ocean. Not only in age, but also in deformation and trend, these offsets differ sharply from all other graben structures of the Gulf of Aden, and primarily of its continental section.

According to LAUGHTON, the Gulf of Aden graben is distinguished by high seismic activity (especially near the offset structures), and by an abnormally high heat flow at the 'continental margin' and at the central sector of the trough. Seismic refraction results are interpreted as an indication of a thin oceanic crust with shallow mantle transition (45 km. depth) below most of the submarine bottom as far as the continental margin. Magnetic anomalies are relatively low at the continental slope and at the main trough but increase in the central rough zone to the abnormal value of $\pm$ 1000 γ considered as the effect of heavy material (assumed swarm dykes?). It is remarkable that the Alula-Fartak trench does not present any magnetic anomalies.

According to WORZEL's chart (1967) Bouguer gravity anomalies are again high on the graben axis, showing + 145 mgls. to + 173 mgls., but decrease considerably at the shore of Aden, where only + 11 mgls. was measured.

No geophysical traverses are known that cross from the Somalian borderland through the ocean to the Arabian graben rim and its hinterland.

Red Sea

Eastern Margin

The geological maps of ARAMCO (Arabian American Oil Company) seldom define genuine marginal faults at the eastern flank of the Red Sea graben. Their failure to do so was probably due to the fact that the border faults, and especially the Vorberge blocks on the mainland, are covered by alluvial fans and other young Quaternary sediments of the Tihana coastal plain. Nevertheless, there is little doubt that N—S directed main boundary faults at the western escarpment of Yemen are cut by typical oblique and perpendicular cross faults. The Yemen boundary faults extend from the Bab el-Mandeb isthmus to the Yemen-Saudi Arabia political boundary (about the 17° latitude opposite the Farsan islands); these faults are also outlined in international geological maps (Furon, Dubertret). Such meridional marginal faults exist along the main escarpment of the Ethiopian plateau of Erythrea and of Tigrai as far the southernmost Sudanese coast. It has already been explained that the East Ethiopian boundary faults form, with those on the western escarpment of the Danakil horst, the graben splay of the Gulf of Zula and the Dallol-Saltplain depression, thus entering from the Red Sea into Afar. The other split of the Red Sea graben — the Bab el-Mandeb splay — is framed by the WNW directed eastern fault rim of the Danakil horst and by the opposite marginal fault of Yemen.

There are still all too few surface faults on ARAMCO's maps to enable us to define the exact position of the Erythrean directed marginal graben faults which separate the downfaulted Vorberge blocks of the Tihana coastal plain from the Precambrian horst-hinterland of Asir and Hejaz. Magmatic intrusive bodies connected with rift faulting are shown in ARAMCO's cross-section of the Asir coastal area (map: 1—216 a). According to Brown & Jackson (1960) at Asir "a minimum vertical displacement of 3000 meters can be measured" for the main boundary fault. In the coastal sector of northern Hejaz, from Ras Baridi (opposite Ras Benas) towards the Gulf of Aqaba a number of Neogene blocks with NE—SW and E—W directions (for example Tuway'il el Kibrit) as well as subsidiary gräben with WNW—SSE direction interlace the main fault zone and Vorberge zone. Although Gawad (1968) considers the Abu Masarib fault a shear or strike slip fault crossing the Red Sea and extending into the opposite Egyptian Eastern Desert, the writer is unable to see in it any structure other than a gravitationally downfaulted trough with Neogene to Quaternary fill, which is characteristic of the coastal block system. Moreover, according to the submarine topography, both of the faults which frame this oblique graben splay continue only for a short distance into the Red Sea. Indeed, none of the characteristic offsets known from the Aden graben (Fig. 10) has so far been discovered in the bottom relief of the Red Sea. It must also be remembered that those offsets were wholly restricted to the graben interior, and there is no trace of them in the mainland.

With the approach of the triangular Sinai horst, the Red Sea graben bifurcates as Aqaba and Suez graben splay. The N—S Aqaba-graben direction prevails henceforth in the region of Midian. Midian consists of a meridional horst limited by the Aqaba graben in the West and the shorter Wadi Ifal graben splay in the East (Fig. 11). The latter which was recognized as a graben feature by Kober (1919), does not appear as such in the ARAMCO survey; nor does it so appear in Mitchell's (1957) intricate net of meridional and Erythrean faults that dissect the crystalline basement and the Neogene sediments of southern Midian. Other "narrow splinters and gräben too — some en échelon, some diverging" (Brown & Jackson, p. 69) that occur along the eastern margin of the graben are also not specifically outlined in ARAMCO's map. either.

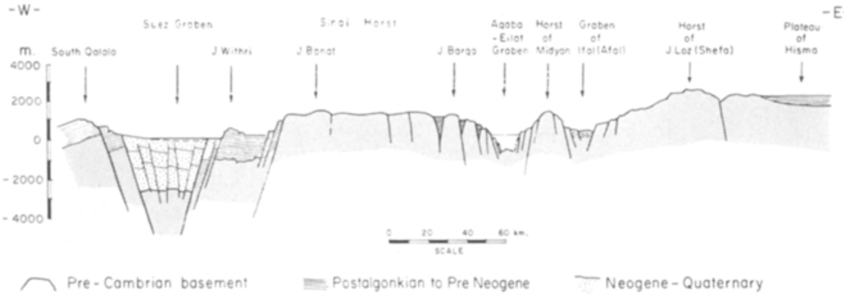


Fig. 11. Cross-section from South Galala (Egypt) through Suezgraben, Sinai, Aqabagraben to Midian and Hisma plateau (Arabia); from PICARD, 1967 (Fig. 2).

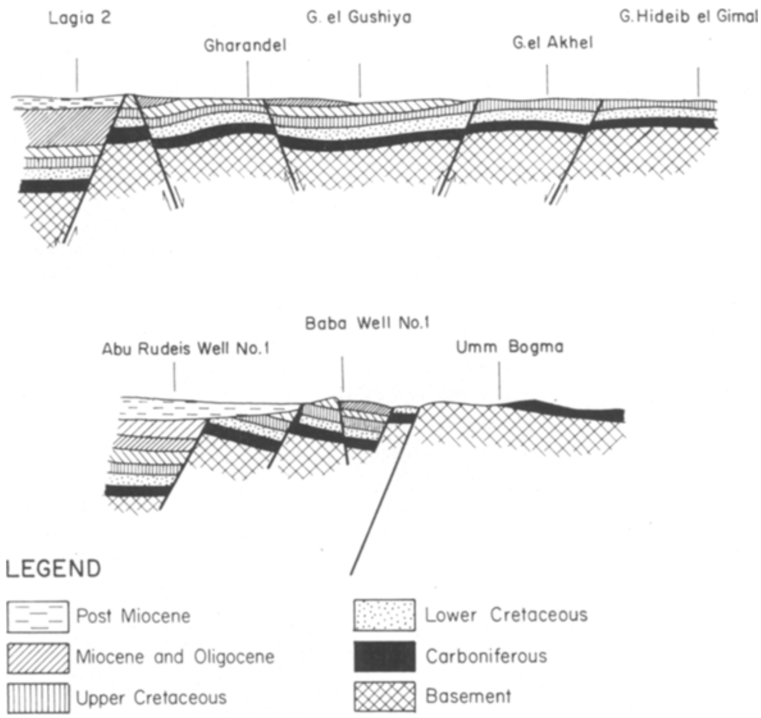


Fig. 12. Cross-sections of the Vorberge-zone in the eastern sector of the Gulf of Suez; from SAID, 1962 (Fig. 26).

Suez graben splay.

The well-explored Suez graben of Erythrean (between NW and WNW) direction is, no les than the Rhine graben, a classical example of a graben structure. SAID's compiled tectonic map (1962, Fig. 25), SHATTA's

(1959, Fig. 20) and SAID's (1962, Fig. 26), HEYBROEK's (1965) and SCHÜRMANN's cross-sections (1966), as well as our cross section (PICARD, 1966, Fig. 2) here reproduced as Fig. 11, illustrate the taphrogenic building of these regions. Comparison of the Vorberge structures of the eastern or Sinai side of the Suez graben (Fig. 12) with that of the eastern side of the Rhinegraben (Fig. 13) should be of further help in reviewing our results. They were these: main marginal faults of the border mountains

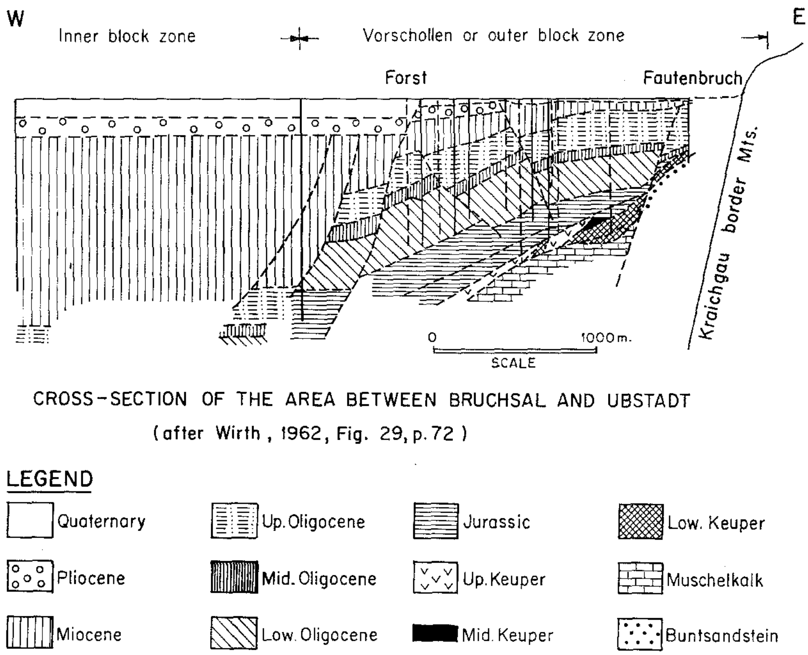


Fig. 13. Cross-section through the Vorberge-zone of the western Rhinegraben, near Bruchsal; from WIRTH, 1962; republished in PICARD, 1968 (Pl. III, Fig. 1).

are followed by a tilted block system including small subsidiary horsts and gräben that form the Vorberge (Vorschollen) or outer-block zone; interior boundary faults often of impressive throw (especially large at the Tuniberg in the SE Rhine graben) separate the Vorberge block zone from the inner block zone or central sector of the main graben. WIRTH's Vorberge structures (Fig. 13) buried by Quaternary sediments may well give an idea of those hidden below many coastal plain — and shelf areas.

En échelon fault arrangement is characteristic of the main boundary faults of the Etbai range (for example Jebel Gharib). The curved outline of the Sinai boundary fault (SAID, Fig. 25), largely masked by the alluvial of the el Qa'a plain, may be the result of fault splintering combined with small and slightly horizontally displaced transversal faults. Oblique cross-

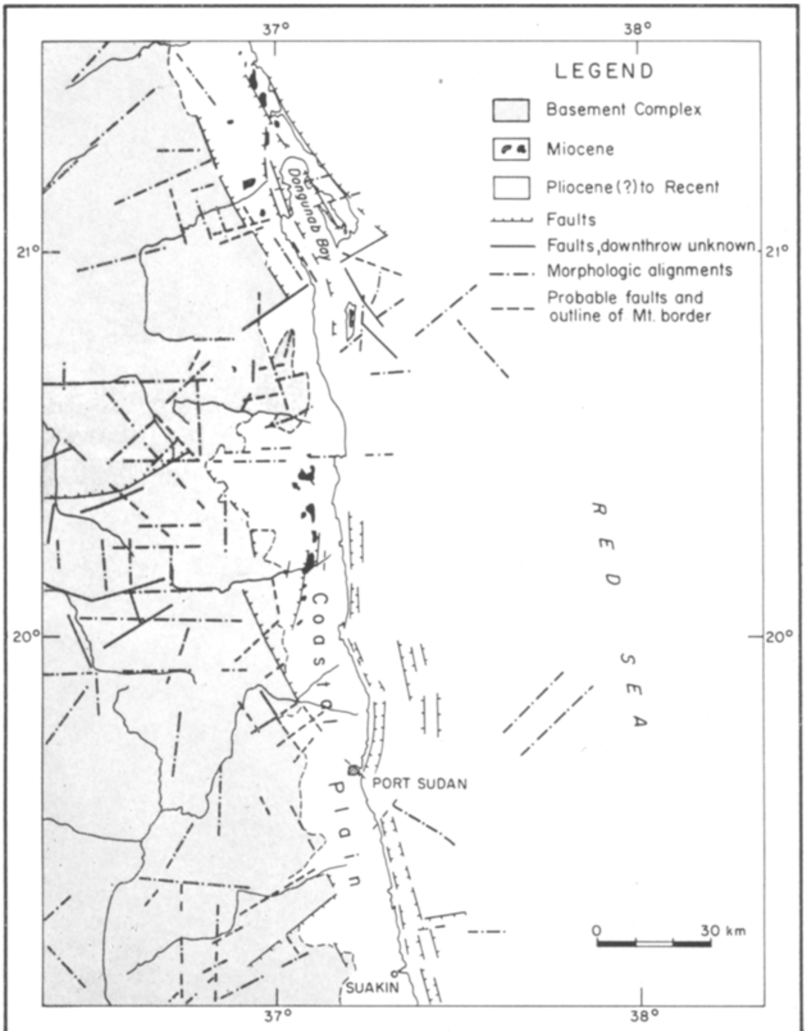


Fig. 14. Fault pattern of the western Red Sea coast in the sector Suakin—Port Sudan—Dongunab bay; from SESTINI, 1965 (Fig.10)

faulting is more frequent in the Vorberge block zone (less on the Egyptian side). Anti- and synthetic tilted blocks, subsidiary gräben and horsts have dismembered the graben interior. Miocene sediments including thick evaporites play a major role as cover beds, while many horst-blocks contain a core of crystalline basement rocks. Uplift and subsidence of the blocks have led to "block-folding", and thereby to a series of anticlines and synclines which run parallel to and belong to the interior of the graben.

These "taphrogeosynclinal" structures, too, may be ascribed to endemic graben tectonics, that occurred on a large scale of this 60 to 70 km. wide Suez graben. In any event, they must be definitely differentiated from the miogeosynclinal or foreland folds of the Levant mega-block which run almost perpendicularly to the folds of the interior Suez graben.

The sudden change of the shallow, 55 m. deep, Gulf of Suez to the 1000 m. deep Red Sea at its southern end, from Ras Mohammed to the Shadwan archipelago, is well expressed by a sharp submarine slope of meridional direction that continues straight northwards into the small shelf and eastern mountain border faults of the Aqaba graben. The submarine marginal fault has consequently downfaulted the Neogene fill of the Gulf of Suez into the depth of the Red Sea and, like its continuation along the eastern shore of the Sinai is of Pleistocene age. This eastern marginal fault of the Sinai is accompanied by many parallel N—S minor graben and minor horsts that cut into the basement rocks of the Sinai horst and extend North to Elath. Many antithetic stepblocks occur at the Sharm el Sheikh area at the Sinai corner in the south. Here, at the junction of the Red Sea, Suez and Aqaba graben, the Bouguer values are zero (PLAUMANN), and become more and more negative (up to — 90 mgls.) in the Suez and in the Aqaba Gulf.

Western margin of the Red Sea

The en échelon pattern of the marginal faults can still be seen in THIEBAUD's structural map published by SCHÜRMANN (1966, Fig. 24, p. 288). Moreover, THIEBAUD's survey reveals a distinct diagonal fault-depression which resembles the Ras Abu Masarib graben of the opposite eastern margin of the Red Sea. It is not a single fault (Duwi fault of GAMAL) but a graben splay of 70 km. length and 10 km. width. The large embayment which begins south of the Vorberge horst block of Ras Benas and even more so, the Suakin bay, both distinguished by young volcanites, may represent further splay-shaped graben features. A southern continuation of the supposed faults forming the Suakin splay might coincide with the faults producing the western escarpments of the Somalian plateau horst (see STEFANINI, Plate 3, Fig. 2). Published surveys in the Sudanese coastal region, however, are still too scarce to verify such structural assumptions. An exception is SESTINI's paper which gives a good insight into the marginal fault and Vorberge structure of a 300 km. long coastal strip, north and south Port Sudan. His Fig. 10 republished in our Fig. 14, clearly reveals the influence of cross-faulting (oblique and perpendicular) upon the meandering, serrated outline of the Erythrean directed main border-fault and its escarpment. Step-blocks with subsidiary horsts and gräben built the Vorberge of the coastal plain and were found to continue in the floor of the shelf. They also formed the small graben of the Dongunab bay and its adjoining horst, the Ras Abu Shagharab peninsula. These features resemble the tectonic pattern of the Zeit bay at the southern end of the Suez graben. As in the latter area, we also meet in the Sudanese coastal plain "block-folded" Neogene, whose anticlines trend parallel to the Red Sea rim. Basing himself on a detailed survey, SESTINI emphasized the tensional, gravitational character of the graben faults.

Red Sea Oceanography

The topographical and geophysical investigations covering part of the Red Sea have been summarized by DRAKE and GIRDLER (1964), NESTEROFF (1955), and KNOTT et al. (1967).

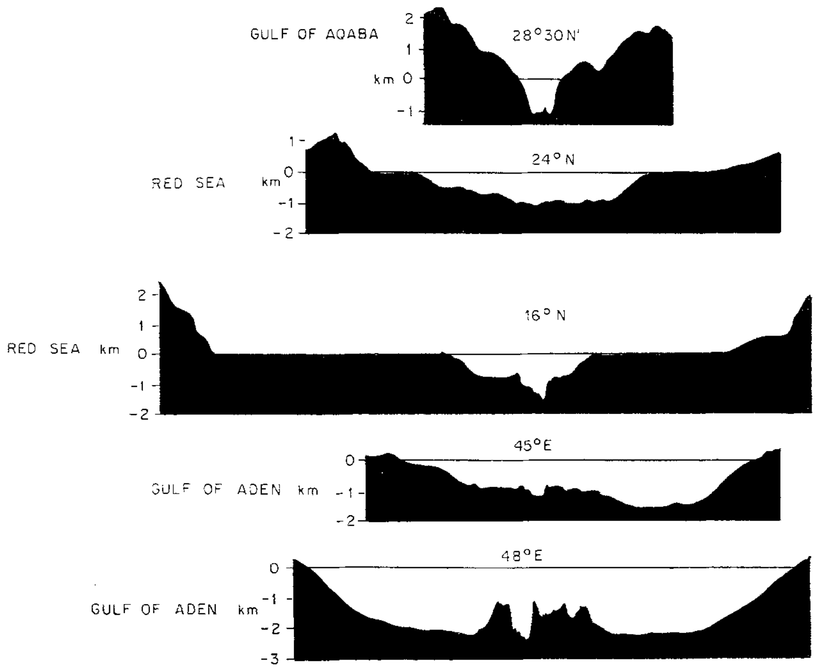


Fig. 15. Topographic profiles across Gulf of Aqaba, Red Sea and Gulf of Aden; from DRAKE & GIRDLER, 1964 (Fig. 16).

The steep continental slope, descending from 200 to 500 fathoms separates the shelf from the so-called main through (Fig. 15). In the centre of the main trough exists a 40 km. wide and 2000 m. deep incision, the proper axial trough or KRENKEL's (1925) graben-in-graben. Topographic similarity is noticed mainly in the northern section of the Red Sea, but not in the southern section (south of the latitude of Port Sudan) where a distinction between shelf and main trough is hardly possible. Towards the southern end, the axial trough diminishes, and disappears as it gets to the Bab el Mandeb splay.

These differences in the bottom relief are probably reflected in the diverse geophysical behaviour of the northern and southern segments of the graben interior. Thus the positive Bouguer anomalies (maximum plus

100 mgls.) which distinguish the axial trough in the north are decreasing gradually in the South. Seismic activities are also mainly concentrated in the southern Red Sea. However, extreme magnetic-anomalies (up to 2000 γ) and high seismic velocities (6,7—7,4 km./s.) are found along the entire axial trough. Together with the gravity surpluses they indicate heavy basic magmatic material in the depth of the rift-in-rift structures — a deduction first reached by KRENKEL. The much lesser gravity anomalies found in the southern part of the Red Sea may be attributed to the density changes deriving from extensive coral-riff formations and enormously (several thousand meters) thick evaporites, stretching almost from coast to coast, as in the expanse from the Dahlak to the Farsan islands. The influence of these formations is still felt in the nearly compensated Dallol-Gulf of Zulu graben of Ethiopia. It is in this southernmost section that all three mega horsts of the West Ethiopian plateau, the Danakil Alps and the Yemen block get closer to one another, and the intervening graben splays of Dallol-Zulu gulf and Bab el-Mandeb extend into the Red Sea. In the absence of a rift-in-rift feature, block structures of the Vorberge type may be assumed to prevail here (Fig. 1). This assumption is also shared by MALONE in his discussion remarks and the gravity profile (in GIRDLER, 1958, p. 103—104) that runs from Yemen through Danakil to the Ethiopian plateau. (Regretfully, most oceanic researchers hitherto concentrated on the main and axial trough, and did not present geophysical traverses that pass from mainland to mainland via the Red Sea graben).

Red Sea evolution

The different geophysical behaviour in the various sectors of the Red Sea graben proper and in its northern (Suez, Aqaba) and southern (Salt-plain Dallol-Zulu, Bab el-Mandeb) splays is apparently an expression of the suitable young Cenozoic paleogeographic history of this region.

The initial or "Lower Miocene Erythrean Rift Valley" (PICARD, 1943, p. 48), of principally Burdigalian age, was followed by the ingression of the Vindobonian sea from the "Mediterranean" in the North through the Suez graben. It never reached, however, as far south as the Miocene Gulf of Aden, as Yemen and Ethiopia had still formed in the Miocene a separating land barrier (see HEYBROEK's, Fig. 10). In the Upper Miocene (principally Pontian) a northern land barrier came into existence also in the area of the isthmus north of Suez (PICARD, 1943, p. 69 and Fig. 14, HEYBROEK, Fig. 11) which has since remained a landbridge. Both, the Danakil and the Suez isthmuses converted the Suez and Red Sea "Mediterranean" gulf into a brackish evaporite-depositing Upper Miocene inland lake.

At the turn of the Miocene to Pliocene the southern barrier was broken by the downfaulted Bab el-Mandeb trough, and probably also by the Afar branch of the Zulu-Dallol splay. It transformed the Red Sea-Suez graben by way of the Bab el-Mandeb splay into an Indian ocean gulf as it is still today, and led to the initial disposition of the Danakil horst.

Pleistocene downfaulting which played such an important role as the major taphrogenic phase of the East Levant graben system (Aqaba-Jordan valley), and of the particularly marked rift-in-rift structures of Ethiopia and Kenya, becomes more impressive in the configuration of the axial graben-in-graben feature of the Red Sea. It attains in its width and its slope-scarps a magnitude comparable to Suez and Rhine-graben. The other Pleistocene taphrogenic movements are obviously reflected by the innumerable faulted Neogene blocks of the Red Sea Vorberge zone and by the interior block-mosaic of Suez and Aqaba-Jordan graben zone. Very young disturbances dissecting the Pleistocene riff formations of the Red Sea are known from the Farsan-Dahlak archipelago (MACFADYAN, HOROWITZ) and from the eastern coast of Jedda where KARPOFF (1956, p. 6—93) supposes fault continuation along submarine scarps. Post-Pliocene beaches and terraces which had been lifted to over hundred meters as in the Tiran islands cannot possibly be the result of eustatic movements.

Drifting Hypotheses

There has been lately a revival of the hypothesis, now almost half a century old, of the anticlockwise rotation and drifting of the Arabian peninsula. In such speculations one must consider not only the breaking up of the Arabo-Nubian shield by the Red Sea, Suez and East Levant graben, but also the adjacent destruction of the Mediterranean and Indian Ocean by submarine gräben, the splaying and splitting of Afar and the southwestern corner of Arabia (Bab el-Mandeb, Sabatain splays) as well as of many other minor gräben in the continental platform. A drifting-apart, therefore, demands a much larger degree of movement than the hitherto postulated 7° around a Sinai-placed rotation axis. Moreover, any eccentric push of this kind, which is believed to have had its impact on the orogeny of the Zagros belt, must have had the same compressional effect on the crustal sectors of the northwestern Mediterranean and northeastern Indian Ocean as well.

Any discussion of this subject must pay due regard to the paleo-geographic late Cenozoic history of this region, especially of the Red Sea. As explained in the preceding chapter, at a time when the first genuine tensional graben of the Red Sea originated in the Miocene and the "Mediterranean" sea filled this trough — South Arabia (Yemen) was still conected with Africa (Ethiopia). No drifting or formation of a graben-in-graben structure had taken place. The thick Burdigalian cong-lomerates found in the basal sediments of the Miocene Suez-graben prove only that continental conditions prevailed during the graben initiation.

The Pliocene Indian Ocean, which entered the Red Sea after the downfaulting of the Bab el-Mandeb graben splay, never spread laterally to beyond the Miocene graben rim (see HEYBROEK; Figs. 10, 11). The Pliocene Indian Ocean gulf had indeed shrunk in the area north of Suez. Instead of the northerly extended Suez graben — as in the Miocene —

a landlocked isthmus had already appeared there in the Pontian or late Miocene and remained intact to this day — a phenomenon that contradicts any assumption of Pliocene and of Pleistocene drift at least in the northern Erythrean graben sector.

Lastly, there remains the axial trough, that is, the graben-in-graben or rift-in-rift structure that cut through the Mio-Pliocene sedimentary fill of the Red Sea Rift Valley. It cannot, therefore, be much older than Pleistocene, an age assigned to the rift-in-rifts of Kenya, of the inner Wonji belt, of the Saltplain-Dallol graben and — although morphotectonically not absolutely comparable — also to the midoceanic ridge of the Gulf of Aden. It is precisely this crustal cleft in the center of the Red Sea main graben that prompted the belief in an intercontinental drifting between Africa and Arabia. However, a Pleistocene (or even Neogene) tearing apart motion of Africa from Arabia, or vice versa, can hardly have caused the formation of the folding belt of Zagros and southern Turkey, whose Alpine orogeny goes back as far as the early Tertiary.

If the assumption of Quaternary age of the axial trough is correct, one arrives for its area of maximum width at a 70 km. separation rate during the last one or one and a half million years or 70 cm. to 50 cm. per year. One might have expected an important lateral stretching of such short duration to have become manifested in frequent recurrent earthquake tremors and also in strong shore line recession processes in recent years.

As to the problem of structural matching, WHITEMAN (1968, p. 234) gives plausible reasons for his opposition to the assumption that "the apparent jigsaw fit of the Red Sea shores as evidence that the Red Sea was formed as a result of drifting apart or rotation of Arabia with respect to Africa". This anti-mobilistic view is shared by other geological workers in the field: By SESTINI (1965, p. 1409) for the Red Sea rift, by BEYDOUN (1964, p. 102) and AZZAROLI (1968, p. 127) for the Gulf of Aden graben.

Final Remarks

The foregoing discussion of intercontinental drift and the peculiar rift-in-rift features calls for a few remarks which go beyond the immediate scope of this paper.

MARTIN (1968) found, in his "critical review" on connection or disconnection between South America and Africa, "that no appreciable widening of the Atlantic rift can have taken place since the Lower Miocene". This is the time when the foundering of the Afro-Arabian gräben started to develop along tensional mega-faults that remained the stable frames ever since. MARTIN also follows the conclusions drawn by EWING and his co-workers (1966) that in view of the occurrence of Miocene sediments in the rift valley of the Atlantic mid-oceanic ridge "the Pleistocene and present tectonic activity along the ridge has probably nothing to do with either drifting or oceanic spreading". This consequential inference throws also some light on the graben-in-graben features of the Red Sea, of the mid-oceanic ridges and of the axial ridge of the Gulf of Aden.

Both, the rift-in-rift of Afro-Arabia and the mid-oceanic rifts are specific tectonic features of the Quaternary that have so far not been recorded by geologists in the preceding stages of the earth history. This lack of documentation may be due to one or another of the following reasons: Either because "the recent tectonic history is not directly related to previous mobility patterns" (De Booy), or because the evolution of the strange morphotectonic traits of the mid-oceanic ridges and of the rift-in-rift structures was so ephemeral as to leave no noticeable field evidence for geological control. The problem is somewhat analogous to that of the pre-Pleistocene glacial phenomena that have been definitively established only where glaciers had long been in existence and where their depositions remaind preserved. Indeed, the question may be asked: Could there have been an interelationsship between the glacial phenomena and the tectonic singularity of mid-oceanic ridges, with their inner rift, in the Pleistocene? The reply to this question, if any, will render more intelligible certain geophysical observations, such as the four successive changes from normal to reserve magnetic polarity during the few million years of the Plio-Pleistocene, as against the permanency of polarity over previous very long periods. Such findings will also lead to a better understanding of the conflicting geophysical views as to the deeper cause and origin of the young Cenozoic Afro-Arabian gräben.

References

ARAMCO (Arabian American Oil Company): Geological map of the Arabian peninsula, compiled by U.S. Geological Survey and Arabian Oil Company; 1 : 2 000 000, U.S. Geol. Surv. Misc. Invest. Map I-270-A; U.S.A., Washington, D.C., 1963.

Azzaroli, A.: Missione geologica in Migiurtinia. — La Ricerca Scientifica, **27**, 2, 301—345, Roma 1957.

—: L'Oligocene e il Miocene della Somalia. — Palaeontogr. Italica. **52** (n. ser. 22), 1—142, Pisa 1958.

—: On the Evolution of the Gulf of Aden. — XXIII. Intern. Geol. Congr., Proc. **1**, 125—134, Prague 1968.

Baker, B. H.: Geology of the Magadi Area. — Rep. No. **42**, Geol. Surv. Kenya, 81 pages, 1958.

—: Geology of the Area south of Magadi. — Rep. No. 61, Geol. Surv. Kenya 27 pages, 1963.

Bender, F.: Geologie von Jordanien. — Beitr. Geol. d. Erde, **7**, 230 pages, Berlin-Stuttgart (Borntraeger) 1968.

Bentor, Y. K.: Petrographical outline of the Precambrian in Israel. — Bull. Res. Counc. Israel **10** G, 19—63, Jerusalem 1961.

Beydoun, Z. R.: Synopsis of the Geology of East Aden Protectorate. — XXI. Intern. Geol. Congress, Proc. Sec. **21**, 131—159, Copenhagen 1960.

—: The Stratigraphy and Structure of the Eastern Aden Protectorate. — Overs. Geol. Min. Res. Bull., Suppl. **5**, 107 pages, London 1964.

—: Eastern Aden Protectorate and part of Dhufar. — Geol. Surv. Prof. Pap. **560**-H, 48 pages, Washington 1966.

BROCK, B. B.: An approach to the Rift Valley problem. — XIX. Intern. Geol. Congr. Proc. sect. **9**, 3, 225—237, Alger 1952.

—: The Rift Valley Craton. — Upper Mantle Symposium, Geol. Surv. Canada paper **66—14,** 99—122, Ottawa 1967.

BROWN, G. F., & JACKSON, R. O.: The Arabian Shield. — XXI. Int. Geol. Congr. Proc., Sec. **9**, 9, 69—77, Copenhagen 1960.

BUREK, P. J.: Structural Effects of Sea-floor Spreading in the Gulf of Aden and the Red Sea on the Arabian Shield; in: Hot Brines and Recent Heavy Metal Deposits in the Red Sea, DEGENS & ROSS, ed. New York (Springer) 1969.

CARELLA, R., & SCARPA, N.: Geological results of exploration in Sudan by Agip Mineraria. — 4th Arab. Petrol. Congr., Beirut 1962, Reference taken from HEYBROEK, 1965.

CHOUBERT, G.: Carte Tectonique internationale de l'Afrique, 1 : 5 000 000, A.S.G.A. UNESCO **1968.**

DAINELLI, G.: Geologia dell' Africa Orientale. — 4 vol., R. Accad. d'Italia, Roma 1943.

DE BOOY, T.: Mobility of the Earth's crust: A comparison between the Present and the Past. — Tectonophysics, **6**, 3, 177—206, Amsterdam 1968.

DE BRUYN, J. W.: Isogams of Europe and North Africa. — Geophys. Prospecting **3**, 1—14, 1955.

DRAKE, C. L., & GIRDLER, R. W.: A geophysical study of the Red Sea, Geophys. — Journ. Roy. astron. Soc., **8**, 5, 473—495, London 1964.

DUBERTRET, L.: Carte géologique internationale de l'Afrique, 1 : 5 000 000, feuille No. 3. — Assoc. Serv. geol. afric., Paris 1959.

—: Remarques sur le Fossé de la Mer Morte et ses prolongements au Nord jusqu'au Taurus. — Rev. Geog. phys. Geol. dyn. (2), **9**, 1, 3—16, Paris 1967.

DUNNINGTON, H. V.: Generation, migration, accumulation and dissipation of oil in northern Iraq, "Habitat of OIL". — Am. Ass. Petrol. Geol. Spec. Publ. 1194—1251, Tulsa 1958.

FURON, R.: Esquisse structurale provisoire de l'Afrique. — Ass. Serv. geol. afric. 1 : 10 000 000, Paris 1958.

EWING, M., SAITO, T., EWING, J. I., & BURCKLE: Lower Cretaceous sediments from the northwest Pacific. — Science, **152,** 751—755, New York 1966.

GAMAL, M. A.: Geological Structures of the Red Sea area inferred from Satellite pictures. Hot Brines and Recent Heavy Metal Deposits in the Red Sea (chapter 4), 1968.

GEUKENS, F.: Contribution à la Géologie du Yemen. — Mem. Inst. Geol. Louvain **21,** 120—180, 1960.

—: Geology of the Arabian-Peninsula, Yemen. — Geol. Surv. Prof. Pap. **560-B,** 23 pages, Washington 1966.

GIRDLER, R. W.: The Relationship of the Red Sea to the East African Rift System. — Q. Jl. geol. Soc. London, **114,** 79—105, 1958.

GOUIN, P., & MOHR, P. A.: Gravity Traverses in Ethiopia. — Bull. Geophys. Observatory, **3**, 7, No. 3, 185—236, Addis Ababa 1964.

GREENWOOD, J. E. G. W., & BLEACKLEY, D.: Geology of the Arabian Peninsula, Aden Protectorate. — Geol. Surv. Prof. Paper **560-C,** 96 pages, Washington 1967.

GREGORY, J. W.: Geology and Fossil Corals and Echinoids of Somaliland. — Quat. Journ. Geol. Soc., **56,** 1900.

—: The Rift valleys & Geology of East Africa. — 479 pages, London (Seeley, Service & Co.), 1921.

HARPUM, J. E.: Some Problems of Pre-Karroo Geology in Tanganyika. — XIX. Int. Geol. Congr. C. R., **20,** Alger 1954.

HEEZEN, B. C., & THARP, M.: Tectonic fabric of the Atlantic and Indian oceans and continental drift. A Symposium on Continental Drift. — VIII, Philos. Transact. Roy. Soc. **258,** 90—106, London 1965.

—: Physiography of the Indian Ocean. — Philos. Trans. Roy. Soc. A. **259,** 137—149, London 1966.

HEYBROEK, F.: The Red Sea Miocene Evaporite Basin. Salt Basins around Africa. — Inst. Petrol., 17—40, London 1965.

HOLMES, A.: Principles of Physical Geology. — (new. ed.), London (Nelson) 1965.

HOROVITZ, A.: The Geology of Museri Island (Dahlak Archipelago, South Red Sea). — Israel Journ. Earth Sc., **16,** 74—83, Jerusalem 1967.

KARPOFF, R.: Esquisse géologique de l'Arabie Séoudite. — Bull. Soc. Geol. Fr. **VII,** sér. 6, 653—697, 1957.

—: Sur quelques failles et "grabens" de l'Arabie centrale et septentrionale. — Compt. rend. Soc. Geol. Fr., 294—296, 3 décembre 1956.

KARRENBERG, H.: Junger Magmatismus und Vulcanismus in Südwestarabien (Jemen). — XX. Intern. Geol. Congr., Sec. **1,** t. 1, 171—185, Mexico 1957.

—: Junger Magmatismus in Südwest Arabian (Jemen). — Techn. Mitt. Krupp, **17,** No. 1, p. 33—36, 1959.

KOBER, L.: Das nördliche Hedschas. — Geol. Forsch. in Vorderasien, Teil II. Denkschr. Akad. Wiss. (math.-naturw. Kl.), **96,** 729—820, Wien 1919.

KRENKEL, E.: Geologie Afrikas. — Erster Teil, 461 pages, Geologie der Erde, Berlin (Bornträger) 1925.

KUPFER, D. H.: A proposed Deformation Diagram for the Analysis of Fractures and Folds in Orogenic Belts. — XXIII. Intern. Geol. Cong. **13,** 219—232, Prague 1968.

LAMARE, P.: Structure géologique de l'Arabie. — 63 pages, Paris (Beranger) 1936.

MACFAYDEN, W. A.: The Geology of the Farsan Islands, Gizan and Kamaran Island, Red Sea, Pt. , — Geol. Magazine, **67,** 310—315, 1930.

MALONE, A. B., in: GIRDLER, R. W.: 1958, 103—104.

MARTIN, H.: A critical review of the evidence for a former direct connection of South America with Africa, in: Biogeography and Ecology in South America, 25—53. — The Hague (Junk) 1968.

MCCALL, G. J. H.: Geology of the Nakure. Thompson Falls-Lake Hannington Area. — Geol. Surv. Kenya, Rep. No. **78,** 1—122, 1917.

MITCHELL, R. C.: Fault pattern of the northwestern Hegaz; Saudi Arabia. — Eclogae. Geol. Helv., **50,** 257—270, 1957.

MOHR, P.: The Ethiopian Rift system. — Bull. Geophys. Observ., **3,** 1, 33—62, Addis Ababa 1962.

—: The Ethiopian Rift system. — Bull. Geophys. Observ., **11,** 1063, Addis Ababa 1967.

—: Major Volcano-Tectonic Lineament in the Ethiopian Rift system. — Nature **213,** No. 5077, 664—665, 1967.

MOHR, P., & ROGERS, A. S.: Gravity Traverses in Ethiopia. — Bull. Geophys. Observ., **9,** 7—58, Addis Ababa 1966.

NAQIB, K. M. AL.: Geology of the Arabian Peninsula, Southern Iraq. — Geol. Surv. Prof. Paper **560-G,** 1—54, Washington 1967.

NESTEROFF, W. D.: Resultats Scientifiques des Campagnes de la "Calypso". — Ann. Inst. Océanog., **30,** 1—53, Paris (Masson) 1955.

PICARD, L.: Zur postmiocaenen Entwicklungsgeschichte der Kontinentalbecken Nord-Palaestinas. — N. Jahrb. Min. etc. Beil.-Bd. **70 B,** 93—115, 1933.

—: Sur l'orogénèse de l'Algonkien supérieur en Arabo-Afrique septentrionale. — Bull. Soc. Geol. Fr., **10,** sér. 5, 49—58, 1940.

—: The Precambrian of the Northarabian-Nubian massif. — Bull. Geol. Dep. Hebr. Univ., **3**, 3—4, 1—30, Jerusalem 1941.
—: Structure and Evolution of Palestine with comparative notes on neighbouring countries. — Bull. Geol. Dep. Hebr. Univ., **4**, 2—4, 1—134, Jerusalem 1943.
—: Disharmonic Faulting. A tectonic concept. — Bull. Res. Counc. Israel, **3**, 1—2, 132—135, Jerusalem 1953.
—: Thoughts on the Graben System in the Levant (Upper Mantle Symposium). — Geol. Surv. Canada, Paper **66—14**, Ottawa 1966.
—: On the Structure of the Rhinegraben. — Proc. Israel. Acad. Sc. Hum., **9**, 1—34, Jerusalem 1968.
—: Intercontinental Graben features with emphasis on the Rhine Valley and Northeast Mediterranean Regions. — (In press.)
PLAUMANN, S.: Kontinuierliche Schweremessungen im Roten Meer mit einem Askania-Seegravimeter vom Typ Gss 2 nach Graf. — Zschr. Geoph., **29**, 5, 233—256, Würzburg 1963.
PULFREY, W.: Shape of Sub-Miocene Erosion Bevel in Kenya. — Geol. Surv. Kenya, Bull., **3**, 16 pages, 1960.
QUENNELL, A. M.: The Rift System and the East African Swell. — Proc. Geol. Soc., London, **116**, 78—86, 1960.
SAID, R.: The Geology of Egypt. — 377 pages, Amsterdam-New York (Elsevier), 1962.
SCHÜRMANN, H. M. E.: The Precambrian along the Gulf of Suez and the northern part of the Red Sea. — 404 pages, Leiden (Brill) 1966.
SCHULMAN, N.: The Geology of the Central Jordan Valley. — Bull. Res. Counc. Israel, **8 G**, 2—3, 63—90, Jerusalem 1959.
SESTINI, J.: Cenozoic Stratigraphy and Depositional History, Red Sea Coast, Sudan. — Bull. Am. Ass. Petr. Geol., **49**, 9, 1453—1472, 1965.
SHACKLETON, R. M.: A contribution to the Geology of the Kavirondo Rift Valley. — Quart. Journ. Geol. Soc. London, **106**, 4, 345—388, 1951.
SHAHAR, Y., REISS, Z., & GERRY, E.: A New Outcrop of Marine Neogene in the Negev. — Israel J. Earth-Sciences, **15**, 82—84, Jerusalem 1966.
SHATTA, A.: Structural Development of the Sinai peninsula (Egypt). — XX. Int. Geol. Congr., Assoc. Serv. Geol. Afr., 226—249, Mexico 1959.
SONDER, R. A.: Mechanik der Erde. — Stuttgart (Schweizerbart) 1956.
STEFANINI, G.: Saggio di una Carta Geologica dell' Eritrea della Somali e dell Etiopia, Note illustrative. — Consiglio Naz. Ricerche, 1 : 2 000 000, Firenze 1953.
TERABILI, E. E.: General Outlines of Epeirogenesis and Sedimentation in the Region between Safaga, Quseir, and Southern Wadi Quena Area, Eastern Desert, Egypt. — Bull. Am. Ass. Petr. Geol., **50**, 9, 1890—1898, 1966.
USSR: Tectonic map of Europe 1 : 5 000 000, sheet 5. — Moskva (Editor A. L. YANSHIN) 1966.
VROMAN, A. J.: On the Red Sea Problem. — Bull. Res. Counc. Israel, **10 G**, 1—2, 321—338, Jerusalem 1961.
WETZEL, R., & MORTON, D. M.: Contribution à la géologie de la Transjordanie. Notes and Memoires Moyen Orient, **7**, 95—191, Beyrouth 1959.
WHITEMAN, A. J.: Formation of the Red Sea Depression. — Geol. Mag., **105**, 3, 231—246, 1968.
WORZEL, J. L.: Pendulum Gravity Measurements at Sea 1936—1959. — Lamont Geol. Observ. Contrib. No. 807, 422 pages, New York (J. Wiley & Sons) 1965.