PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Eastern Margin of the Red Sea and the Coastal Structures in Saudi Arabia

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Eastern margin of the Red Sea and the coastal structures in Saudi Arabia

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[Plates 6 to 8]

Results of many investigations since 1950 show that the eastern margin of the Red Sea and associated coastal structures in Saudi Arabia have a long geologic history, starting with the deposition of Precambrian eugeosynclinal sedimentary and volcanic rocks before 1000 Ma ago and extending to recent geologic time. The northeastern flank of the Red Sea rift valley is in a shield area affected by possibly four plutonic events at 1000, 720 to 735 (?), 660 to 670, and about 570 Ma. Cratonization of the shield occurred during all or part of the span 520 to 590 Ma.

Nubian-type sandstone of Cambrian and Ordovician age laps up on the shield from Jordan southeastward around the rim of the Great Nafud basin, and along the eastern edge of the shield southeastward to 45° E longitude where it is overlapped by Permian limestone. The sandstone reappears to the south and extends southward and westward to the Asir Mountains at the Yemen border. Isolated sandstone outliers are present in the central shield, proving that lower Paleozoic sandstone covered most, if not all, of the basement as now exposed.

The Mesozoic era was almost entirely a time of uplift and non-deposition except a middle to late Jurassic fringe marine invasion in the south and a possible narrow invasion from the Gulf of Suez at the end of the era.

Marine and non-marine sedimentary deposits of middle and late Tertiary age are found along the Red Sea coast, and Oligocene basaltic flows are present at both low and high altitudes in the coastal ranges. Evidence for important volcanism during Oligocene and earliest Miocene time is widespread, and within the eastern rift fault zone early Miocene hypabyssal intrusives cut the shear zones. Major rifting occurred just before or during early Miocene when the flanks of the rift valley were ramped upward. Shortly after this volcanism a thickness on the order of 3500 m of middle Miocene marl and evaporite beds filled the Red Sea trough. Evidence also exists for widespread subaerial erosion in the Pliocene.

Younger lava flows are Pliocene in age but the youngest, near Al Medinah, came as late as A.D. 1250. Lake-bed deposits are very probably in large part Pliocene throughout the shield.

The Red Sea coastal plain in Saudi Arabia rises gently eastward from a 3 m littoral surface, generally underlain by dead reef from the Yemen border northward to Al Wajd, a distance of 1400 km. At Jizan, in the south, a salt dome has pushed the 3 m surface up to an elevation of about 50 m. From Al Wajd northward, Pleistocene terraces have been faulted, culminating in several surfaces as high as 520 m above the Red Sea at Tiran Island.

Ramping of major fault-bounded blocks along the eastern side of the Red Sea trough—the Midian block in the north, a poorly defined central block, and the Asir block in the south—is connected with renewed movement on regional Precambrian faults. Drainage patterns of wadis in these blocks are characteristically affected by the ramping, and stream capture is common in the Midian and Asir blocks.

Introduction

Systematic reconnaissance mapping of the eastern shores of the Red Sea in Saudi Arabia was begun by R. O. Jackson and me during 1950 as part of a cooperative geologic exploration programme of the U.S. Geological Survey and the Saudi Arabian Government. Before that time no geological work of any consequence had been done, and, except for the pioneer work of Doughty (1888), and, in the north by Kober (1919), the region was *terra incognita*. No one can work in western Arabia, or for that matter anywhere in the Kingdom, without credit to H. St John Philby, who geographically explored the country, meticulously recorded his travels, and freely made his knowledge available to us. From December 1952 to March 1953, Philby's travelling in northwestern Arabia was in the company of R. G. Bogue, U.S. Geological Survey, who recorded the geology as well as the bearings and distances of the geographic landmarks.

Also, before the beginning of our work, the redoubtable W. Thesiger had traversed the southern Tihama (coastal plain) and the crest of the mountains to the east. The Saudi Arabian Mining Syndicate, under the direction of K. S. Twitchell, sought ancient gold mines and was exploiting one of them. We were able to locate positions on aerial photographs which for the first time were available and which together with astronomical fixes, enabled us to put the geography and geology on a quantitative basis. The results of the work in no way detract from the magnificent journeys of Philby and Thesiger.

During the period of our work in 1950–6 the region was briefly visited in 1953 by Dr Roman Karpoff of the Societe Lyonnaise des Eaux et de l'Eclairage and in the spring of 1954 by Drs G. Richter-Bernburg, W. Schott, H. von Gaertner, and H. Schurenburg of the Amt für Bodenforschung. More recently detailed maps of restricted areas have been made by Drs V. P. Kahr and K. Nebert of the Saudi Arabia Ministry of Petroleum and Mineral Resources staff, and more extensive mapping has been done by the French Bureau de Recherches Géologiques et Minières (B.R.G.M.). The U.S. Geological Survey began a mineral reconnaissance of the entire shield in 1963, which was completed in 1966, and have since made detailed studies of specific areas and topics. The most recent detailed work along the coast has been done by geologists of the French B.R.G.M. from Al Wejh southward to Umm Lajj; by Dr C. Finali, who studied Tertiary rocks from the Yemen border northward to about Al Lith; and by Dr M. Gillmann of Auxirap and geologists under his direction, who have carefully mapped most Tertiary outcrops from the Yemen border to the Gulf of Aqaba. Members of the Japanese Geological Survey have prepared detailed maps of the area near Al Wajd and northward.

The Precambrian northeast flank

Lithology and ages

The Precambrian rocks along the northeastern flank of the Red Sea rift valley is exposed in a typical shield area of granite batholiths and stocks part covered by more-or-less metamorphosed sedimentary rocks and lava flows in roof pendants and inter-batholithic areas. Within 100 km of the western edge, more than half of the crystalline rocks are intrusive—most are granite or granodiorite but include considerable masses of syenite, adamellite, diorite and gabbro.

The older intrusive rocks are syntectonic, many are gneissic and concordant, and contain many inclusions and zenoliths; most of the intermediate granites are discordant, massive, evenly grained and calc-alkalic, whereas the youngest are chiefly post-tectonic discordant, and generally in the form of circular stocks and batholiths of syenite or sodic granite.

The major plutonic events seem, from radiometric determinations, to have occurred at about 1000, 720 to 735 (?), 660 to 670 and about 570 Ma†. The last major event is most likely to be equated with the Baikalian or Assyntian orogenic period further north, or the Pan-African event to the west as described by Schürmann (1964). This event, in Arabia as elsewhere, caused widespread loss of argon from older rocks, and was accompanied by plutonic invasions; as there is no later widespread intrusive epoch (although there were important extrusive and hypabyssal events in the Tertiary), most argon determinations reflect this period of metamorphism and

† These figures are based mostly on Rb–Sr determinations, using a decay rate of ^{87}Rb 1.39×10^{-11} a^{-1}, and were first determined by Dr T. Aldrich of the Carnegie Institution of Washington. Later additional samples were analysed by C. E. Hedge, R. R. Marvin, H. H. Mehnert, and Violet Merritt, U.S. Geological Survey; in addition K–Ar determinations were made by Isotopes, Inc., and Geochron Co.

local invasion. Undoubtedly many of the intermediate ages are mixed, and reflect the influence of several events. Older rocks are in a rubidium-poor and strontium-rich provenance, which hampers accurate Rb–Sr determinations. Fortunately, there are some exceptions, but the ages determined from our reconnaissance sampling must be considered preliminary and tentative.

The non-plutonic rocks are largely eugeosynclinal types having a total thickness on the order of some tens of kilometres—very thick andesite and greenstone units interbedded with and underlying thick siliceous slate and phyllite but including some beds of conglomerate and limestone (marble) and some ophiolitic ultramafic intrusives. The older and lower strata are found throughout the shield, and it is not clear whether any eugeosynclines are involved.

Certainly these older rocks are cut by intrusives of the 1000 Ma epoch and thus are pre-'Kibaran', especially along the southern end of the Red Sea coast. The upper portion in the eastern part of the shield is composed of at least 6000 m of slate, phyllite, and quartzite containing a conglomerate and marble near the base; this upper part is a younger cycle whose synclinal axis lies in the eastern part of the shield, not necessarily above the axis of the older eugeosynclinal rocks. The widespread youngest rocks lie above the thick and monotonous slate section and tend to be miogeosynclinal, consisting of more limestone (marble), red beds, molasse-type conglomerate, arkosite, tuff, and silicic effusive rocks. The tuff and silicic effusive rocks, mostly rhyolite, are especially common in the northern part of the shield where gradual dying out of orogenic movements can be seen in these beds.

Terminal events in the development of the craton are well recorded in the north-central part of the shield where wacke, cherty limestone, argillite, chert, and conglomerate dip 30° northward beneath nearly flat-lying sandstone of early Paleozoic age. The underlying unmetamorphosed andesite flows gave an age of 520 ± 20 Ma based on K–Ar determinations from biotite, and an unmetamorphosed andesite dike in the basement rocks truncated by the lower Paleozoic sandstone gave a whole rock K–Ar age of 521 ± 15 Ma. There is always the possibility that some argon may have been lost, perhaps during Tertiary volcanism, from, say, andesite of 570 Ma age, but these flows and dykes are fresh and structurally are the youngest of the cratonized shield rocks. Farther east, in the extreme northeastern corner of the shield, a peralkaline granite gave a 590 Ma age on Rb–Sr analyses, which I consider a much safer terminal date for the Arabian Precambrian. This granite is nonconformably overlain by the Saq Sandstone of Cambrian and Ordovician age. In Jordan a marine tongue in basal Paleozoic Nubian-type sandstone is of uppermost early Cambrian age, but this tongue has not been found in Arabia; as far as I am aware, the oldest organic evidence in this basal sandstone is the arthropod crawl-track *Cruziana* sp., which has a published range of middle Cambrian to late early Ordovician-Arenig (Picard 1942; Cloud 1966). These tracks have been found in the Arenig of Portugal and Iraq (written communication from C. Teixeria and A. Seilacher to P. E. Cloud, jun). I have seen the tracks some tens of metres above the basement in the sandstone immediately northeast of the dyke dated 521 ± 15 Ma. Unfortunately, a fault intervenes, and an unknown thickness of sandstone, most likely older than Arenig, laps up on the shield. From the above evidence we can conclude that shield cratonization occurred during all or part of the 520 to 590 Ma span.

Faults

The shield is traversed by many faults (figure 1), the most conspicuous being a system of wrench or transcurrent fractures that trend northwest, and enter the Red Sea rift at 26 to 27° 45′ N latitude. The most conspicuous is at 27° 20′ parallel to and in line with the Gulf of

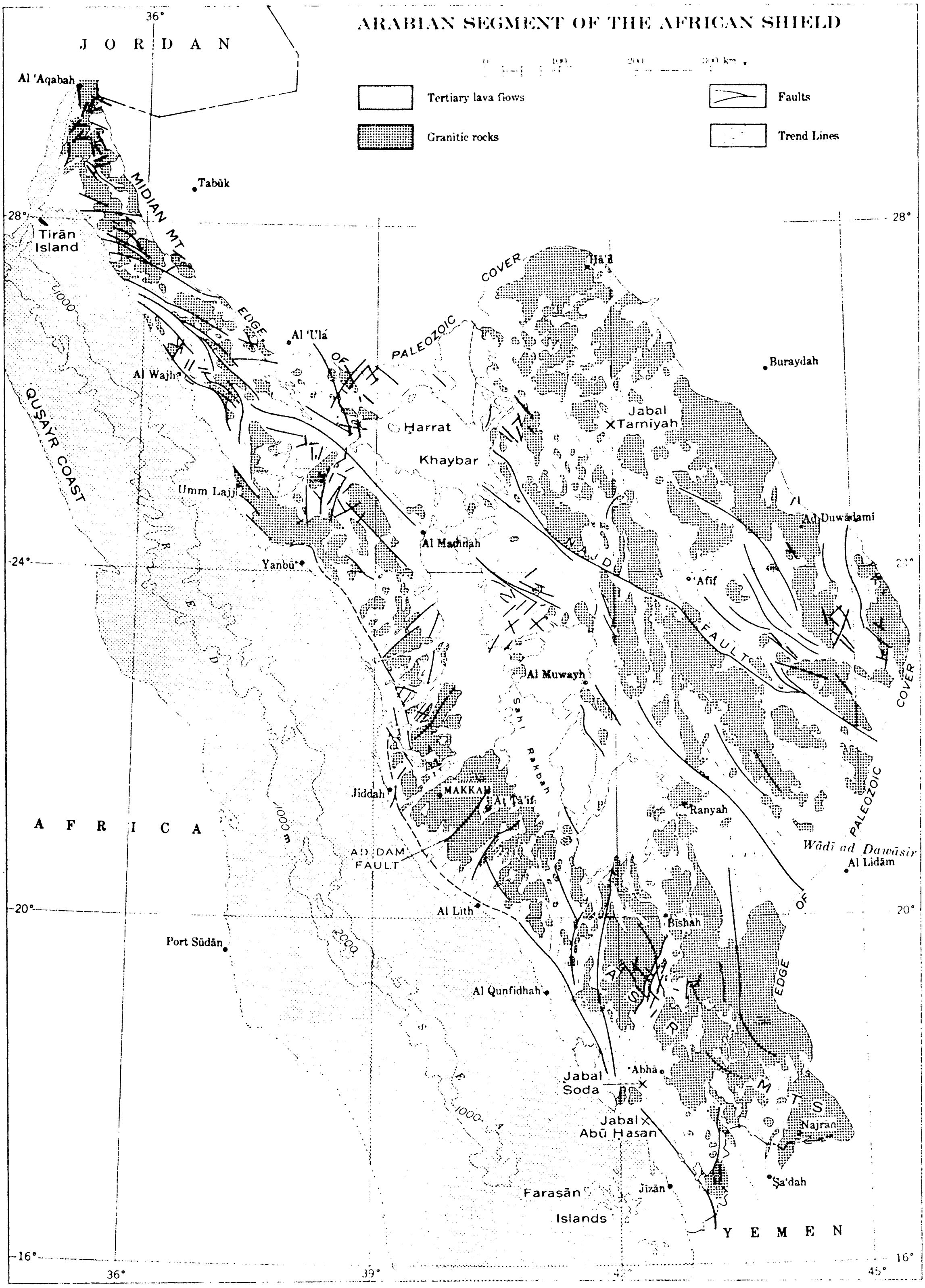
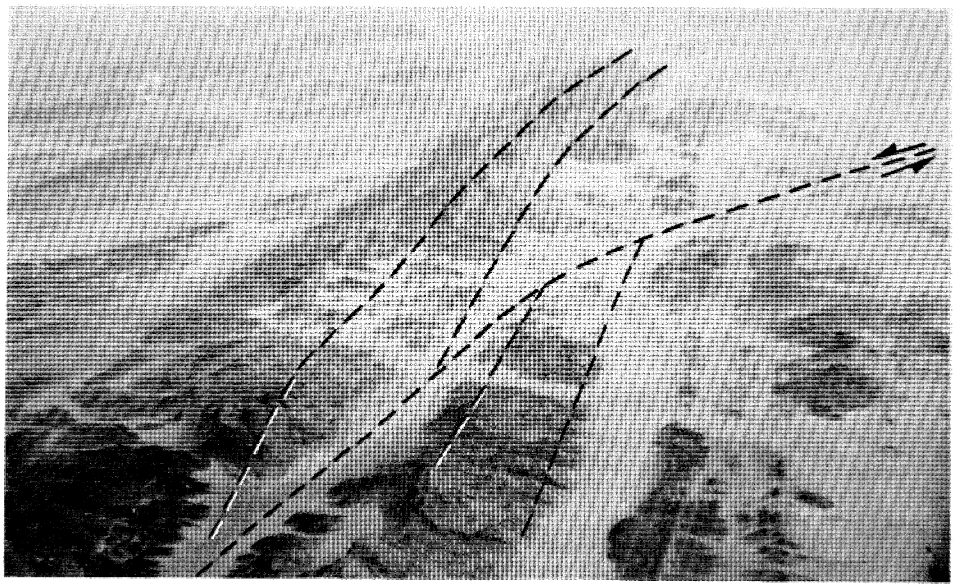


FIGURE 1. Fault pattern in the Arabian Shield.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

2



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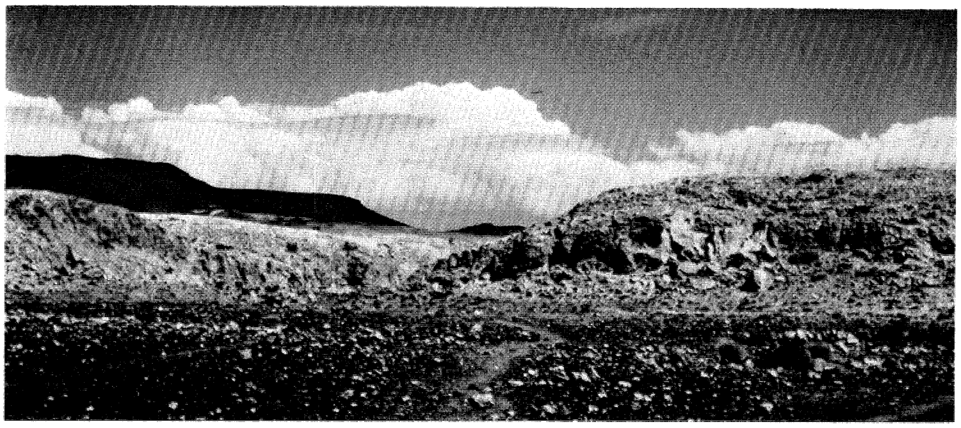

FIGURE 2. Wrench fault as seen from aircraft NE of Al Wajd, showing offset in arkosite.

FIGURE 4. Jabal Abu Al Ḥasan near the Yemen-Saudi Arabian border. Sandstone of Cambrian and Ordovician age forms the intricately eroded terrain in the foreground and caps the crystalline rocks in the background. Mesozoic clastic rocks overlie the Paleozoic sandstone on the left (north).

FIGURE 6. Sirat Mountains on the Yemen–Saudi Arabian border, where Oligocene and lower Miocene basalt (dark skyline to the left) overlies a leached and weathered zone approaching laterite in composition.

(*Facing p.* 78)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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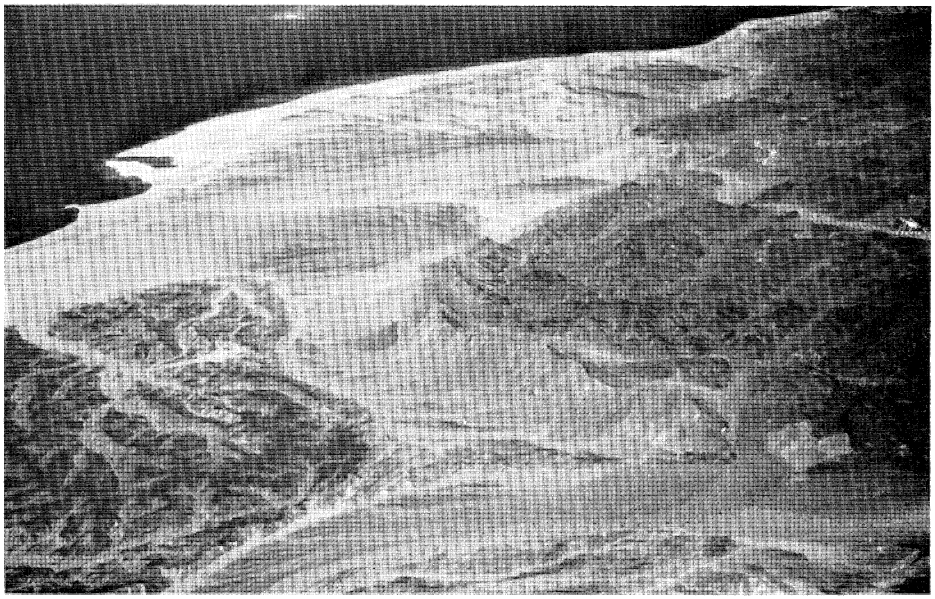

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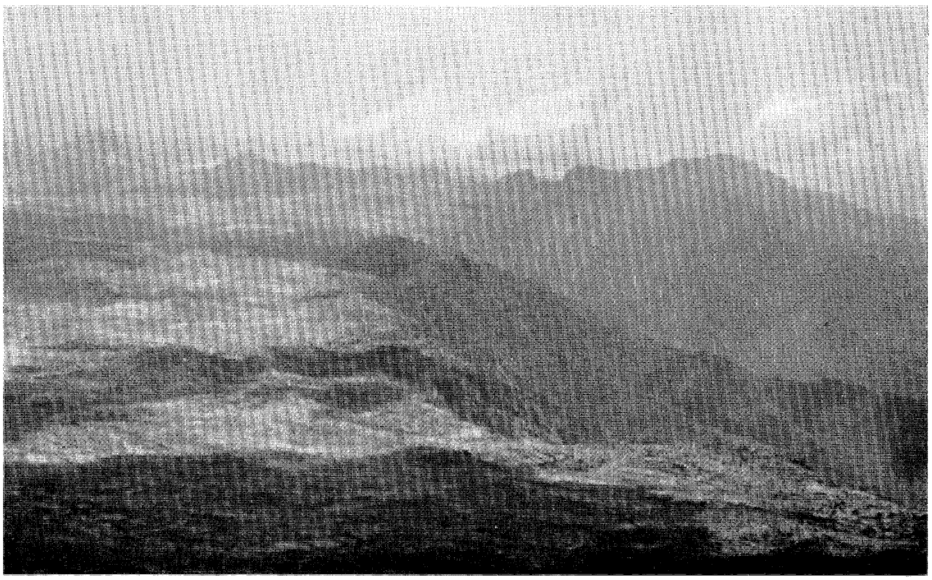
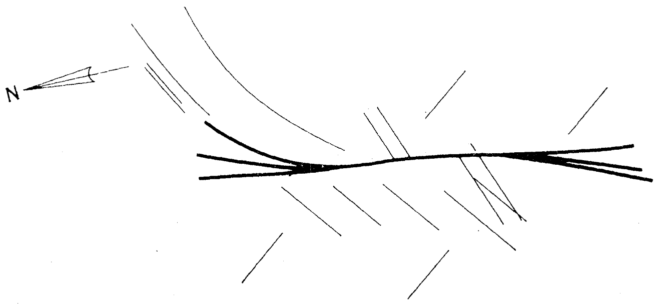


FIGURE 7. The Miocene Raghama Formation near Dubah forms a sinuous rimrock but dips under the younger Tertiary clastics and rests on Precambrian greenstone on the landward lip. View from southeast.

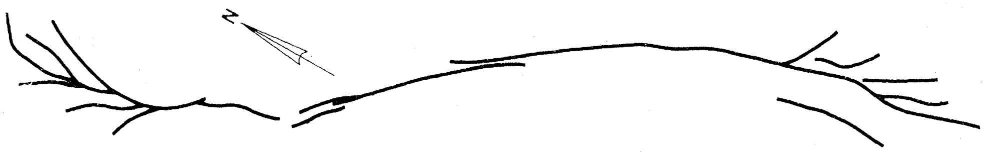
FIGURE 8. Same area as figure 7 but viewed from the east.

FIGURE 9. Aerial view south of the Hijaz crest. The Red Sea rift lies to the right (west) and the flat upland represents the middle Tertiary surface of Africa. The highest peaks are on the scarp and the gentle eastward slope reflects the middle Tertiary ramping of the rift.

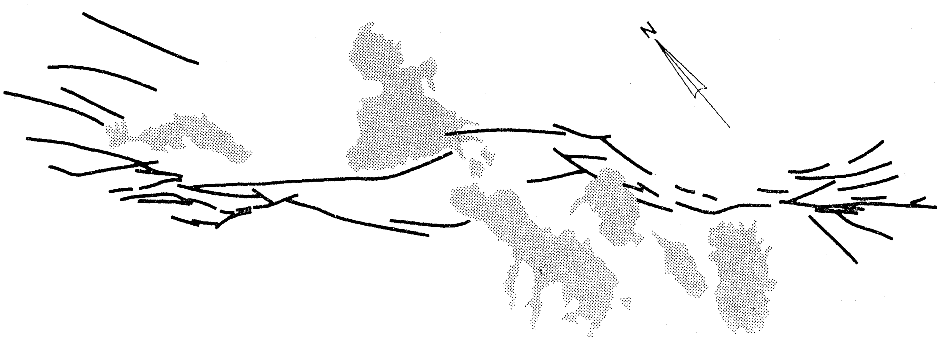
Suez (figure 2, plate 6). This Najd (Central Arabian) wrench fault zone, which can be followed for 1200 km except where covered by young lavas and alluvium, has characteristics of other similar faults, such as the system in Jordan (de Sitter 1962) and the Philippines (Philippine Bureau of Mines 1963), particularly in the curves and the splays at either end (figure 3). At 150 km northeast and about 130 km farther northeast of the southern part of the Najd fault, we have been able to map discontinuously two more similar transcurrent faults. A fourth fault zone at the extreme eastern edge of the shield trends in a more northerly direction (figure 1).



I. Jordan fault—approximate length 650 km



II. Philippine fault—approximate length 1500 km



III. Nejd fault—approximate length 1300 km

Figure 3. Wrench faults from different terranes. The Jordan fault (I; after DeSitter 1962) is of Pleistocene age whereas the Philippine fault (II, after Philippine Bureau of Mines, 1963) dates from middle Tertiary, and the Najd fault in Saudi Arabia (III) is Precambrian.

All seem to be high angle, as shown by overthrusting. The easternmost fault seems to be high-angle reverse near its southern end, according to geophysical data (Mabey, written communication, 1964), but results of geologic mapping at the northern end near the Paleozoic cover can be construed to show 60 km of dextral movement (G. Eijkelboom, B. Henry & G. Vincent, 1966, written communication). Movement on the others is difficult to estimate from exposures as the fault zones are generally composed of schist which erodes readily to form wadi valleys. Movement has occurred both before and after the plutonic rocks were emplaced.

In the southern part of the shield most of the mapped faults trend north or north-northeast, and correlations across the Red Sea to the Sudan as mapped by I. Gass seem reasonable (Whitman 1968). Southeast of Jiddah some conspicuous faults trend northeast, the most prominent being Ad Dam, which forms a lineation 100 km in length, and extends over the Hijaz escarpment to the west of Ta'if. We have been unable to discern wrench movement in the outcrops along the flanks of these faults.

The Paleozoic arch

Sandstone of Cambrian and Ordovician age laps up on the shield from Jordan southeastward around the rim of the Great Nafud basin in northern Arabia and along the eastern edge of the shield southward to 45° E longitude where it is overlapped by the Permian Kuffs Limestone. It appears again from underneath the Permian south of Wadiah Dawasir at the western side of the Rub Al Khali and continues on southward into the high plateau of Yemen. Formerly this southern segment, called the Wajid Sandstone, was undated except that it was known to be pre-middle Permian, but recent palynologic evidence in well cores examined by Dr Hemer has proven a Cambrian and Orodovician age (L. Dubay, 1968, written communication). In Saudi Arabia the sandstone extends west along the Yemen frontier to the point where it is eroded away in the Asir Mountains. However, outliers are found on the crest of Jabal Soda at the highest altitude in the Kingdom (3130 m) and on other isolated peaks to the south, such as Jabal Abū Ḥasan (figure 4, plate 6).

Within the shield isolated sandstone outliers lie along the wrench fault valley northeast of Al Madinah and at Jabal Tamiyah in the centre of the northeastern quadrant. Thus, it appears that this Nubian-type sandstone must have covered a large part, if not all, of the shield, yet the eastern flank was uncovered by Permian time. Indeed the deep weathering beneath the Permian, and the level erosional surface and occasional monadnocks forming the Precambrian Lipalian peneplain, point to a long erosional interval before Cambrian and Ordovician time, and continued erosion through the remainder of the Phanerozoic.

McKee (1962) studied the Cambrian and Ordovician sandstones in southern Jordan and concluded that they were largely water laid, the lowermost being perhaps 'foreset accumulation in standing bodies of very shallow water, such as ponds on flood plains or shallow lagoons', and having a generally northerly direction of sand transport. The lack of deep marine sediments, together with the large truncated wedge structures and the evenly grained composition of the sets wherever exposed in Arabia probably means that the sandstones accumulated near base-level on a Lipalian peneplain under predominately sub-aerial conditions with only rare, short partial marine incursions. The shield appears to have been a positive element ever since.

Mesozoic and early Tertiary history

The Mesozoic era was almost entirely a time of uplift and non-deposition. With the exception of a middle to late Jurassic marine invasion from the south that was limited to 18° N latitude (figure 4), the only incursion is a questionable Maestrichtian invasion that extended southward from the Gulf of Suez to the Qusayr Coast of Egypt and possibly southward to 22° N latitude at Usfan, 55 km northeast of Jiddah (Karpoff 1957). This invasion carried a Mediterranean fauna. At about that latitude, outcrops in the Sudan contain an ostracod fauna considered transitional from Cretaceous to Paleocene (Carella & Scarpa 1962). The Usfan fauna was first described by M. Steineke & E. Berg (written communication 1938) and considered to be of middle Eocene age. I collected from two localities at Usfan. F. Stearns McNeil, U.S. Geological Survey, examined the molluscan fauna and considered it to have Paleocene affinities. L. R. Cox at the British Museum believed the same fauna to be of Eocene age, and that there was insufficient evidence for assignment to a definite stage of the Eocene. The collection was re-examined by N. F. Sohl, U.S. Geological Survey, whose opinion was that the molluscan assemblage has a Tertiary aspect and that Cox's analysis is as reasonable as can be expected with the material at hand. These localities may be different from Karpoff's, but the outcrops of the Usfan Formation covers a relatively small area. More recently, Dr M. Gillmann (oral communication) has collected Maestrichtian fossils in the Usfan area; it thus appears that beds of both uppermost Cretaceous and lowermost Eocene age are present. Ages of 42.8 ± 1 and 55.2 ± 1.2 Ma have been obtained from K–Ar ratios in glauconite from the Usfan beds. Although these are Eocene and Paleocene dates, they should be considered only minima because of opportunity for argon loss; and certainly do not rule out a Maestrichtian age.

Middle and late Tertiary history

A sequence of clastic sediments containing oolitic iron ore, a dicotyledonous flora, and both marine and non-marine molluscan fossils in a graben east of Jiddah at Wadi Shumasi has been studied by Shanti (1966), who submitted the fossils to L. R. Cox of the British Museum. Cox was able to identify the forms as of Oligocene age; furthermore, a lava flow at the top of the sediments has been dated from two drill core samples by the K–Ar total rock method as 32 ± 2 Ma, and 25 ± 3 Ma (figure 5). Comparable lava associated with red beds directly across the Red Sea at Khor Shin'ab gave a comparable date, i.e. latest Oligocene or earliest Miocene, according to Dr I. Gass (Whitman 1968). In addition to the evidence of Oligocene age of the lava in Wadi Shumasi, the 320 m thick series of basaltic flows of the Sirat range near the Yemen border give K–Ar dates of 29 to 24 Ma the older date applying to the basal flow and the younger to the topmost flow. Thus a laterite (figure 6, plate 6) exposed beneath the lava is early Tertiary. Furthermore, a sample from the northern end of the plateau basalts at Asmara gave a K–Ar whole-rock age of 36.3 ± 1.2 Ma, thus placing it at the beginning of the Oligocene; this agrees in general with the Eocene and Oligocene age of the Trap Series in Yemen (Geukens 1966). There is widespread evidence for important volcanism during Oligocene and earliest Miocene.

Within the Saudi Arabia fault zone that forms the eastern edge of the Red Sea rift valley, we now have K–Ar dates falling within early Miocene; these are from hypabyssal intrusive rocks cutting pre-existing rift shear zones from Jiddah southward to the Yemen border; they range in age from 20.6 to 24.3 Ma. Thus major rifting occurred just before or during early Miocene. A thickness on the order of 3500 m of middle Miocene *Globigerina* marls and evaporite beds filled the Red Sea trough shortly after this volcanism. Our evidence for this is as follows:

Miocene corals were early identified by J. W. Wells (written communication, 1953) from the basin east of Yenbo, 200 km north of Jiddah. The form *Montastrea* sp. cf. *M. pedunculata* (Duncan) was previously known from the Miocene Gaj Formation of West Pakistan, and also from

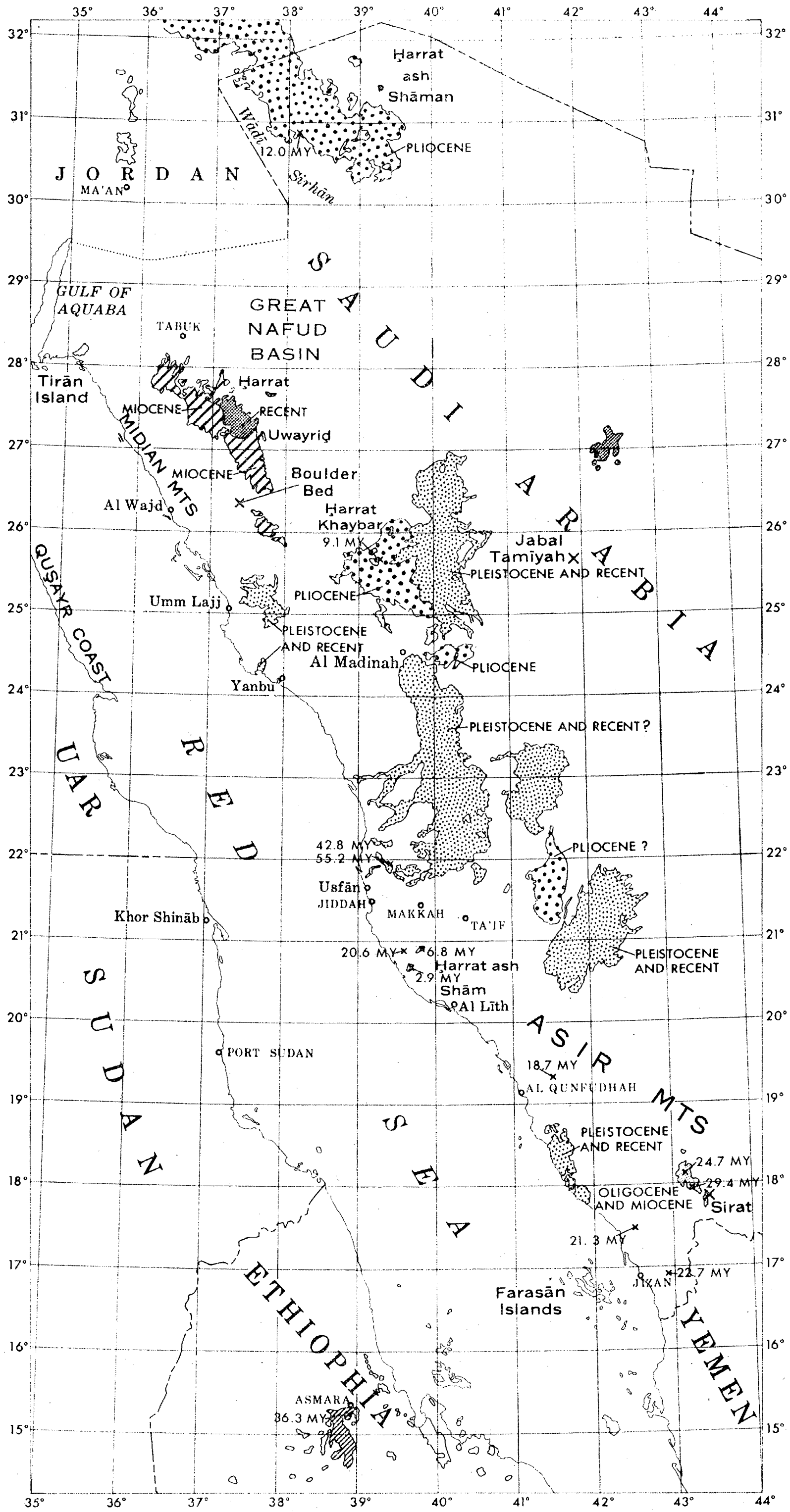


FIGURE 5. K–Ar ages from total rock samples collected in western Saudi Arabia. Analysed by Isotopes, Inc., and Geochron Co. All patterned areas indicate lava flows.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the reef outcrops east of Al Qunfidah, 300 km south of Jiddah, where *Favites* sp. cf. *F. profunda* (Michelotti), previously known from the Miocene of Italian and Red Sea areas, has been found.

The oyster *Ostrea crasissima* (synonymous with *O. gryphoides*) was found by us north of Umm Lajj, but was later collected from many new localities (figures 7 and 8, plate 7) and identified by geologists of the Amt für Bodenforschung (Richte-Bernburg & Schott 1954, p. 29), who considered the oyster and some unspecified microfossils as of Miocene age. However, this oyster is known from the Pliocene of the Indian Ocean and thus cannot be considered alone as evidence for Miocene age (Cox 1929). Indeed Cox makes a strong case for a Pliocene invasion of the Red Sea rift valley from the Indian Ocean, and the fauna at the base of the Pleistocene coral reefs is now generally recognized as such (Heybroek 1965).

Finally, in regard to the Miocene fossils, we found freshwater fish in the Jizan basin on the Tihama north of the Yemen boundary within a non-marine section of tuffaceous beds which we named the Baid Formation (Brown & Jackson 1959), and which has recently been mapped in detail by Gillmann (1968). Dr D. H. Dunkel, U.S. National Museum (written communication, 10 February 1953) commented on the fish as follows: 'Included among this suite of specimens are representatives of two families of freshwater fishes of widespread distribution in Asia and Africa today. One of these fishes is a cyprinid or minnow, which falls within the structural range of the recent genus *Barbus*. The other is of a cichlid, close, if not identical, to the living *Tilapia*. The incompleteness of the present specimens makes specific comparisons unfeasible. The past history, although very incompletely known, suggests a middle Tertiary age for this occurrence...late Oligocene or Miocene.'

Recent studies of the Miocene Raghama Formation southeast and near the mouth of the Gulf of Aqaba (A. J. Bodenlos & Lari Adnan, written communication, 1969), where the evaporite beds are best exposed, indicate three major divisions separated by unconformities. The lowermost and thickest is a coarse sandstone and conglomerate with major facies changes seaward; the middle unit is fine grained clastic rocks and gypsum; and the upper unit is medium grained clastic rocks with gypsum. The lower unit could possibly be Oligocene and correlative with the continental beds of the Gulf of Suez, but seem more likely to represent the Charandal Group at the base of the Miocene section in the Suez Clysmic Gulf, a molasse-type accumulation that followed major rift faulting. There is much evidence, palynological and otherwise, for assigning the widespread middle evaporite unit to middle and upper Miocene (Heybroek 1965). The upper unit of the Raghama could be equivalent to the Pontian (late Miocene to early Pliocene) in the Levant where similar red beds are associated with silts and conglomerate (Freund, Zak & Garfunkel 1968). Certainly Bodenlos found at Raghama that the upper unit underlies beds of definite Pleistocene age.

During the mapping of Precambrian units 110 km inland at 26° N latitude, we found a patch of siliceous boulders containing Eocene fossils. The site is on top of a late Precambrian batholith at an altitude of about 1100 m, and some 400 km south of Eocene outcrops in Jordan that contain the same fossils. The gravel seems to have been preserved under lava fields whose remnants can now be seen not far to the northeast. The boulders must have been transported from the outcrops at some time before ramping of the rift flank which is now so obviously a part of the rift structure (figure 9, plate 7), as their transport from an altitude of 1000 m, the projected pre-rift altitude to the north, is not possible. The time of widespread subaerial erosion is thus limited to Oligocene if the ramping was concurrent with the well-established late Oligocene-early Miocene rifting. In the Harrat Uwayril, the deep erosion of the older

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

basalt lavas under which the gravel lies in the Midian Mountains, points to a probable Miocene age similar to that of the Sirat, which ranges from late Oligocene to early Miocene. However, except for the pluvial episodes of the Pleistocene, the rainfall is somewhat less in the Midian range, and such an age comparison can only be speculative until we have isotopic dates.

Some of the younger lava flows are of Pliocene age. The three lower southeastern prongs of the basalt in the Harrat ash Shāman on the north side of Wadi Sirhan and extending into Jordan have an average age of 12.3 Ma (K–Ar total rock determination by Isotopes, Inc.). A single date from the large plateau-type flows at Harrat Khayber north of Al Madinah is 9.1 Ma (K–Ar total rock determination) but the youngest flows along the east side of this field are historical. Finally, remnants of a flow on the low hills of the coastal plain 70 km south of Jiddah have an approximate age of 6.8 Ma, whereas the Harrat Sham nearby is 2.86 Ma (K–Ar total rock). The latter flows are on a pediment formed at the base of the scarp mountains, proving that its pediment was far advanced by the end of the Tertiary and was well advanced by mid-Pliocene, according to the 6.8 Ma age of the lavas on the nearby low hill crests.

As the Pliocene was a period of epeirogeny in Arabia, one would expect to find the Pliocene deposits only below sea level and, certainly, wherever we have collected on the Tihama, the forms have been classed as either Pleistocene or Miocene. In northern Arabia Newton Layne collected freshwater ostracodes from fine silty lake beds near Taima, and I. G. Sohn (U.S. Geological Survey, written communication 19 July 1960) considers the faunal assemblage older than Holocene and probably not older than late Miocene: most likely Pliocene. Other lake bed deposits throughout the shield are very probably Pliocene, following the development of undrained depressions on the widespread terminal middle Tertiary peneplain.

Quaternary structure

The fault forming the eastern boundary of the Red Sea rift valley is mostly concealed under the Tihama, the eastern part of which is a pediment; the fault has recently been located by shallow well drilling and geophysical surveys. The zone seems to be high angle and tensional; where displacements can be measured, they are as much as 3 km vertically after ramping. The zone is commonly 1 or 2 km wide and contains brecciated rocks cut by porphyritic hypabyssal intrusives.

The coastal plain from the Yemen border northward to the vicinity of Al Wajh, a distance of about 1400 km, rises gradually eastward from above a littoral 3 m surface. At Jizan a salt dome has pushed the 3 m surface up to an altitude of about 50 m, but elsewhere higher surfaces are limited to remnants under lava flows and patches at the eastern edge of the plain which have the appearance of fossil alluvial fans. At many places the 3 m surface is underlain by dead coral reef; at the saline water plant northwest of Jiddah samples of the reef were tested by Meyer Rubin (U.S. Geological Survey, written communication, 1969), for ^{14}C and found to be older than 40 000 years. Thus the sea wherein the reef grew when the water table was higher than at present must have been pre-Würm. In this connexion, numerous drowned estuaries called sherms are fossil erosional features that formed when rainfall was heavier than at present and the sea level was considerably lower. As there is at present no active erosion within the sherms I have examined—only silt deposition—the sherms must have originated during the last pluvial (Würm).

From Al Wajh northward the Pleistocene terraces have been faulted, culminating in several

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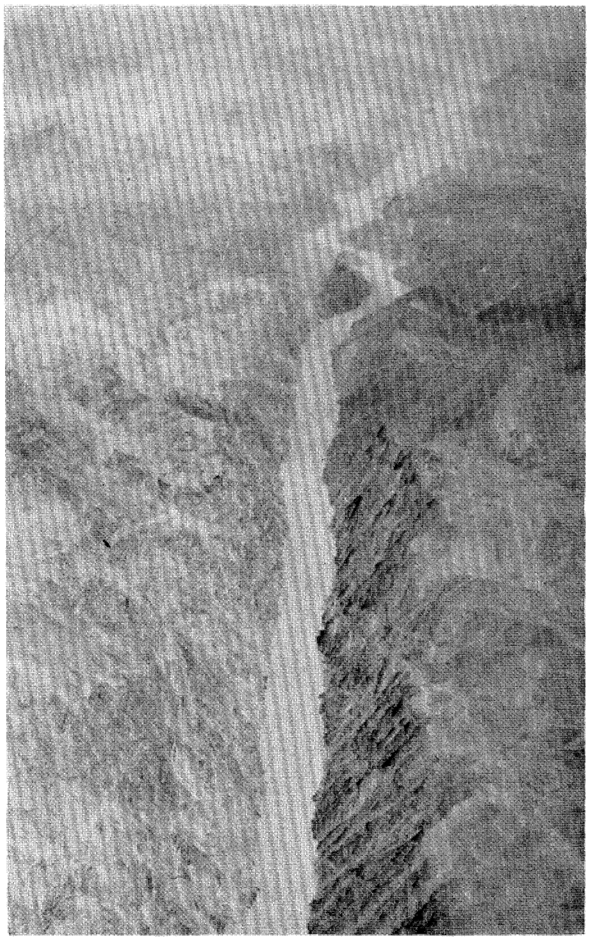

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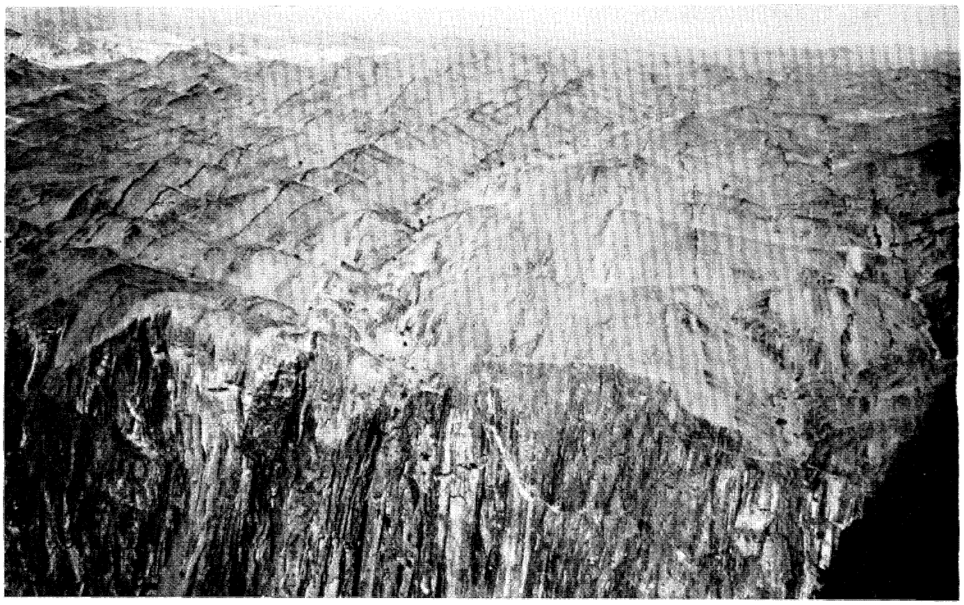

FIGURE 10. Aerial view southward of the eastern shore of the Gulf of Aqaba.

FIGURE 11. Aerial view of young fault in crystalline rocks; movement was a hinge action similar to closing a book, with very little vertical and no recent wrench displacement.

FIGURE 12. Aerial view northward above the precipice of Wadi Tiyah in the Asir scarp mountains. The middle Tertiary pediplain here rises to the left (west) as a result of the ramp-tilting of the upland surface. Schistose greenstone laced with diabase dykes.

(*Facing p.* 86)

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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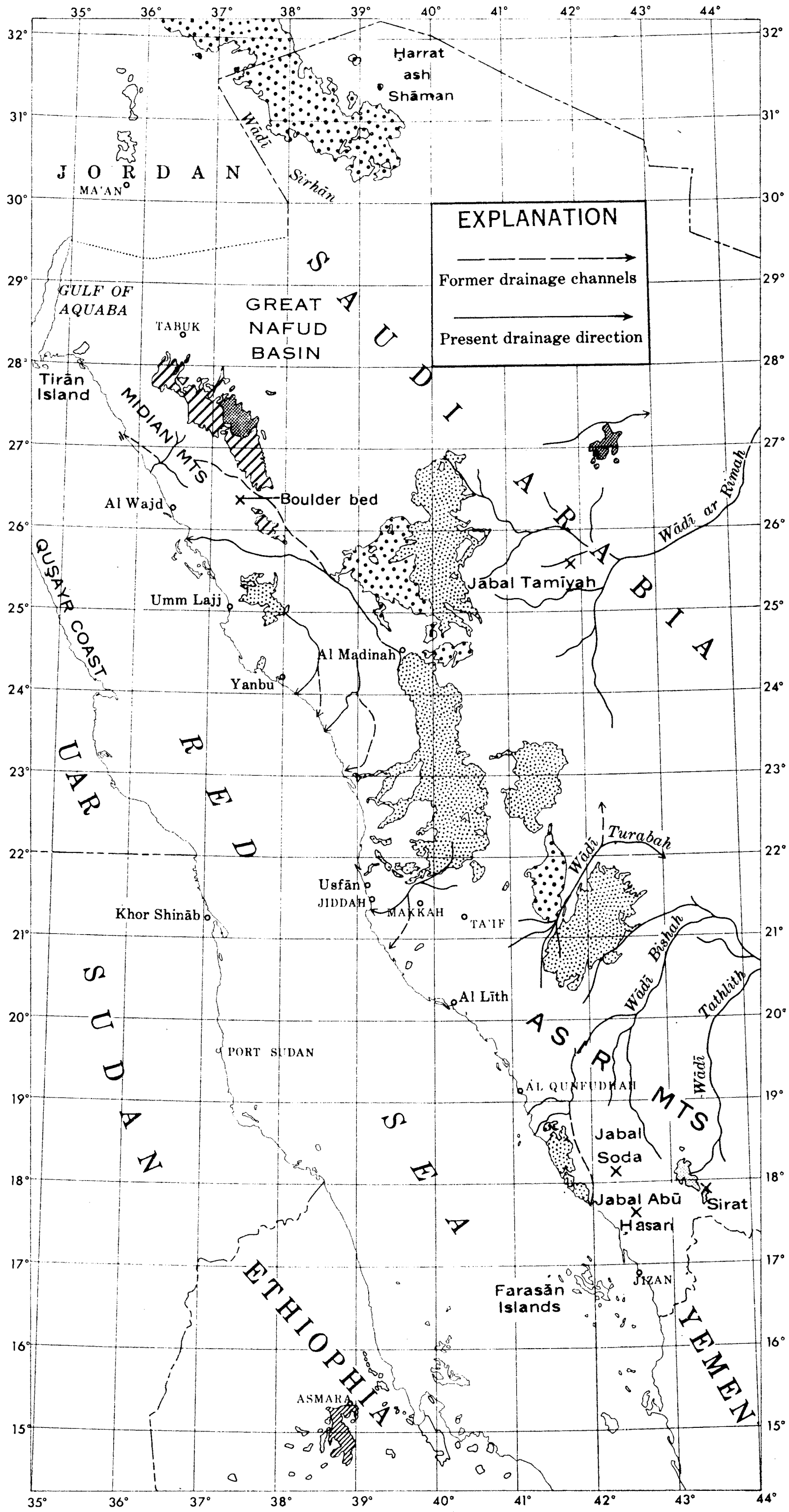

Figure 13. Drainage changes resulting from stream capture and tilting of blocks in western Saudi Arabia. For outcrop legend see figure 5.

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Karpoff, R. 1957 Sur l'existence du maestrichtien au nord de Djeddah (Arabie seoudite): *C. r. hebd. Séanc. Acad. Sci., Paris* **245**, 1322–1324.
Kober, L. 1919 Geologische Forschungen in Vorderasien. II Teil. C. das nordiche Hegaz: *Wein Akad. Wiss. Math. Natur. Kl.* **96**, 779–820.
McKee, E. D. 1962 Origin of the Nubian and similar sandstones: *Geol. Rdsch.* **52**, 551–587.
Philippine Bureau of Mines 1963 Geological map of the Philippines: scale 1:1 000 000. Manilla: Philippine Bureau of Mines.
Picard, L. 1942 New Cambrian fossils and Paleozoic problemetica from the Dead Sea and Arabia: *Bull. geol. Dep. Hebrew Univ.* **4**, 1–18.
Richter-Bernburg, G. & Schott, W. 1954 Geological researches in Western Saudi Arabia: Saudi Arabia Directorate General Mineral Resources, unpubl. rept. in files of Directorate, 69 pp.
Schürmann, H. M. E. 1964 Rejuvenation of Pre-Cambrian rocks under epirogenetical conditions during old Palaeozoic times in Africa: *Geol. Mijnb.* **43** e, 196–200.
Shanti, A. M. S. 1966 Oolitic iron ore deposits in Wadi Fatima between Jeddah and Mecca, Saudi Arabia. *Saudi Arabia Ministry Petroleum and Mineral Resources, Bull.* no. 2.
Sitter, L. U. de 1962 Structural development of the Arabian Shield in Palestine: Geologie Mijnb. **41**, 116–124.
Whitman, A. J. 1968 Formation of the Red Sea depression: *Geol. Mag.* **105**, no. 3.

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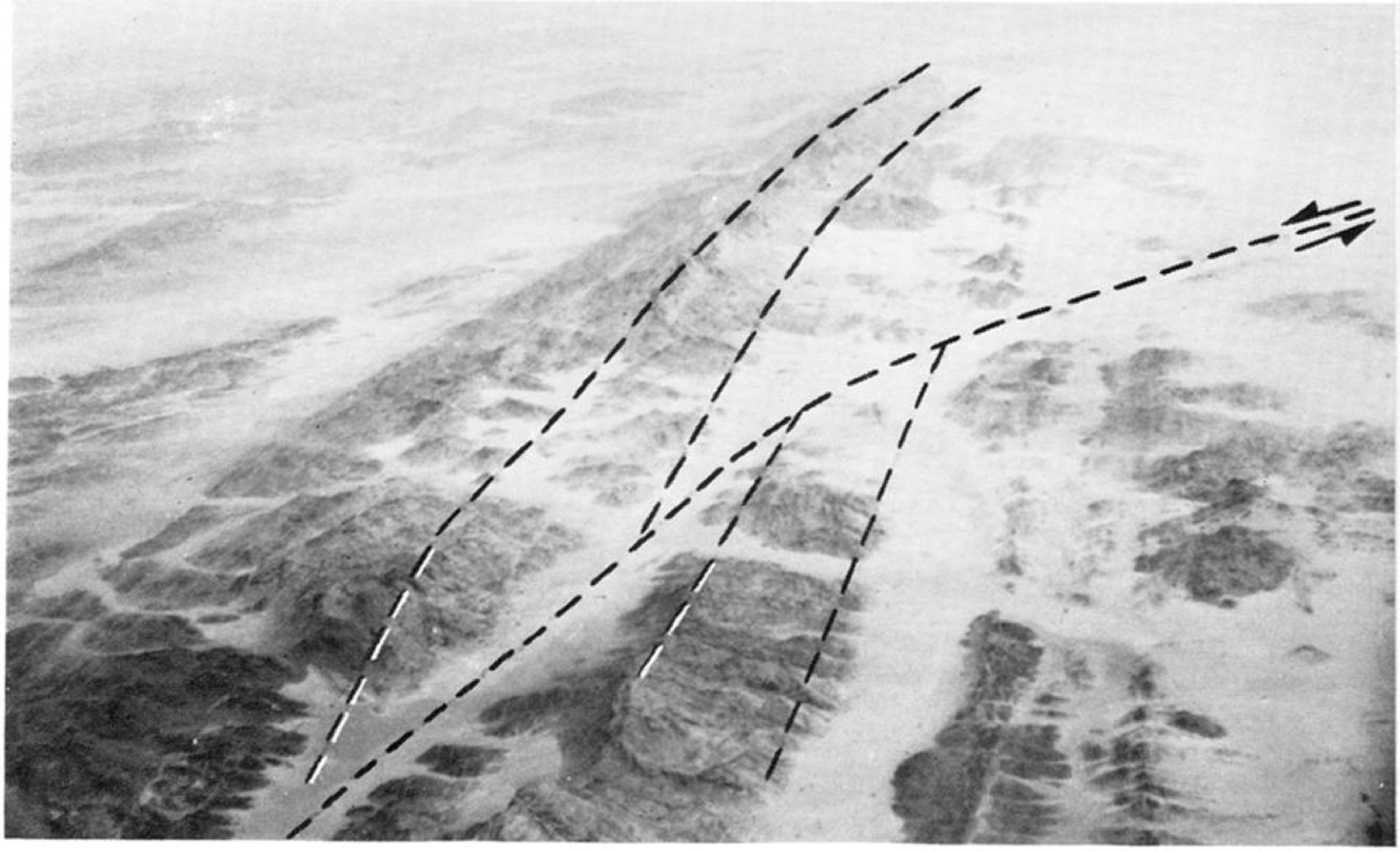

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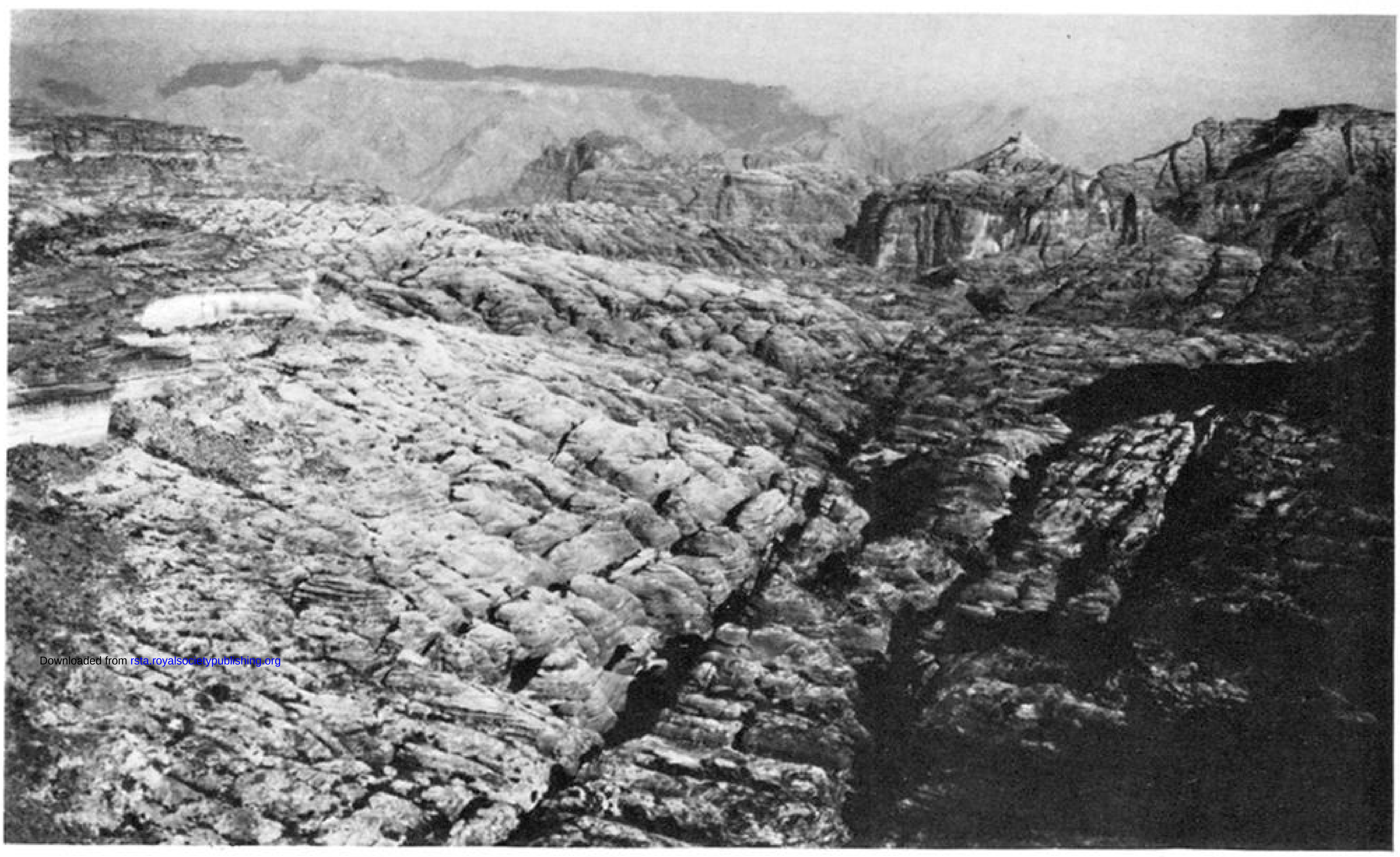

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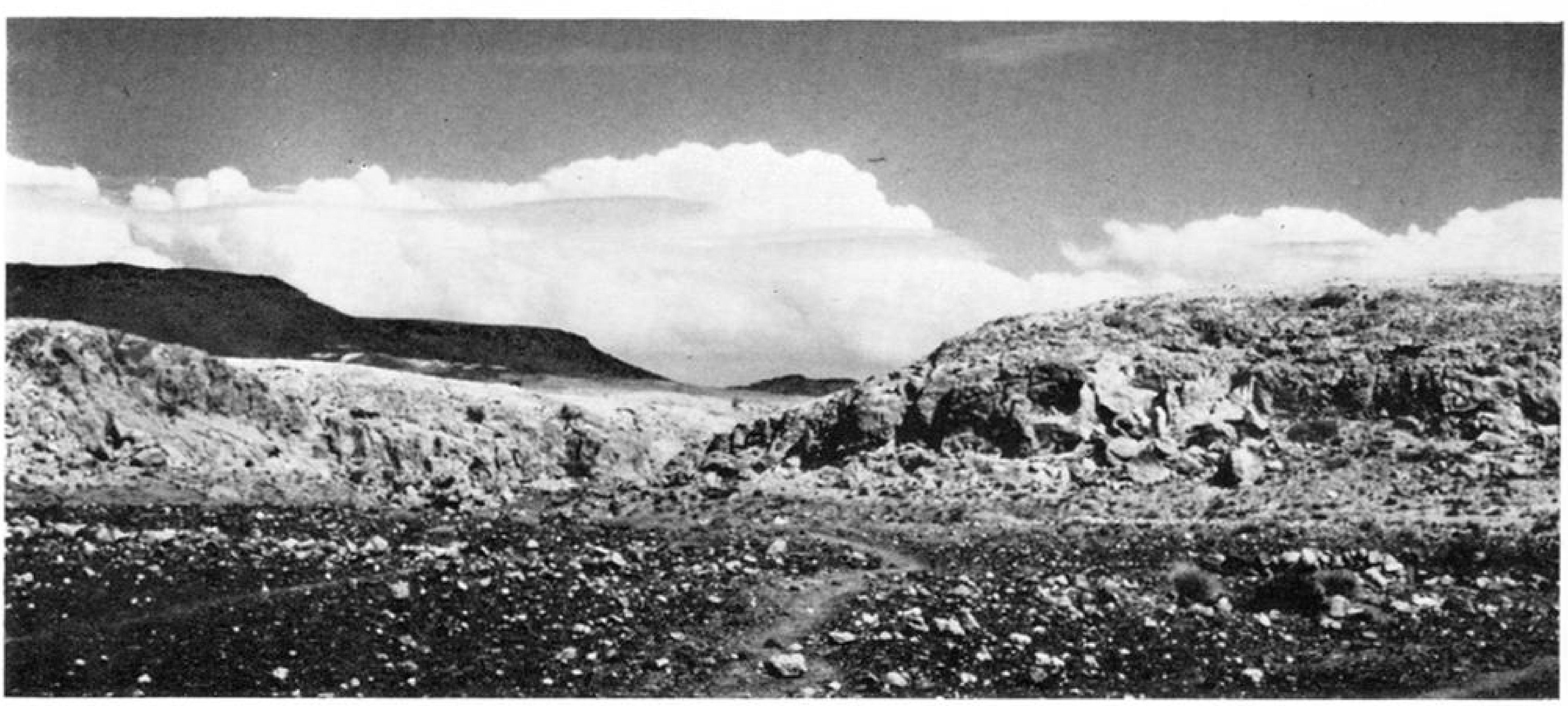

Figure 2. Wrench fault as seen from aircraft NE of Al Wajd, showing offset in arkosite.

Figure 4. Jabal Abu Al Ḥasan near the Yemen-Saudi Arabian border. Sandstone of Cambrian and Ordovician age forms the intricately eroded terrain in the foreground and caps the crystalline rocks in the background. Mesozoic clastic rocks overlie the Paleozoic sandstone on the left (north).

Figure 6. Sirat Mountains on the Yemen–Saudi Arabian border, where Oligocene and lower Miocene basalt (dark skyline to the left) overlies a leached and weathered zone approaching laterite in composition.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

FIGURE 7. The Miocene Raghama Formation near Dubah forms a sinuous rimrock but dips under the younger Tertiary clastics and rests on Precambrian greenstone on the landward lip. View from southeast.

FIGURE 8. Same area as figure 7 but viewed from the east.

FIGURE 9. Aerial view south of the Hijaz crest. The Red Sea rift lies to the right (west) and the flat upland represents the middle Tertiary surface of Africa. The highest peaks are on the scarp and the gentle eastward slope reflects the middle Tertiary ramping of the rift.

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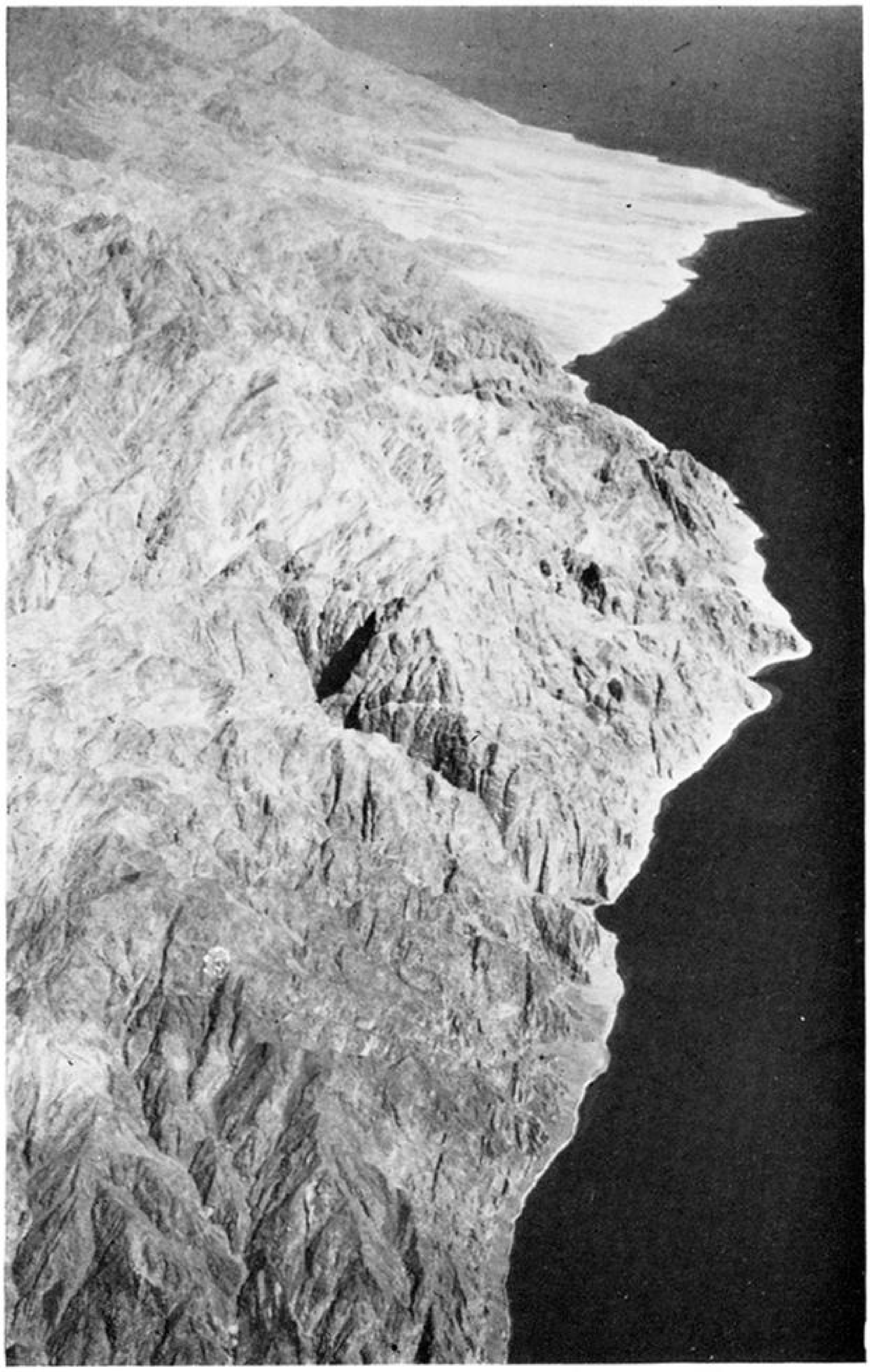

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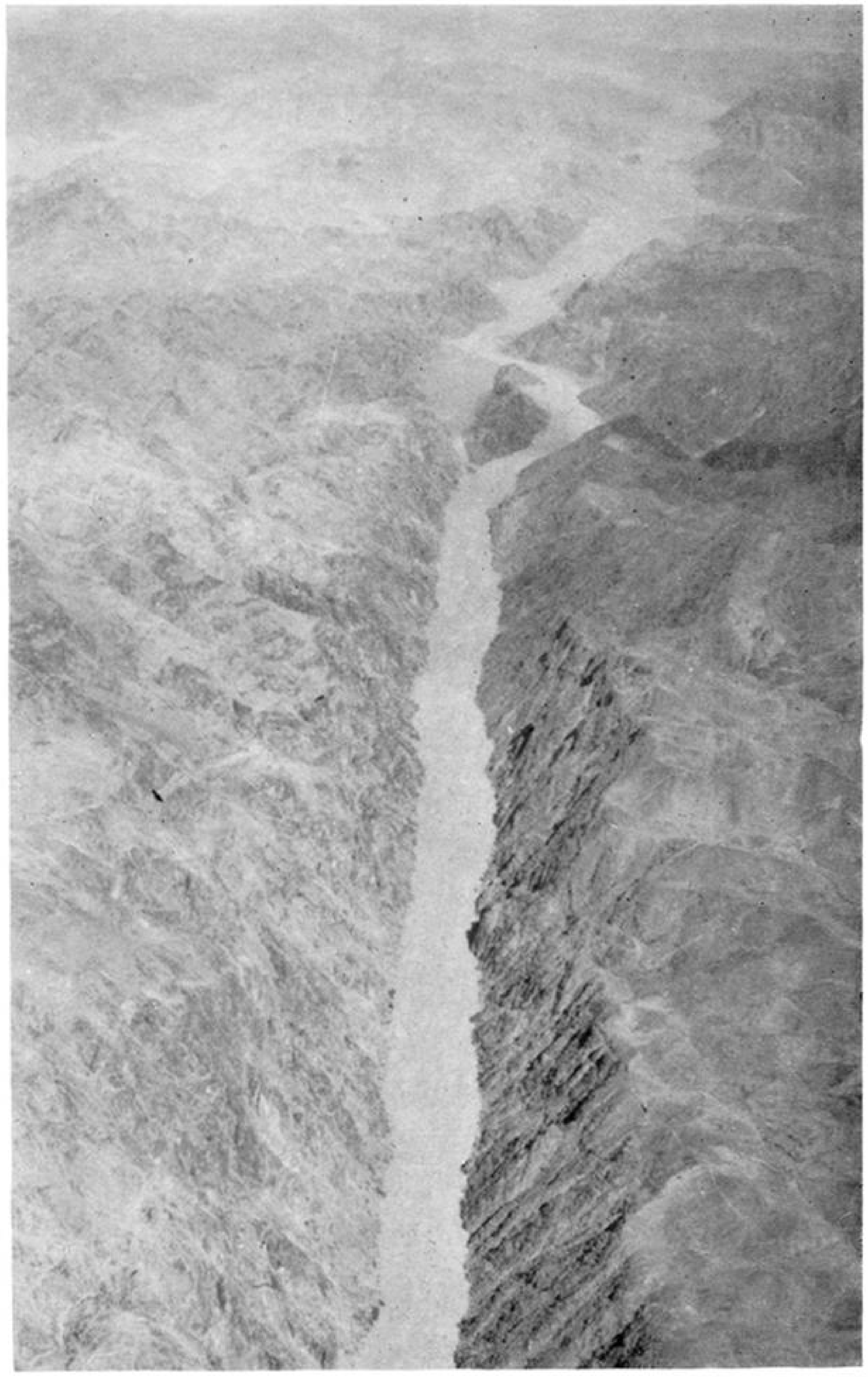

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