Interpretation of Satellite Photographs of the Red Sea and Gulf of Aden [and Discussion]

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Interpretation of satellite photographs of the Red Sea and Gulf of Aden

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[Plates 1 to 4]

Geological structures observed in Gemini and Apollo colour photographs suggest that large-scale translational movements could have taken place in the Red Sea and Gulf of Aden.

In the northern Red Sea the apparent displacement of two pairs of shear zones and three pairs of serpentinite belts is consistent with a movement of Arabia towards the NNE of some 150 km. In the southern part of the Red Sea evidence of displacement is derived from correlation of Precambrian trend-lines, particularly at points where there is an abrupt change in the regional grain; at Ras Kasr–Al Lith (latitudes 18° N and 20° N) the total movement could be 225 km.

Across the Gulf of Aden observations are in general agreement with the pre-Miocene fit proposed by Laughton (1965). Study of satellite photographs provide the following additional evidence: (1) The continuity of the Hadramawt folds (southern Arabia) in the Somali Plateau; the southern Hadramawt arch appears to be extended in the northern Somali arch. (2) Pre-drift correlation of several fault zones of WNW–ESE trend across the Gulf. The NE–SW faults, on the other hand, show poor correlation across the Gulf and appear to be related to fault lineaments within the Gulf of Aden.

Across the Strait of Bab El Mandeb geological and morphological similarities in the distribution of Quaternary sediments, volcanic fields, intervening alluvial deposits, fault and drainage lineaments suggest a left-lateral displacement of Arabia some 40 km to the NNE since the Plio-Pleistocene. Such a movement could have resulted in the final opening of the Bab El Mandeb Strait.

1. INTRODUCTION

Students of the Red Sea rift have long been hampered by lack of knowledge concerning the geology and structure of vast areas of its surrounding land. This major rift zone which cuts boldly across the Precambrian shield (Arabian–Nubian massif) was one of the principal targets selected for synoptic terrain photography experiments from satellites by the United States' National Aeronautics and Space Administration [Nasa] (P. D. Lowman, jun., personal communication). Most of the colour photographs taken over that area during Gemini III to XII (1965–6) and early Apollo missions (Apollo 7, 1968) are of useful quality for regional geological interpretation. This is largely due to the prevailing clear weather and the general aridity of the area which results in minimum soil and vegetative cover and reduced haze effect.

The pictures were taken by astronauts through glass windows of the spacecraft by a Nasa modified Hasselblad camera on colour films. Under variable conditions of photography the individual frames differ in quality, areal coverage, scale and degree of distortion. This great variation in perspective has proved very useful in studying geological structures and following their extension for hundreds of kilometres over varying rock terrain.

In studying the structure of the Red Sea rift from satellite photographs, one recognizes a number of important problems which may lend themselves to direct observation and critical scrutiny based upon published field data. In the case of the absence of ground information the structures inferred require to be checked by studies.

The first problem is whether we find geological structures (which predate the rift) on one side of the rift which have continuations on the other side. The relative position of these structures may thus provide evidence for or against translational movements. The amount of separation as related to the age of the rocks affected may also provide a measure of the magnitude or rate of movement with time.

The second problem is the nature of the fracture patterns which affect the surrounding terrain and their relation to the rift. The distribution and orientation of fissure systems and their displacements and relative ages are matters of importance bearing on the nature of the rift. Except for horizontal offsets in very gently dipping strata which could result from essentially vertical movements, even the many 'small' lateral displacements of 5 or 10 km which are observed in the Precambrian shield must be considered as indications of significant lateral movements of no minor importance, particularly when we consider that the maximum vertical throws from the highest peaks to the deep trenches is only 4 km.

It is the objective of this paper to present several lines of evidence along the Red Sea and Gulf of Aden where many geological structures which predate the rift appear to have displaced continuations on the other side of the rift indicating large-scale translational movements which in places may have started in the Upper Cretaceous. Displacements observed across the strait of Bab El Mandeb suggest that a left-lateral movement of some 40 km may have opened the strait in the Plio-Pleistocene time interval. In describing these features the writer will present supporting field data derived from the published literature. The photographs used as illustrations are black and white reproductions selected for their broad areal coverage from among more than 50 high quality colour pictures used in this study. Most features described here are therefore better observed in the early generation colour reproductions of various scales and perspectives.

DESCRIPTION OF PLATE 1

FIGURE 1. Gemini XI photograph of the Red Sea and Gulf of Aden. This colour picture shows the critical junction where three rifts meet: the Red Sea, Gulf of Aden, and East African rift. Major physiographic provinces shown are: foreground, the Precambrian shield in Africa (left centre), Ethiopian Plateau (mostly under cloud cover), volcanic province of Afar, Somali Plateau; background, Arabian Precambrian shield, volcanics of Yemen horst, Hadramawt Plateau and the great sand sea: Ar Rub Al Khali. Note influence of N–S and WNW–ESE trending fault on Red Sea configuration (in area directly above spacecraft antenna). Consult annotations in figures 3, 8, and 9. (Photo S-66-54534, courtesy of Nasa.)

FIGURE 2. Apollo 7 photograph of Northern Red Sea, Gulfs of Suez and Aqaba. The Red Sea extends in a NW–SE direction along the Gulf of Suez and bifurcates into the Gulf of Aqaba, enclosing the triangular horst of Sinai. In Sinai, the southern highlands consist of Precambrian basement complex overlapped by Paleozoic, Mesozoic, and Tertiary strata, gently dipping towards the Mediterranean Sea (upper left). In the northern part of Sinai the structure is dominated by NE–SW deep-seated faults expressed on the surface by prominent folds belonging to the 'Syrian Arc' system.

Although the Gulf of Aqaba shows evidence of rifting and left lateral movement since Upper Cretaceous, it was not inundated by sea water until the Pliocene and Pleistocene; note straight transcurrent fault between northern tip of the Gulf and Dead Sea.

Marine Miocene rocks exposed at southeastern part of Gulf of Aqaba (triangular light coloured area, right centre) may have been part of the old Gulf of Suez prior to the Aqaba sinistral movement. The Gulf of Suez existed as a shallow trough since at least the Carboniferous. Coastal strips between the present coasts and Precambrian blocks of Sinai and Red Sea hills (lower left corner) are covered by Marine Miocene and younger sediments underlain by Eocene, Mesozoic, and Upper Paleozoic rocks in depth. Evidence of intense faulting and deepening is recorded since Upper Cretaceous. Through Miocene, Pliocene, and Pleistocene the structural and stratigraphic history of the Gulf is extremely complicated and confusing. Although strong evidence of many small scale strike-slip movements are known, suggestions of major translational movements are still highly conjectural. (Photo AS 7-5-1623, courtesy of Nasa.)

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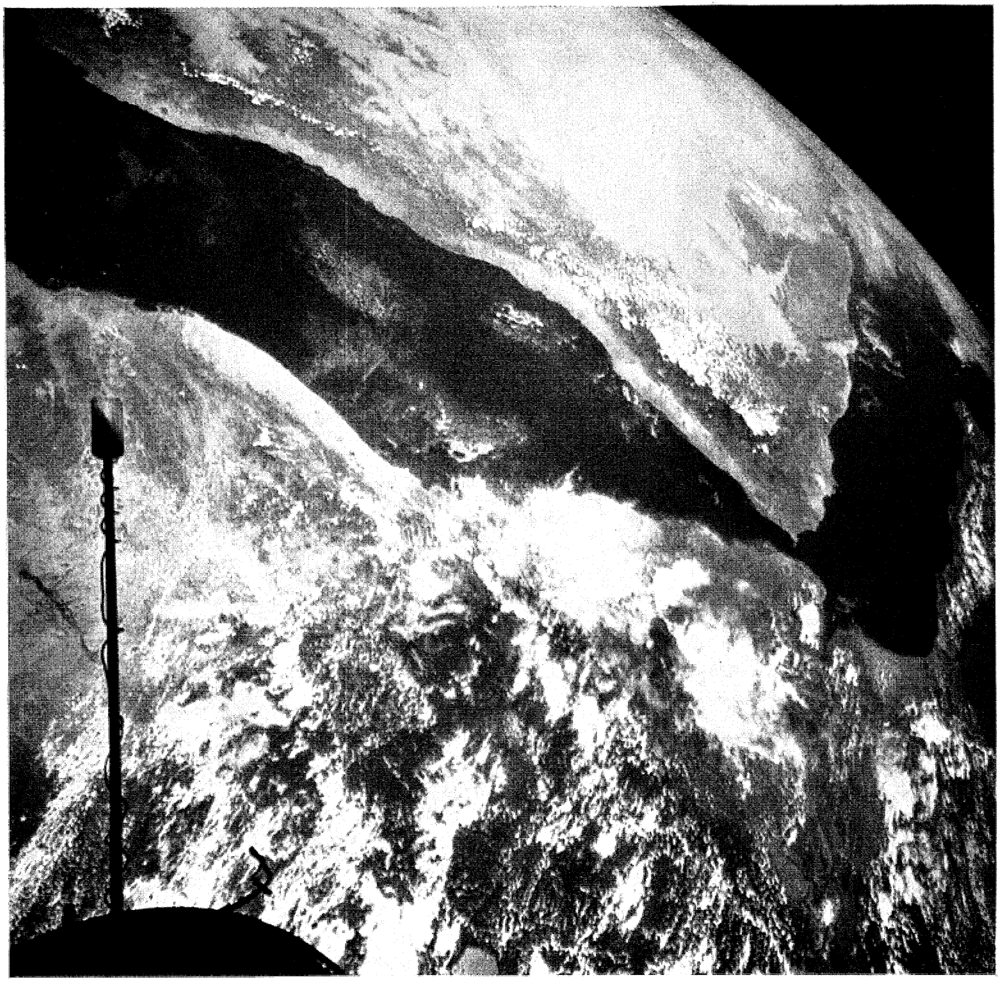

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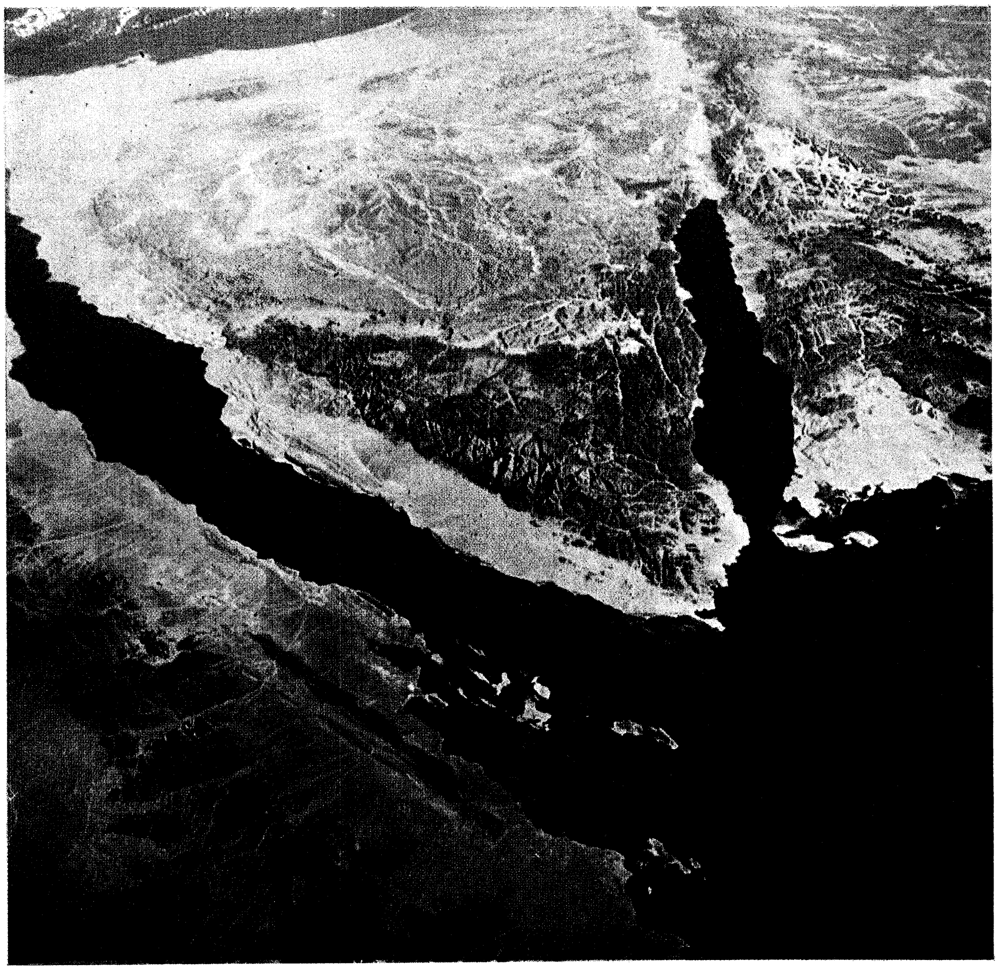

FIGURES 1 and 2. For legends see facing page.

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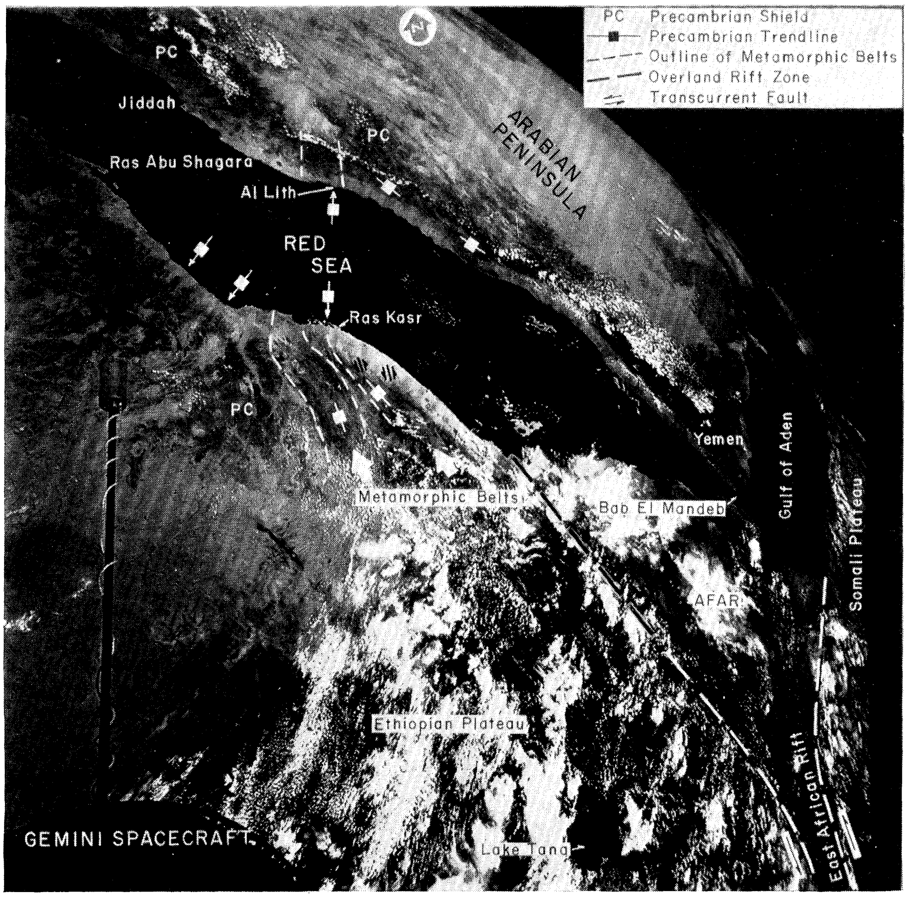

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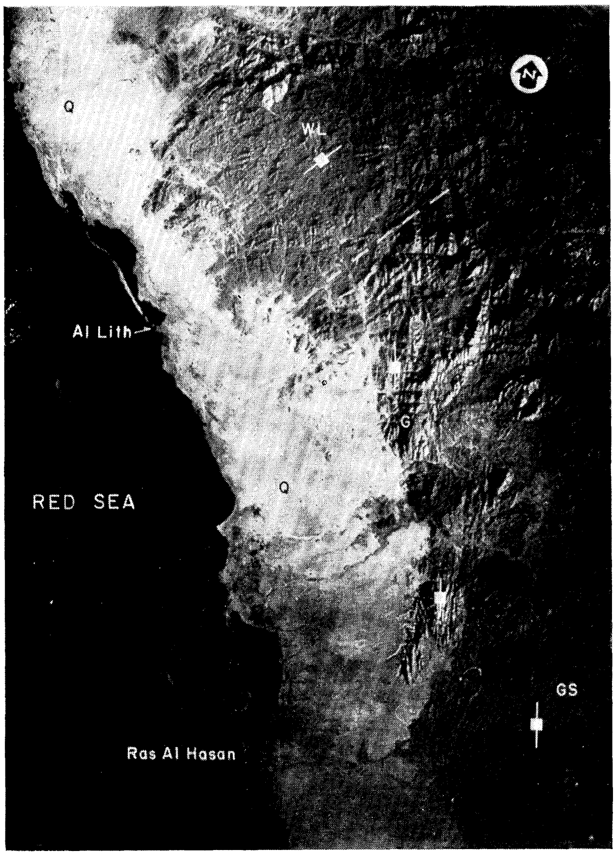

5

-■- Precambrian trendlines
--- outline of Wadi Lith series

-■- trendline
F ——→ fault trace
——— outline of (Nf) approx.

FIGURES 3, 4 and 5. For legends see facing page.

2. Displaced structures across the Red Sea

(*a*) *Trends in the Precambrian basement*

Crystalline rocks forming the basement complex of the Arabian–Nubian massif are widely exposed in the marginal highlands of the Red Sea. These rocks are mostly Precambrian, and in part Paleozoic, with some Cretaceous intrusives.

In satellite pictures the Precambrian terrain often shows distinctive metamorphic trendlines which probably represent old folding trends and zones of shear. The regional trendlines which are also reflected locally in the schistosity and cleavage are accentuated by differential weathering which produces gross lineaments in the morphology and the drainage pattern. The pattern of trendlines in the Arabian Precambrian is fairly well known (Brown & Jackson 1960, figure 1). On both sides of the Red Sea the pattern of trendlines shows significant variations in direction which, when compared across the rift, consistently indicate a northward displacement of Arabia.

(i) *North–south trends*

Meridional lineaments in which we include NNE–SSW and NNW–SSE trends are observed throughout the Precambrian basement. This N–S trend, however, dominates the structure in southwestern Arabia and in northweastern Ethiopia (Eritrea). In northern Eritrea, Mohr (1961, figure 4) distinguished three metamorphic zones in the Precambrian exposed in the area to the west and north of the Afar depression. The metamorphic zones occur in the form of long and relatively narrow 'orogenic belts' which in northern Eritrea run in a N–S to NNW–SSE direction and consist mostly of slates, phyllites, schists, gneisses, quartzite, and large marble lenses. Mohr's map does not show the extension of these belts north of approximate latitude

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Description of plate 2

Figure 3. Gemini XI photograph (looking northeast) showing the sinuous Red Sea rift cutting across the Precambrian Arabian–Nubian massif (PC), the Gulf of Aden rift separating southern Arabia from the Somali Plateau; the funnel shaped Afar volcanic province and nothern part of the East African rift separating Somali and Ethiopian Plateaus.

North of the Afar depression the metamorphic belts of the Ethiopian Precambrian basement have a northerly trend which abruptly changes towards the northeast near Ras Kasr. Across the Red Sea on the Arabian side the Precambrian trend lines are northerly in the southern part and change abruptly towards the northeast near Al Lith. North of Ras Kasr and Al Lith the Precambrian grain trends generally northeast. (Photo S-66-54533, courtesy of Nasa.)

Figure 4. Apollo 7 photograph of Al Lith area in Arabia. This nearly vertical picture shows the high Precambrian terrain (dark area on the right) and the downfaulted coastal strip covered with Quaternary (Q) surficial deposits of gravel, sand, silt, and raised coral reefs. The Precambrian basement consists of Wadi Lith metamorphic series (WL) (meta-diorite, meta-gabbro, schists, slates and quartzites) and granite and granite gneiss (G) and Greenstone (GS). Note abrupt change in Precambrian trendlines from N–S in the southern part to NE–SW in Wadi Lith series. Similar trends are observed across the Red Sea near Ras Kasr (figure 3). (Photo AS 7-5-1613, courtesy of Nasa.)

Figure 5. Apollo-7 photograph of the Precambrian of Red Sea Hills in northeast Sudan. This nearly vertical photo shows the NE–SW trendlines of the Precambrian metamorphics, particularly evident in the Nafirdeib formation (Nf) which include large marble lenses (mb). Batholithic granites (G) intrude the metamorphics; some ring dikes (R.D.) are also evident. The coastal strip is covered by Tertiary (T) and Quaternary (Q) sediments, with isolated outcrops of basalts (*b*). Mukawwar Island is known for the presence of marine Upper Cretaceous which indicates that the Red Sea was in existence at that time probably as a narrow rift flooded with sea water. (Photo AS 7-5-1666, courtesy of Nasa.)

16° N. However, we note in figure 3, plate 2 the extension of these belts from the area west of Lake Tana northward, becoming quite distinct in northern Eritrea. There, an eastern belt trending NNW converges [near the Ethiopian–Sudan border] with the western belt which trends N–S. Near Ras Kasr the two merging belts show an abrupt change in direction towards the northeast and appear to extend along this anomalous direction under the sedimentary cover of the coastal plain. In fact, it appears from figure 3 and the topography (Topographic map, Port Sudan sheet NE 37, Millionth World Map Series) that the NE trend extends very close to the Red Sea coast and may indeed continue for some distance offshore. This abrupt change of trend in the Ethiopian metamorphic belts to the northeast near Ras Kasr is very similar to trendlines near Al Lith in Arabia. There, we find also that the N–S grain which predominates much of the Precambrian basement south of Al Lith changes suddenly to a NE–SW trend, particularly evident in Wadi Lith metamorphic series (figure 4, plate 2). The series consist of metavolcanics, amphibolites, slates, quartzites, schists and marble, an assemblage which may be related to similar rocks in the Ethiopian belts. The trendlines of Al Lith area appear in the Apollo 7 picture (figure 4) which may be compared to the geological maps (U.S.G.S. I-201A and I-216A, Brown, Jackson, Bogue & Maclean 1962; Brown & Jackson 1958). The similarity of the Ras Kasr and Al Lith trendline anomalies is striking and becomes more significant when considered together with other lines of evidence. Between Ras Kasr and Al Lith the amount of separation is about 225 km, estimated from the proposed reconstruction (figure 7). Along the southern segment of the Red Sea, the rift is generally parallel to the Precambrian grain or cuts it at a small angle.

(ii) *Northeast–southwest trendlines*

Two large segments of the Precambrian basement bordering the Red Sea are characterized by predominantly NE–SW trendlines. The Arabian segment covers much of the southern Hijaz highlands from Al Lith to Ras Baridi (figures 3 and 6, plates 2 and 3). Except for the Apollo 7 picture of Al Lith area (figure 4) this part of the Precambrian in Arabia has so far been inadequately covered by satellite photography, but the NE–SW grain is quite evident in the geological maps (U.S.G.S. I-204A and I-210A, Brown *et al.* 1963, 1962). The corresponding segment in Africa, on the other hand, was covered by Gemini and Apollo 7 photography. Thus, between Ras Kasr and Ras Hadarba the Precambrian metamorphics of the Red Sea hills in eastern Sudan have a predominantly NE–SW regional grain, similar to the corresponding segment in Arabia. Examples of this trend are indicated by symbols in figures 3 and 5, plate 2.

In Ras Abu Shagara–Ras Hadarba area the NE–SW grain is recognizable in the nearly vertical Apollo 7 photograph (figure 5). In that area, the exposed rocks include old gneisses of limited extent, relatively younger and highly tectonized Nafirdeib formation (Nf) which consists mainly of metamorphic schists, tuffs, agglomerates, quartzite, and marble, intruded by several granitic masses (G) (Gabert 1959; Schürmann 1966, p. 268). Within the folded Nafirdeib formation the NE–SW grain is particularly indicated by the orientation of the huge marble lenses (mb). In Arabia Brown *et al.* (U.S.G.S. Map I-210A, 1962) mapped a similar NE–SW trend in the Precambrian rocks east of Ras Masturah, particularly in the chlorite schists (gs), gneissic diorite and granodiorite (dg). The rock assemblage in the area also includes andesites, slates with marble and quartzite (gd), similar to those in northeastern Sudan, all intruded by alkalic and per-alkalic granites. The relative position and orientation of trend-lines near Ras Abu Shagara (Sudan) and Ras Masturah (Arabia) are shown in figure 7. It is worthy to note that in that segment the Red Sea rift cuts boldly across the Precambrian grain at a high angle.

(iii) *Northwest–southeast trendlines*

North of latitude 22° N in Africa and about latitude 23° 40′ in Arabia, the Red Sea coastlines curve to the west forming the embayment of Foul Bay and a corresponding bulge in Arabia between Ras Baridi and Ras Abu Madd (figure 6, plate 3). In that area the bay to bulge fit is suggested by the remarkable similarity in the shape of the coastlines and the more significant 500 m depth contour and the gross outline of the Precambrian blocks overlooking the coastal strips and parallelism of their bounding fault scarps. In addition to these structural similarities we note that the Precambrian west of Al Wadah plain adjoining Foul Bay has a rather distinct NW–SE trending grain, more or less parallel to the general direction of the Red Sea (8, figure 6, see also Gemini IV photo S-65-34785 (not shown in this article)). This trend is very similar to the NW–SE trendlines observed in the granite gneiss of Jabal Hajinah (inland from Ras Baridi in Arabia) (9, figure 6; see also U.S.G.S. Map I-204A).

(*b*) *Displacement of shear zones*

In the northern segment of the Red Sea between Ras Benas–Ras Abu Madd and the southern tip of Sinai, the writer has drawn attention to the remarkable similarity of two shear zones which cut the Precambrian basement in Arabia to a pair of similar structures in Africa. A more detailed account of this evidence was given elsewhere (Abdel-Gawad 1969*a*, *b*). In brief, the writer believes that the Abu Masarib shear zone in Arabia (B–B) has a displaced continuation along the Gebel Duwi shear zone in Egypt (A–A, figure 6). Both structures are characterized essentially by wrench faults which deviate in their general WNW–ESE trend from the clysmic (NW) trend of the Red Sea and intersect the coastline at similar angles (about 30°). In both areas the zone of wrench faulting appears to have been accompanied by non-clysmic gravity faults, which allowed the invasion of both shear zones by the Miocene sea. This is evidenced by the presence of marine Miocene sediments deep inland along each structure in a narrow belt separated from the coastal Miocene sediments by two complementary wedge-shaped blocks of apparently similar Precambrian rocks, (+, figure 6). In Gebel Duwi area Youssef (Said 1962) describes large strike faults and intensive deformation of the Precambrian, Cretaceous and Eocene strata. Although Schürmann (1966) interprets the structure as an unusual graben, the present writer believes that the huge ridge-valley structure of that area and the intensive deformation of the basement indicate wrench faulting was active until the Eocene. In Arabia, the true nature of the wrench faults has been recognized (Brown *et al.* 1963).

The southern pair of similar shear zones: Wadi Alhamd in Arabia (D–D) and Wadi Hafafit, Africa (C–C, figure 6) are intersected by the Red Sea at a larger angle (about 45°). Both zones are characterized by intense shearing deformation and trends in the Precambrian and remarkable morphological lineaments and greatly reduced elevation with conforming drainage lines. Thus the two pairs of shear zones (Abu Masarib-Duwi and Alhamd-Hafafit) were probably two continuous structures which were intersected by the Red Sea rift and displaced to their present postion. The displacement amounts to about 150 km, depending upon how far the structures continue off shore. Figure 7 shows a diagrammatic summary of the Precambrian trendlines and their relationship across the Red Sea.

(*c*) *Ultramafic belts*

The distribution of ultramafic rocks in the Precambrian basement of Arabia and Egypt shows significant patterns which lend support to the displacement hypothesis. Serpentinite occurrences are generally found in the crystalline rocks of the Eastern Desert (Egypt) between latitude 23° N and 28° N, with little or no occurrences to the north (northern Eastern Desert) or south (northern Sudan). They also appear to be conspicuously absent in Sinai Peninsula. This applies to 'ultrabasic igneous rocks, viz. pyroxenite, hornblendite, troctolite, and periodotite, all four easily altering to serpentinite' (Schürmann 1966). In the Precambrian of the western Arabian Peninsula we find that the ultramafic occurrences are mostly confined to the area bound by latitudes 25 to 29° N.

Within these two general areas Schürmann (1966) draws attention to the fact that in Egypt and Arabia these occurrences appear to form two E–W trending belts separated by vast areas where ultramafic rocks are conspicuously absent. Although Schürmann does not subscribe to the displacement hypothesis and regards the Gulf of Suez and Red Sea as grabens, his observations regarding the occurrence of two serpentinite belts are none the less significant. If we consider those known occurrences of ultramafic rocks, we find that they form three (rather than two) 'belts' or provinces on each side of the Red Sea and if we assume that the three belts were continuous before the development and widening of the rift, it becomes evident that their present position appears to be displaced in a manner consistent with the offset of shear zones and Precambrian trend lines.

The northern 'belt' in the Arabian peninsula is confined to a rather limited area which lies east of the southern part of the Gulf of Aqaba. In that area large serpentinite occurrences appear in Jabal Maqla and Jabal Umm Hayfah (U.S.G.S. Map I-200A, Bremkamp & Brown

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DESCRIPTION OF PLATE 3

FIGURE 6. Gemini XI photograph of the northern Red Sea showing displaced shear zones and serpentine belts. The Red Sea rift cuts across the Precambrian basement (PC) and bifurcates into the Gulfs of Suez and Aqaba. The shield is overlain by Paleozoic, Mesozoic, and Tertiary sediments in the Nile valley area (lower left), northern Sinai (upper left) and Arabian Peninsula (upper part). Quaternary basic volcanics are extensive in Arabia (V).

There is evidence that Gebel Duwi shear zone (A–A) and Abu Masarib shear zone (B–B) were one continuous zone of wrench faulting before their displacement by the Red Sea rift. Note similarity of terrain in wedge-shaped blocks (+). Similarly, the shear zones of Wadi Hafafit (C–C) and Wadi Alhamd (D–D) formed a continuous structure. The displacement which here amounts to about 150 km is also indicated by the displaced position of three ultramafic provinces: northern (1) and (2), middle (3) and (4), and southern (5) and (6).

NE–SW faults along and south of Wadi Al Atrash show probable sinistral movement about 7 km (7), indicated by offset of circular drainage. Note also similarity of NW–SE Precambrian trend lines west of Foul Bay (8) and East of Ras Baridi bulge (9). (Photo S-66-54664, courtesy of Nasa.)

FIGURE 8. Gemini XI photograph showing the Horn of Africa and south-western corner of Arabia, separated by the Red Sea and Gulf of Aden.

In Arabia (upper part) the photo shows Precambrian terrain (PC), overlain by sedimentary strata of the Hadramawt Plateau, the great sand desert (Ar Rub Al Khali) and the volcanic terrain of Yemen (V).

In Africa (foreground) sediments of the Somali Plateau and volcanic fields of Afar (V) appear under the cloud cover. A system of faults trending WNW–ESE could be correlated across the Gulf of Aden (1–8). The NE–SW faults show poor correlation across the Gulf, but appear to be related to fault lineaments within the Gulf.

The great arches of Hadramawt (A, B) and the syncline appear to be related to similar arches in Somali (see figures 9 and 10). (Photo S-66-54536, courtesy of Nasa.)

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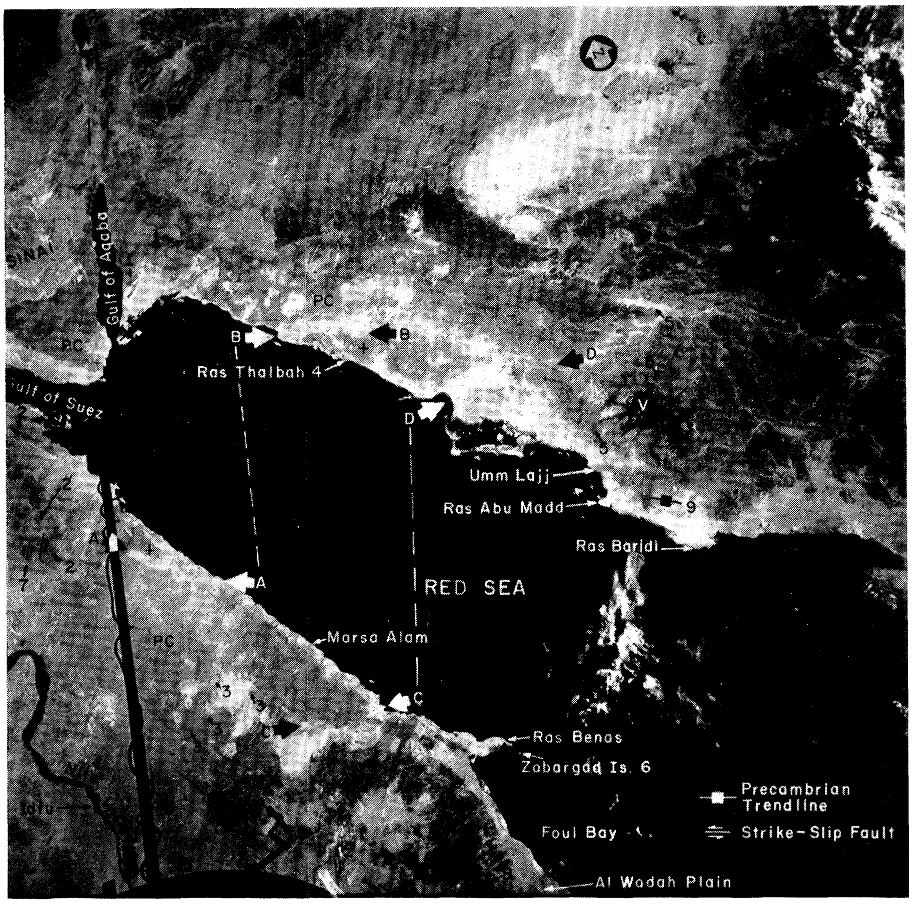

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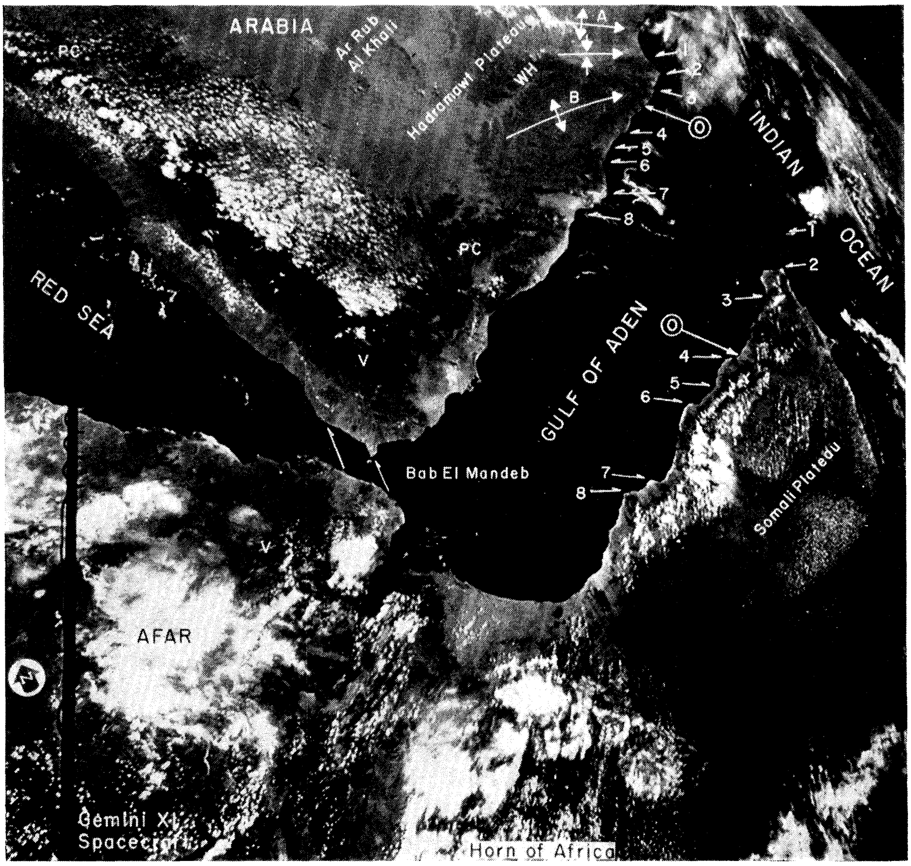

FIGURES 6 and 8. For legends see facing page.

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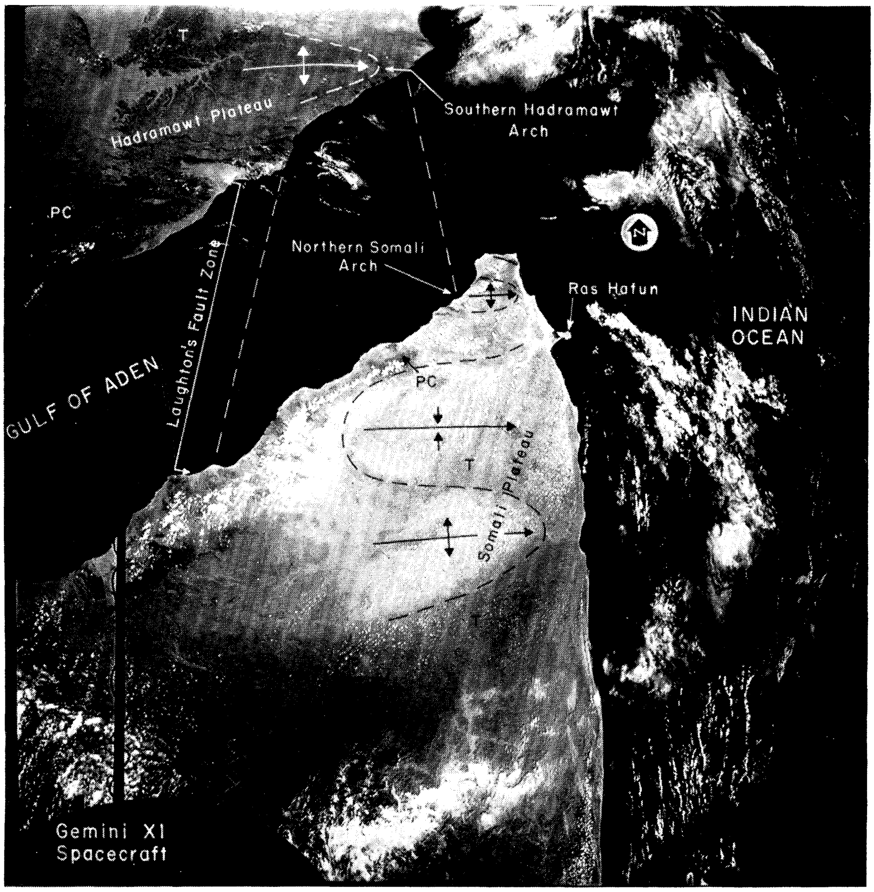

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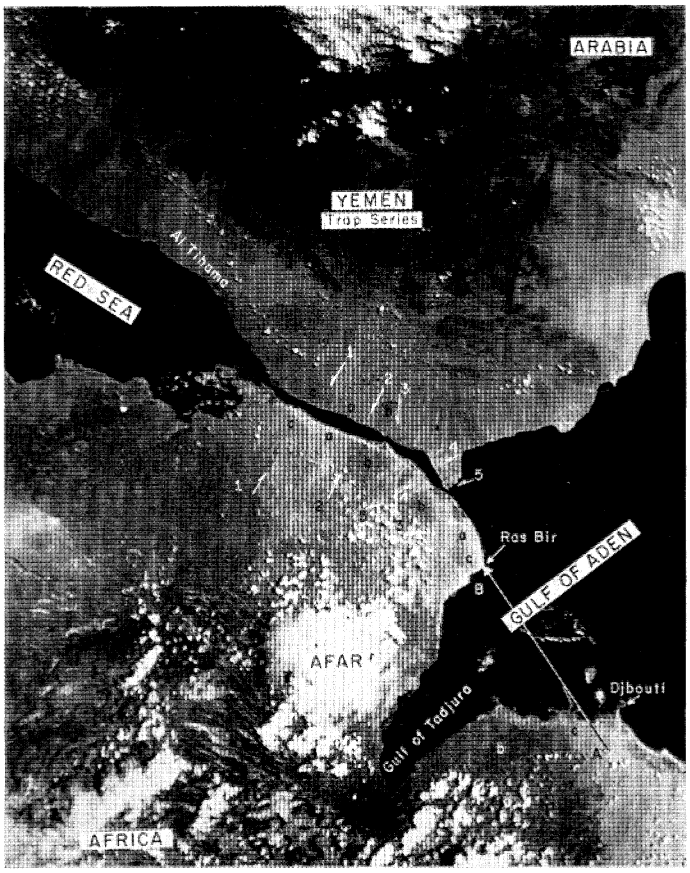

FIGURES 9 and 11. For legends see facing page.

1963). This belt has a southern limit at about the 28° 30′ N latitude. In Gemini and Apollo pictures the ultramafic rocks are among the darkest rocks observed (1, figure 6).

Considering that this serpentinite province has no known counterpart, across the narrow Gulf of Aqaba, in Sinai (Schürmann 1966), we are inclined to correlate it to the ultramafic occurrences on the southwestern side of the Gulf of Suez. The latter area represents the northern ultramafic province in the Precambrian basement of the Eastern Desert (Egypt). Schürmann (1966) reported two occurrences of serpentinite in Esh Mellaha range and others at Gebel Um Disi and Wadi Ghosar (2, figure 6). The Gulf of Suez and Gulf of Aqaba serpentinites may represent the displaced parts of the northern 'belt' of ultramafics in the Arabian–Nubian massif. It is indeed striking that both occurrences are separated from the nearest known serpentinites (middle belt) by some 220 km in Arabia and about 200 km in Egypt.

The middle ultramafic 'belt', the most widely known and better studied, forms an E–W belt in the central Eastern Desert, lying along the Idfu (Nile Valley)–Marsa Alam (Red Sea) road which runs approximately along the 25° N latitude. The 'belt' includes the Baramiya mining district (Attia 1948), Gebel Dunqash (Ramly & El Far 1955) and Gebel Mudargag (El Shazly & Hamada 1954) and several other occurrences (3, figure 6).

The Idfu–Marsa Alam belt appears to have a displaced extension on the Arabian side as indicated by the occurrence of ultramaficis inland from Ras Thalbah, (4, figure 6; longitude 36° 15′ E, latitude 26° 40′ N approx., U.S.G.S. Map I-204A, Brown *et al.* 1963). Between this narrow middle belt and the southern belt there is a large area some 200 km wide on both sides of the Red Sea where the Precambrian basement is essentially devoid of ultramafics.

The southern ultramafic occurrences in Arabia form an E–W trending belt (5, figure 4) in the neighbourhood of the Quaternary basaltic volcanic field of Harrat Lunayyir (V), inland from Umm Lajj harbour. The largest exposures are located in Jabal Marran where chromite and iron deposits are known (U.S.G.S. Map I-204A, Brown *et al.* 1963). This belt appears to correspond to an E–W serpentinite 'belt' in Foul Bay area where Hume (1937) reported serpentinites in Gebel Abu Dahr (SW of Ras Benas Peninsula) and in Zabargad Island, (6, figure 6). Gemini pictures indicate (Abdel-Gawad 1967) that the chromite bearing ultramafic province of Gebel Abu Dahr area appears to be about five times larger than indicated in Ball's geological map of the Southeastern Desert (Hume 1934, plate 44).

In summary, there appears to be three distinct ultramafic provinces or 'belts' in the northern part of the Arabian–Nubian massif separated by wide areas where the Precambrian basement

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Description of plate 4

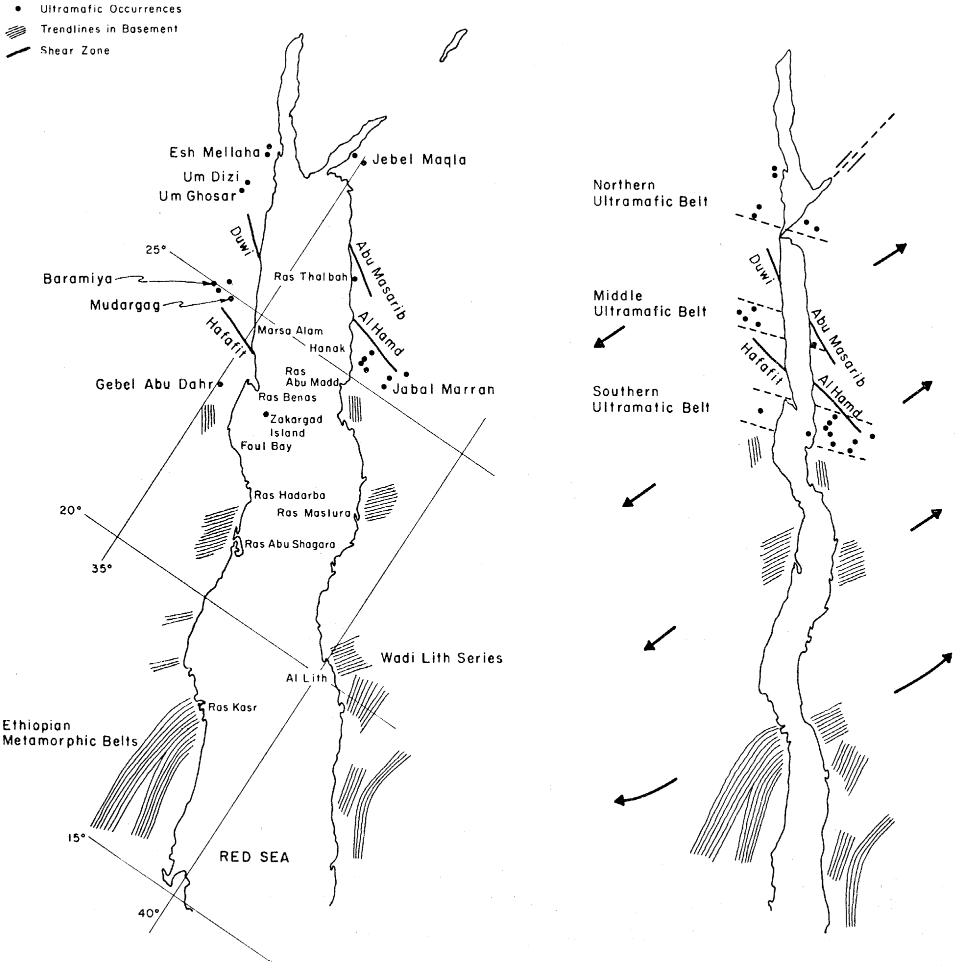
Figure 9. Gemini photograph of Horn of Africa and southern Arabian coast. The rocks exposed on both sides of the Gulf of Aden consist mostly of Precambrian basement (PC), overlain by Mesozoic and Tertiary (T) strata. The Somali Plateau appears to be folded in broad arches similar to those known in the Hadramawt Plateau. The arcuate pattern of plunging folds is indicated by dashed line. The southern Hadramawt arch may correspond to the northern Somali arch inferred from satellite pictures. (Photo S-66-54538, courtesy of Nasa.)

Figure 11. Reconstruction of blocks across Bab El Mandeb. In this enlargement of Bab El Mandeb area, the Arabian block (upper part) has been moved about 40 km towards the SSW essentially closing the strait of Bab El Mandeb. The relative movement of the African block (lower left) is indicated by arrow A–B. Note the striking similarity in the distribution of the Quaternary sediments (c), young basaltic fields (b), alluvium (a), fault and drainage lineaments (arrows 1–5). This movement may represent the final opening of Bal El Mandeb strait, which may have started sometime between Plicoene and Recent. Compare to presen position in figure 8.

is essentially devoid of serpentinites. The present position of these belts is such that the restoration of the Arabian block, some 150 km towards the south (SSE) closer to Africa, will bring corresponding belts in Africa and Arabia to a more compatible structural position (figure 7).

3. Displaced structures across the Gulf of Aden

Laughton (1965) described several geological features across the Gulf of Aden which indicate a mean displacement of southern Arabia some 400 km towards the northeast relative to Africa. Our study of satellite photographs is in general agreement with Laughton's observations and provide additional evidence not previously reported. Figure 8, plate 3, shows the general similarity of the Hadramawt Plateau in southern Arabia to the northern part of the Somali Plateau in Africa. Both areas are covered by Eocene strata overlying Cretaceous and Jurassic sediments. According to Laughton the major drainage of Wadi Hadramawt (WH)—which



(*a*) present position (*b*) reconstructed position

Figure 7. Displacement of shear zones, trendlines and ultramafic belts across Red Sea. The displacement of Gebel Duwi (Africa) from Abu Masarib (Arabia) and Wadi Hafafit (Africa) from Wadi Alhamd (Arabia) suggested by Abdel-Gawad (1969) was found to be consistent with the displacement of trendlines and three ultramafic belts in the Precambrian basement. The displacement of Duwi-Abu Masarib is about 150 km between Ras Kasr and Al Lith about 225 km, indicating relative northward movement and counterclockwise rotation of Arabia.

runs for a considerable distance along the synclinal axis between the northern and southern Hadramawt arches (A,B)—appears to be continued across the Gulf along the drainage system which runs from the northern Somali coast towards Ras Hafun on the Indian Ocean coast (Ⓞ, figure 8). The most striking of Laughton's observations, however, is the displacement of a major fault zone which cuts diagonally across Yemen with what appears to be a continuation of this fault zone cutting diagonally across the horn of Africa (8, figure 8). When we take Laughton's model of the Pre-Miocene reconstruction of Gulf of Aden (Laughton 1965, figure 10) as a basis for correlation of satellite photographs we find that many additional structures appear to be continued across the Gulf.

(*a*) *Regional folds*

In southern Arabia, the Mesozoic and Tertiary sediments are gently folded along E–W axes forming two arches separated by a syncline (Beydoun 1964). The characteristic nose pattern of outcropping strata produced by these arches is evident in southern Arabia (A, B, figure 8). Due to the lack of detailed information in Somalia the extension of the southern Hadramawt arch across the Gulf of Aden was uncertain (Laughton 1965). We have noted in many Gemini pictures of the Somali Plateau, however, that the regional outcrop configuration shows a broad acuate pattern characteristic of plunging folds with axes lying generally parallel (WNW–ESE) to the fold axes in southern Arabia. The folds in Somalia appear to form two arches plunging ESE towards the Indian Ocean separated by a broad syncline plunging WNW towards the Gulf of Aden. The approximate axes of these folds and the general outcrop trend are shown in figure 9, plate 4.

Figure 10 shows a diagrammatic representation of the arches on both sides of the closed Gulf, which suggests that the northern arch in Somalia may very well be an extension of the southern arch of Hadramawt.

(*b*) *WNW–ESE faults*

Gemini pictures† show that the horn of Africa is cut diagonally by WNW–ESE fault lineaments which suggest the extension of similar fault trends in southern Arabia. Considering Laughton's pre-Miocene model of reconstruction from east to west, the following fault zones appear to show reasonable correlation across the Gulf of Aden (figures 8 and 10).

1. In Arabia the fault occupied by Wadi Zahwan–Wadi Jiz which intersects the coast north of Ras Fartak at Al Ghaydah (see also the Unesco Geological Map of Africa) appears to have an extension with the 500 m depth contour off the tip of the horn, (1).

2. The fault line which intersects the southern Arabian coast at Ras Fartak appears in the Geological Map of Africa (Unesco) and may have an extension along the coastline of the Horn at Alula, (2).

3. The fault zone which controls much of the main trunk of Wadi Hadramawt and intersects the southern Arabian coast at Ras Sharwayn appears to correspond to a fault zone which cuts across the tip of the horn between Bargal (north of Ras Binnah) and Durbu (Gulf of Aden), (3).

4. The fault zone extending from Ascira (near Ras Hafun) to Ras Adado on the Gulf of Aden appears to have an extension along a fault intersecting the Arabian coast at Al Qarn, near Sharma Bay, (4).

5. The fault along the drainage of Wadi Madi and southern part of Wadi Adim which intersects the Arabian coast near Shihr may also correspond to a fault at Las Khoreh which

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† See particularly Gemini photos 65-HC-2444, S-66-54785, S-66-54538.

appears to cause notable WNW–ESE offsets in the Precambrian block which outcrops inland, (5).

6. The fault controlling Ras Sura (southern coast) corresponds to a fault intersecting the northern coast near Ras Al Mukalla, (6).

7. The fault which intersects the southern Arabian coast near Ras Al Kalb appears to be extended in Somalia near Ras Ankhor on the Gulf of Aden and extending inland along the eastern cliffs of the Dokakuli range, (7).

8. The fault zone (Laughton 1965) which marks the eastern edge of the main Precambrian block in Yemen, intersects the southern Arabian coast near Ras Safwan (longitude 47° 35′ E) and appears to continue near Ras Khanzira in an ESE trend across Somalia, (8).

(*c*) *Northeast–southwest faults*

Several faults trending NE–SW cut the land on both sides of the Gulf of Aden (figure 8). One notes, however, that there appears to be little or no correlation in the position of faults cutting the southern Arabian coast and those cutting the Somali coast. In fact, several of the major faults of this trend in Africa lack counterparts in southern Arabia. The absence of continuity in the NE–SW fault lines across the Gulf suggests that their development did not predate the rift. The NE–SW faults appear rather to be related to the NE–SW faults and bathymetric lineaments within the Gulf of Aden.

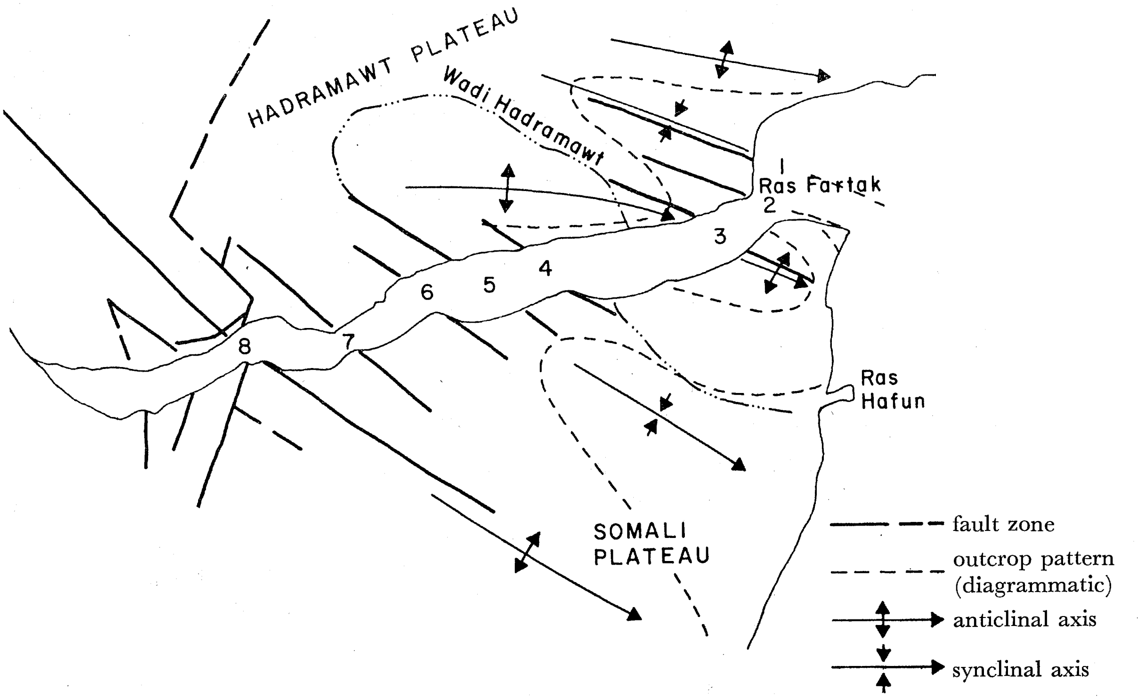

Figure 10. Correlation of pre-drift structures across Gulf of Aden. The pre-Miocene reconstruction suggested by Laughton (1965) is substantiated by correlation of WNW–ESE faults (1–8) and folds inferred from satellite pictures. The NE–SW faults show poor correlation across the Gulf and appear to be related to fault lineaments within the Gulf of Aden.

In summary, satellite pictures of the Gulf of Aden provide many additional lines of evidence consistent wih Laughton's model for the pre-Miocene fit of southern Arabia to Somalia at the shelf lines. The Hadramawt folds appear to have continuations in Africa; the southern Hadramawt arch may very likely be related to the northern Somali arch.

Furthermore, several WNW–ESE fault zones, which probably predate the opening of the Gulf, may be correlated across the closed Gulf. The NE–SW faults observed on land show poor correlation across the Gulf and are more related to fault lineaments within the Gulf of Aden.

4. Yemen and Afar

Figures 3 and 8 show the area where the three rift zones meet. The Gulf of Aden, the Red Sea, and the East African rifts separate this great Tertiary uplift into three highland sectors: Somali Plateau, Ethiopian Plateau, and Arabian Peninsula. The structure at this intersection is complicated by the presence of the triangular lowland province of Afar.

The Afar province consists largely of Upper Tertiary and Quaternary volcanic rocks (V) of basaltic and rhyolitic composition. Very little is known about the geology of the interior of Afar. One notes from satellite pictures, however, that the area is cut by fault lineaments of Red Sea trend particularly north of the Gulf of Tadjura; ENE–WSW and NE–SW faults such as those controlling the Gulf of Tadjura itself and NNE–SSW fault lineaments in the area of the Danakil Alps. According to Mohr (1968) the Ethiopian block shows a left-lateral movement relative to the Somali block along the East African rift and the Funnel of Afar (figure 3). Along the Wadi Barka fault Mohr also shows a left-lateral movement, which agrees with our observation that a series of sinistral faults trending N–S appear in the Precambrian basement south of Ras Kasr (figure 3). The high Danakil Alps block is the only area within Afar where Precambrian basement and a cover of Paleozoic and Mesozoic sediments are known to occur. The Danakil Alps are believed to be a remnant continental block which was detached from the splitting land masses and surrounded on all sides by volcanic rocks (Laughton 1965).

The Yemen block bears more fundamental similarity to the Ethiopian Plateau. Both are horst blocks of great elevation which consist of a foundation of Precambrian (PC) and Mesozoic sediments. This foundation is intensively broken by faults and covered by a thick section (1500 m) of stratiform lava flows and tuffs of predominantly basic composition. This Trapp Series represents the start of extensive volcanic activity which started in Upper Cretaceous and continued through the Tertiary and Quaternary (Geukens 1966; Lamare 1930).

(a) *The opening of the Bab El Mandeb Strait*

The opening of Bab El Mandeb and the development of the Gulf of Tadjura must have taken place in relatively recent times. Both features perhaps represent events of the last stages in development of the Red Sea and Gulf of Aden rifts.

Stratigraphic evidence shows that the opening of the Strait of Bab El Mandeb could not have been older than the Pliocene as indicated by the first evidence of mixing of Indian Ocean and Mediterranean fauna in the Gulf of Suez (Said 1962) some 2000 km to the north. Geukens (1966) states that deformation along faults during the Pliocene and Pleistocene played a most important role in the present morphology in the Bab El Mandeb area.

This rather narrow strait (27 km) could have been opened merely by simple downfaulting of a rather small block, a relatively insignificant event. Geological evidence, however, indicates that the Pliocene was marked by extensive movements and volcanic activity in the entire region, which coincide with the later stage orogeny in the Taurus Zagros–Oman folded mountains.

(*b*) *Evidence of lateral movement*

We wish to present here preliminary evidence that the opening of Bab El Mandeb was most probably due to a relatively recent phase of lateral movement of Arabia some 40 km to the north, relative to Africa. It is reasonable to assume that if a young translational movement has taken place, we may be able to correlate displaced morphological and geological features in the immediate areas which border the strait.

The present position of the blocks is shown in figure 8. The suggested movement is indicated by arrows. Figure 11, plate 4, is an enlargement of Bab El Mandeb area in which the Arabian block has been moved about 40 km to the SSW, in a position believed to represent the approximate relation of the two blocks before the final opening of the strait. At that position where the strait is virtually closed, we note a very striking similarity in the areal distribution of Quaternary sediments (*c*), the volcanic fields (*b*), the intervening alluvial deposits (*a*) and continuity of faults and fault controlled drainage lineaments (arrows).

The available information concerning the detailed geology of these areas is very scanty, particularly in Yemen. De Chardin's (1930) pioneering work in Eritrea has been useful in identifying many of the observed features. On the northern side of the Gulf of Tadjura, De Chardin (1930, figure 3) reports that the volcanics consist of a rhyolite layer between older and younger basalts. According to his map, most of the basaltic terrain (*b*) in figure 11 belongs to the younger basalts. Lacking a more definitive age these 'recent' basalts are most probably of Plio-Pleistocene age. This age appears to be reasonable because De Chardin emphasizes that this young basalt is definitely older than the old coralline and gravely raised terraces which occur up to 60 m above the sea level.

In any case, this similarity of rock terrain, structure, and gross terrain texture is substantiated by correlation of optical density profiles measured along both sides of the strait in photographic transparencies.

Further, figure 12 shows a corresponding similarity in the topography and drainage lines of the same blocks, traced from the topographic map (Aden Sheet ND-38) Millionth World Map Series, and reconstructed in a manner similar to that of figure 11. Some of the structural continuities inferred from the space photographs are also shown.

Although this evidence requires field confirmation, particularly concerning age and lithology, this interpretation is supported by geological evidence elsewhere. The 40 km displacement along Bab El Mandeb corresponds in magnitude and direction to Quennell's (1956) last phase of movement along the Aqaba–Dead Sea rift. It is also comparable to the average width of the deep central Red Sea trench and the width of the rough zone in the western part of the Gulf of Aden. During the Miocene the Red Sea must have had a very restricted access to the oceans at both ends as indicated by the widespread occurrence of thick evaporites. As mentioned before the opening of Bab El Mandeb must have started in the Pliocene and continued through the Pleistocene as indicated by the intermixing of Mediterranean and Indian Ocean fauna in the Gulf of Suez area. The amount of displacement during this last stage (40 km), represents a rate of movement in the order of from 1 to 2 cm a^{-1}, an estimate consistent with an average rate of 2 cm a^{-1} (Laughton 1965) in the Gulf of Aden.

Gemini and Apollo photographs used in this study are reproductions made available through the courtesy of the U.S.A. National Aeronautics and Space Administration. The author wishes

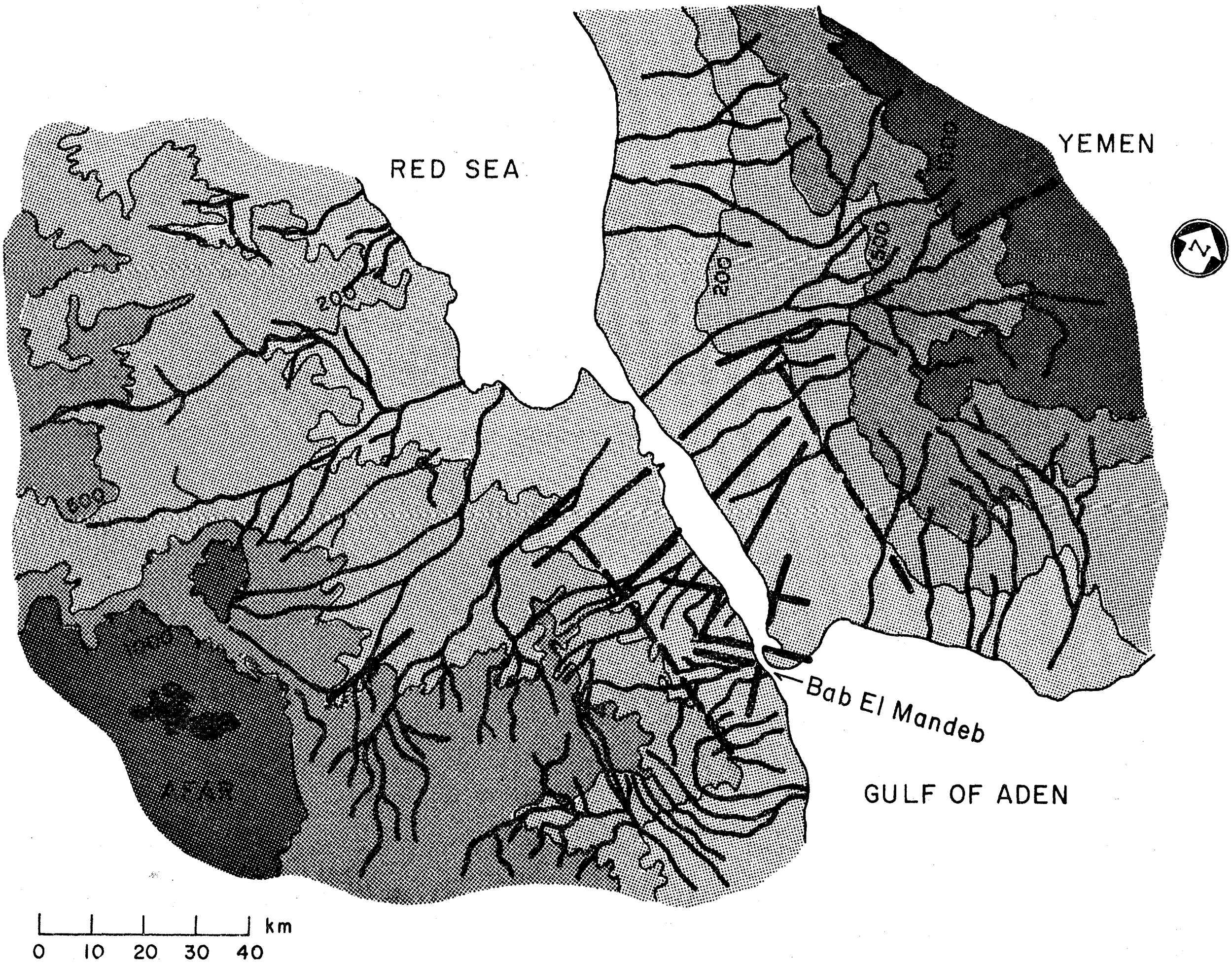

FIGURE 12. Reconstruction of topography and drainage across Bab El Mandeb Strait. Topographic contours and drainage lines were traced from Aden sheet (Millionth Map Series, sheet ND-38). The Arabian block was moved to the SSW about 40 km similar to figure 11. Existing drainage patterns were probably established by structure and morphology before the movement which opened the Strait of Bab El Mandeb. ꟿ, drainage lines; ——, fault lineaments. The topographic contours are in metres.

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Discussion

I. G. Gass (*Leeds University*). Dr Abdel-Gawad's paper records a fascinating exercise in satellite photography interpretation—its prime importance however might well be to emphasize the need for strict ground control over any such interpretation. Having worked, as a field geologist, on both sides of the Red Sea and in particular having a relatively detailed knowledge of the NE Sudan (figure 5) and SW Arabia (figure 11) I have the following comments to make.

In describing the NE Sudan Abdel-Gawad is absolutely correct in stating that the region consists of interbedded ancient sediments and volcanic rocks invaded by granites of various ages. With particular reference to his figure 5, the whole of the area was mapped by the Sudan Geological Survey during the period 1952–5. The faults indicated by Abdel-Gawad do not exist but are junction lines between blown sands and trend ridges in the crystalline basement. Prominent features in the structural pattern of this area are a series of E–W faults—although clearly visible on the satellite photograph, Abdel-Gawad does not mention them. Many comments of this type can be made but rather than list them I would draw attention to the fact that the metamorphic grade in the ancient sediments and volcanics of NE Sudan is generally low, chlorite being the common metamorphic mineral present. In Saudi Arabia, at similar latitudes, higher grade granulites and amphibolites are the dominant rock types.

Abdel-Gawad suggests the presence of a N–S wrench fault through Ras Bab El Mandeb. As Perim Island is part of the western flank of an Upper Miocene volcano whose central vent forms Jebel At Turbah, the SW promontory of Arabia, the proposed fault would have to pass through the western, wider section of the straits of Ras Bab El Mandib.

J. V. Hepworth (*Institute of Geological Sciences*), said that he was impressed with both the dramatic view of the terrain provided by satellite photographs, by Abdel-Gawad's background knowledge of the area, and by the care which Abdel-Gawad had evidently taken to check his conclusions by ground information as far as this was possible.

Nevertheless, he felt obliged to express his scepticism as to the value of the evidence provided by satellite photographs.

It was very difficult to make a balanced judgement about satellite photographs because of the tremendous impact they made on the imagination, by their awe-inspiring view of Earth, the exciting circumstances in which they were taken and their vivid aesthetic appeal. There was also pressure to present them as a revolutionary new method which would justify the enormous expenditure which it took to produce them.

His own view was that satellite photographs should be considered as one source of data in the same way as photographs taken from aircraft, as geophysical data or geological mapping, and that all of these should contribute towards synoptic maps showing the geomorphology, paleogeography and structural history of the area. There was a danger in thinking that any one of these by itself might provide a conclusive answer. He had to admit that he himself found a strong temptation on looking at these magnificent photographs to accept the present-day morphology as overwhelming evidence that drifting apart had taken place.

It was essential to keep continually in mind that satellite photographs for the most part did only show present-day topography, and that rather inadequately; they were practically non-stereoscopic, showed only coarse detail and suffered from exaggerated perspective effects. They were really rather poor material for the kind of detailed interpretation which could be undertaken by photogeologists and photogeomorphologists in regional studies (i.e. using airborne photography of suitable scale.)

Abdel-Gawad had placed reliance upon four categories of observation to support his proposition that the Red Sea satellite photo-study is consistent with a dilatation of 150 km. First the matching of three shearbelts in the basement, secondly the existence of areas of serpentinites on either side of the Red Sea, thirdly the apparent continuation of faults across the Gulf of Aden, and fourthly the correspondence of double arches in the Hadramaut and Somalia.

The first question in assessing the value of the satellite photographs relative to these points was 'Did they allow recognition of these structures? If they were known before, did the satellite photographs make them clearer?' If the answer to either question was 'Yes' then the satellite photograph had given us something new and of value.

One might then go on to a different issue and inquire as to the significance of this evidence. Thus one might think that bundles of three shear belts were not such unique features in the Basement as to allow any two to be identified and correlated over 150 km, with any certainty. One would like to know a great deal more about both of them before accepting the correlation with any enthusiasm. The same argument applied to the faults on either side of the Gulf of

Aden. On the scale of the satellite photograph they seemed to match quite well, but fractures alone were not particularly significant and needed to be considered together with such features as the age of faulting, which beds they displaced and so on.

The same queries should be placed against each of the four categories of evidence. He concluded that while in each case there seemed to be a reasonable match when looked at on a very small scale, the kind of detail required to amount to something like certainty was lacking. Finally it might be worth pointing out certain features, highly relevant to the problem, which the satellite photographs did not and could not distinguish: it was impossible to distinguish erosion scarps from fault scarps; to recognize associated bevels and subsidiary erosion surfaces; to recognize the regional upwarps and downwarps; and it was impossible to deduce any time relationships or the sequence of development of structures and associated landforms from them.

J. R. Vail (*Department of Geology, University of Khartoum*). There is no doubt that geological features can be clearly seen from suitable satellite photographs, as some of the examples presented in the paper by Abdel-Gawad admirably demonstrate. However, the application of satellite photography, like all geological methods, requires some caution and it is on the interpretive aspects that I wish to comment. In particular, basement structural trends can be observed which provide useful information on the configuration of the Precambrian rocks which in turn provide evidence on the subsequent tectonic history of the crust. However, unless adequate ground control is available it is likely that an incomplete picture might be obtained and consequent conclusions may be erroneous. Sudan, Egypt, Ethiopia and Arabia are not well-mapped areas and it might appear from figure 7 in the paper that additional information is not available. This is not the case, geological maps do exist for these areas, published by various Geological Surveys, and also in the literature listed in Abdel-Gawad's references. From these sources I have compiled a tectonic diagram (see figure) based on the 1:5 000 000 scale A.S.G.A./Unesco International Tectonic Map of Africa (1968). A comparison of Abdel-Gawad's figure 7 (p. 30) and my figure (13) shows interesting discrepencies in basement geology.

In brief these are: (1) Basement trends tend to be irregular in many places and supposed changes of direction, such as indicated by Abdel-Gawad in northern Ethiopia and southern Arabia, must be treated with caution. (2) Trends within Sudan are generally northeasterly, matching those in central and southern Arabia but the strike changes in southeastern Egypt and northern Arabia to northwesterly and to due west near the Gulf of Suez. There is thus an important swing in direction which is evident on both sides of the Red Sea. (3) The 'ultramafic belts' of the northern Red Sea margins are, in my opinion, problematical, especially when compared with many similar serpentine masses in eastern Sudan. If ultramafic belts are to be invoked it would be more appropriate to consider a zone striking from southern and western Ethiopia, along the Red Sea Hills of Sudan, into the Eastern Desert of Egypt, and extending over into Saudi Arabia. Throughout this zone a similar geological environment prevails. (4) Lineaments interpreted as faults and shear zones must be treated with caution. For example, there is no published evidence yet for faulting of Tertiary rocks against the basement in northern Sudan, and the conclusion that the Duwi and Abu Masarib and the Hafafit and Al Hamd Shears are continuous, while intriguing, is geologically not yet supported. (5) Numerous smaller lineaments in NE Sudan and western Arabia are at right angles to the Red Sea coast and appear to have been ignored. Many of these are probably faults, while many others are most certainly dykes. Reference to Schürmann (1966) Brown, Jackson, Bogue & Maclean

Figure 13. Compilation of basement trend lines and ultramafic occurrences adjacent to the Red Sea.

(1962) and the published maps of the Sudan, for example, will show numerous dyke swarms in various orientations. Most of these dykes are Precambrian in age and form a composite pattern in Africa and Arabia which was probably continuous before the development of the Red Sea (Vail 1970). More detailed geological and geophysical work on these rocks should be rewarding. (6) Finally, examination of the International Tectonic Map of Africa will show a number of ring structures alined N–S in northeastern Sudan. Several more are know in southern Egypt and similar phenomena undoubtedly exist in Saudi Arabia, although as yet they have not been described in the literature. It seems unlikely that the ring complexes follow narrow belts, the extensions of which might be sought across reconstructed continents, but they are yet another feature indicating the close similarity in geology of the two sides of the Red Sea. Whether such similarity indicates continental matching, and what is the nature of the displacement are matters which can only be properly answered when as complete a picture of the geology has been assembled as possible; to this end satellite photography will be a useful tool.

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J. F. Mason (*Continental Oil Company*) called attention to a fault contact of metamorphics with upper Cretaceous and Eocene sediments west of Ras Ghareb, which in the field he had considered to indicate sinistral strike slip movement.

J. G. W. Greenwood (*Institute of Geological Sciences*) has recently made an assessment of the role of satellite photographs in geology by comparing Gemini photographs over parts of the former Aden Protectorate with vertical air photographs of areas already mapped on the ground with which he was familiar. Colour transparencies (70 mm) were obtained on loan through the United States Geological Survey and the following selected for study, Gemini IV 16–40, Gemini VII 25–19, 25–20, and 25–21 (Gemini IV 16–40 overlaps Gemini VII 25–20). Mr Greenwood's conclusions have been published in a letter to *Nature* (**224**, 506, 1969). His general summary was 'Except where plotting of megastructure or gross lithological units would give significant data, satellite photographs should be regarded as supplementary to air photographs. When so regarded their possible applications are numerous.'

See also the contribution by C. E. Thiebaud & D. A. Robson in the General Discussion section at the end of this volume, drawing attention to fundamental geological facts.

M. Abdel-Gawad (written reply). Figure 5 is primarily used in the discussion of Precambrian trendlines and not the fault pattern. The E–W (Tethyian) faults constitute an important element in the fault pattern of the Red Sea at large and were discussed elsewhere (Abdel-Gawad 1969*a*, *b*; see also my paper on the Gulf of Suez, p. 44).

The fact that the two inferred faults (figure 5) lie at the junction lines between the Precambrian terrain and the sand-covered coastal plain block is not, in my opinion, a valid argument against their probable existence which is suggested by physiographic evidence such as sharpness of the Precambrian edge and linearity of the junction for some 10 km which coincides with a marked difference in relief. They may be faultline scarps, with the fault traces probably concealed and therefore not observed in the field; one of the inferred faults cuts across the trendlines.

As to the chlorite–amphibolite relationship, my main argument rests on the premise that one should *not* compare areas of similar latitudes because of the suggested displacement; the area that should be compared to figure 5 is near 39° E, 23° N where the NE–SW trending chlorite schists (gs on the U.S.G.S. map) are as abundant as the amphibolites.

A more detailed description of the two pairs of shear zones is now published and should be consulted by the reader in order to make a more balanced judgement (1969*b*). These structures and the serpentinite 'belts' are in my opinion significant and should receive very careful and objective investigation in the field. Although figure 7 is diagrammatic, it shows more consistencies than discrepancies with the more complete trendline map of Vail (figure 13).

I certainly agree with my colleagues that orbital photography is one additional method with its limitations and advantages and should certainly be subject to objective checking in the field. It will be wise, however, not to dismiss offhand the potentials of high altitude and orbital photography. One must remember that in the advent of aerial photography there has been undue reluctance to accept their value in many fields, geology included.

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FIGURES 1 and 2. For legends see facing page.

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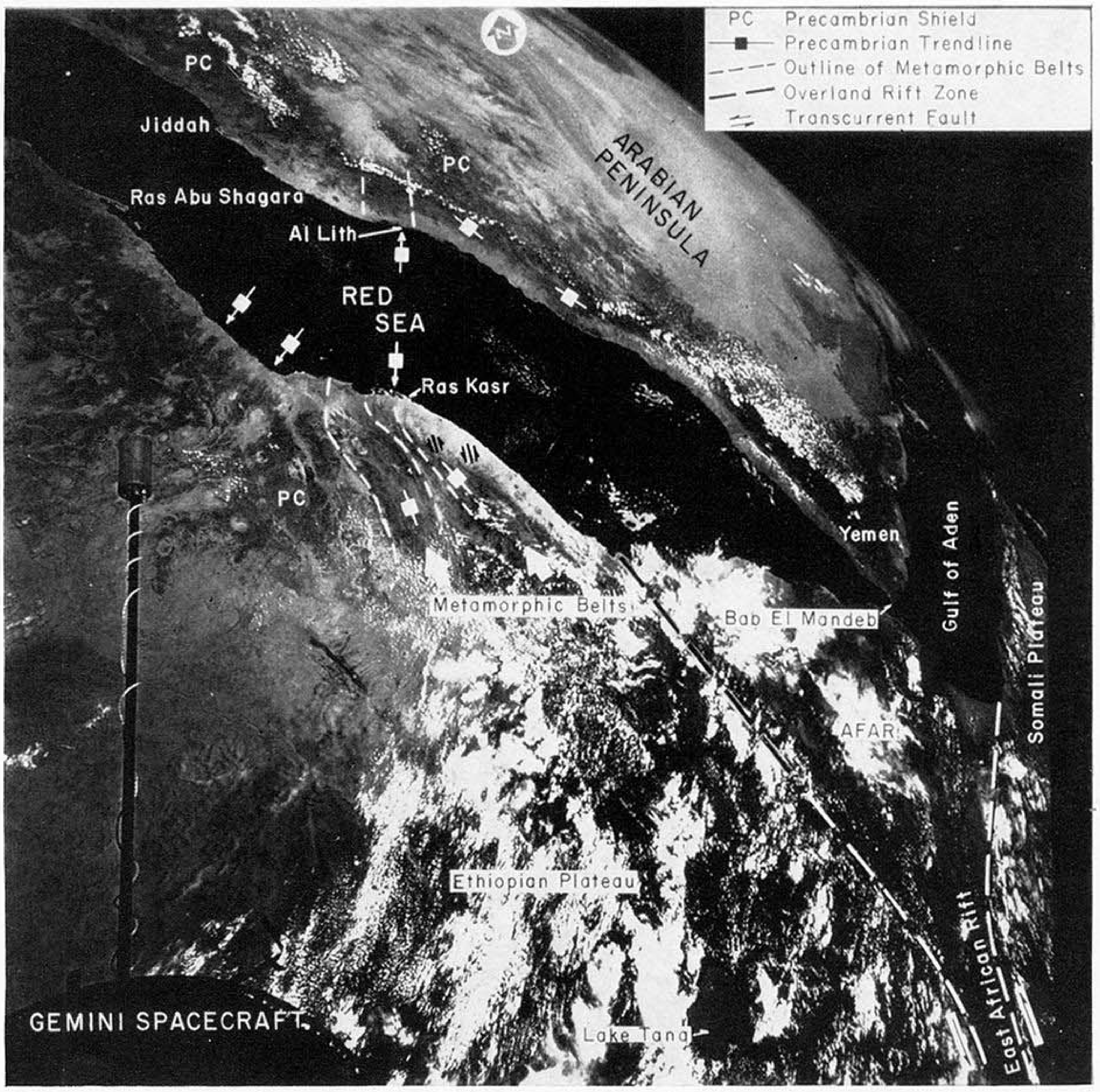
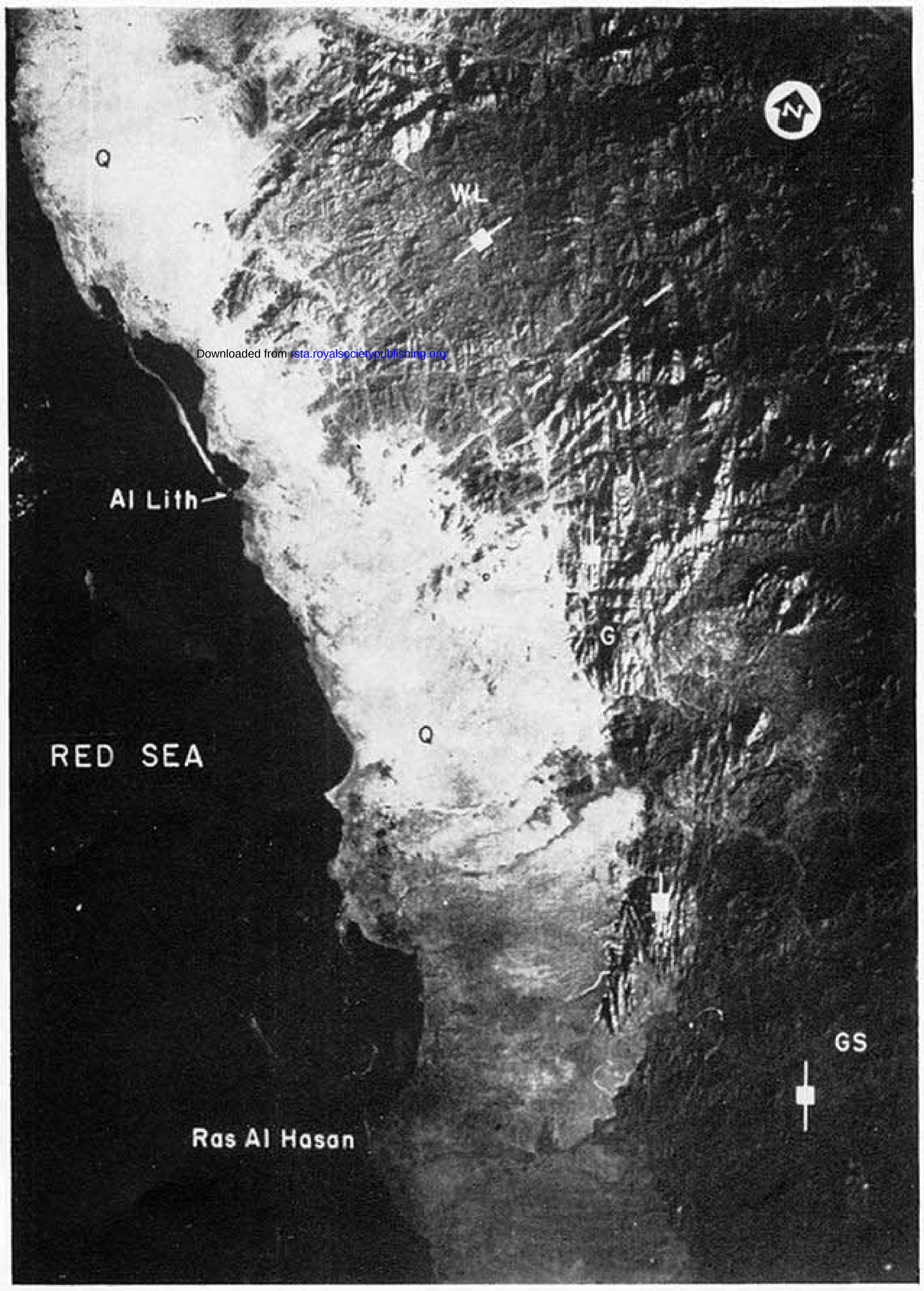
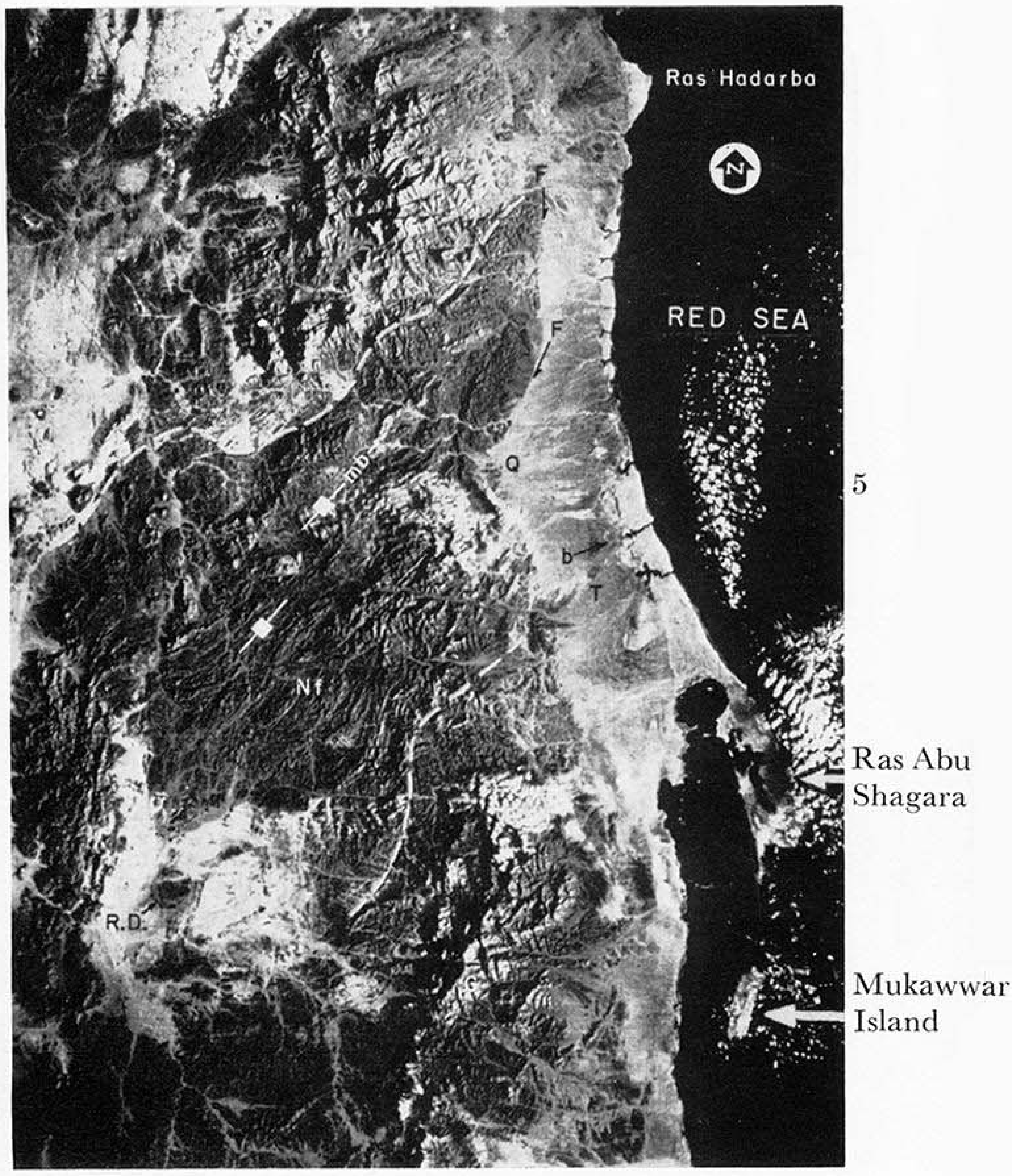




■ Precambrian trendlines
--- outline of Wadi Lith series

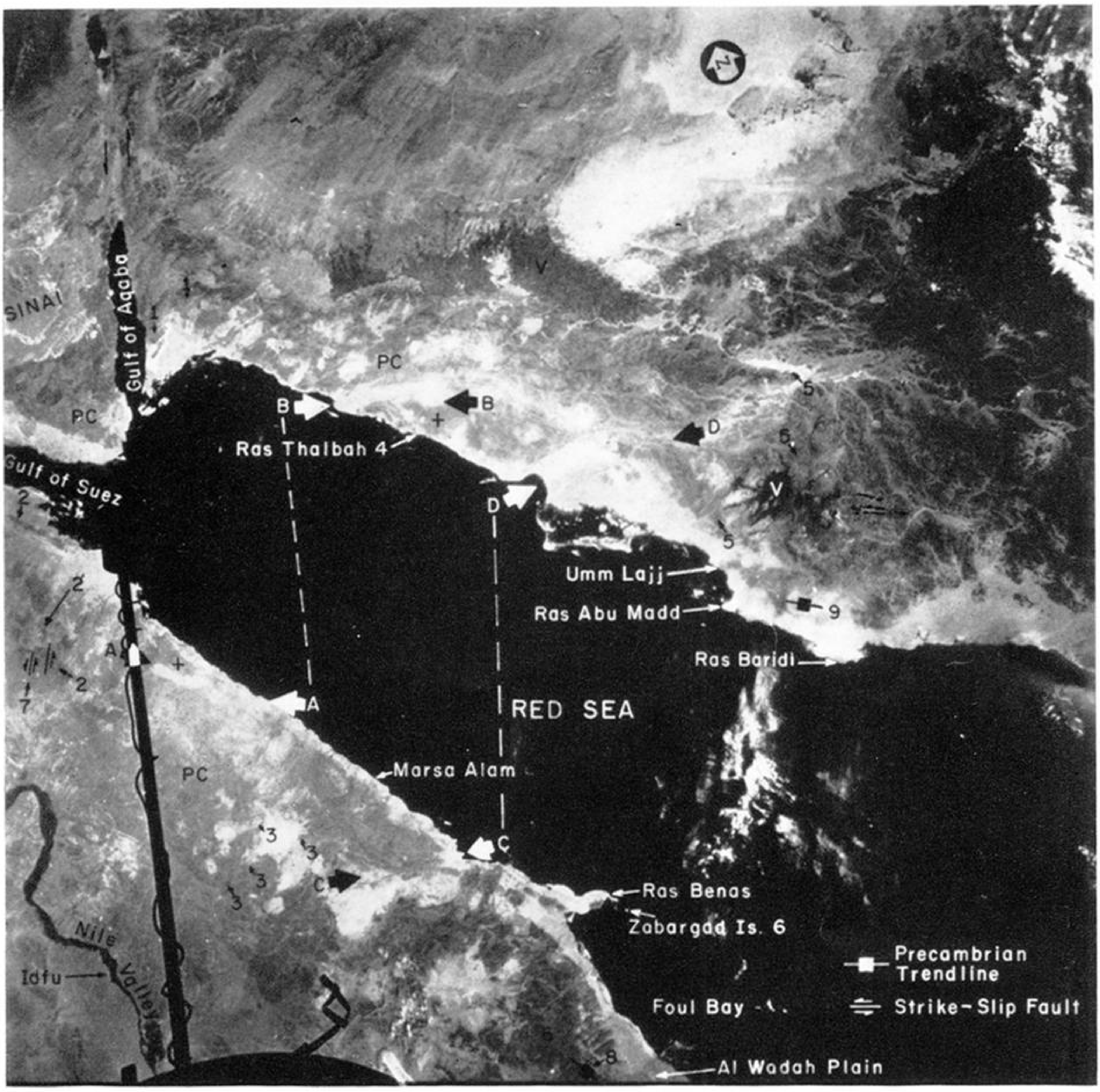
5

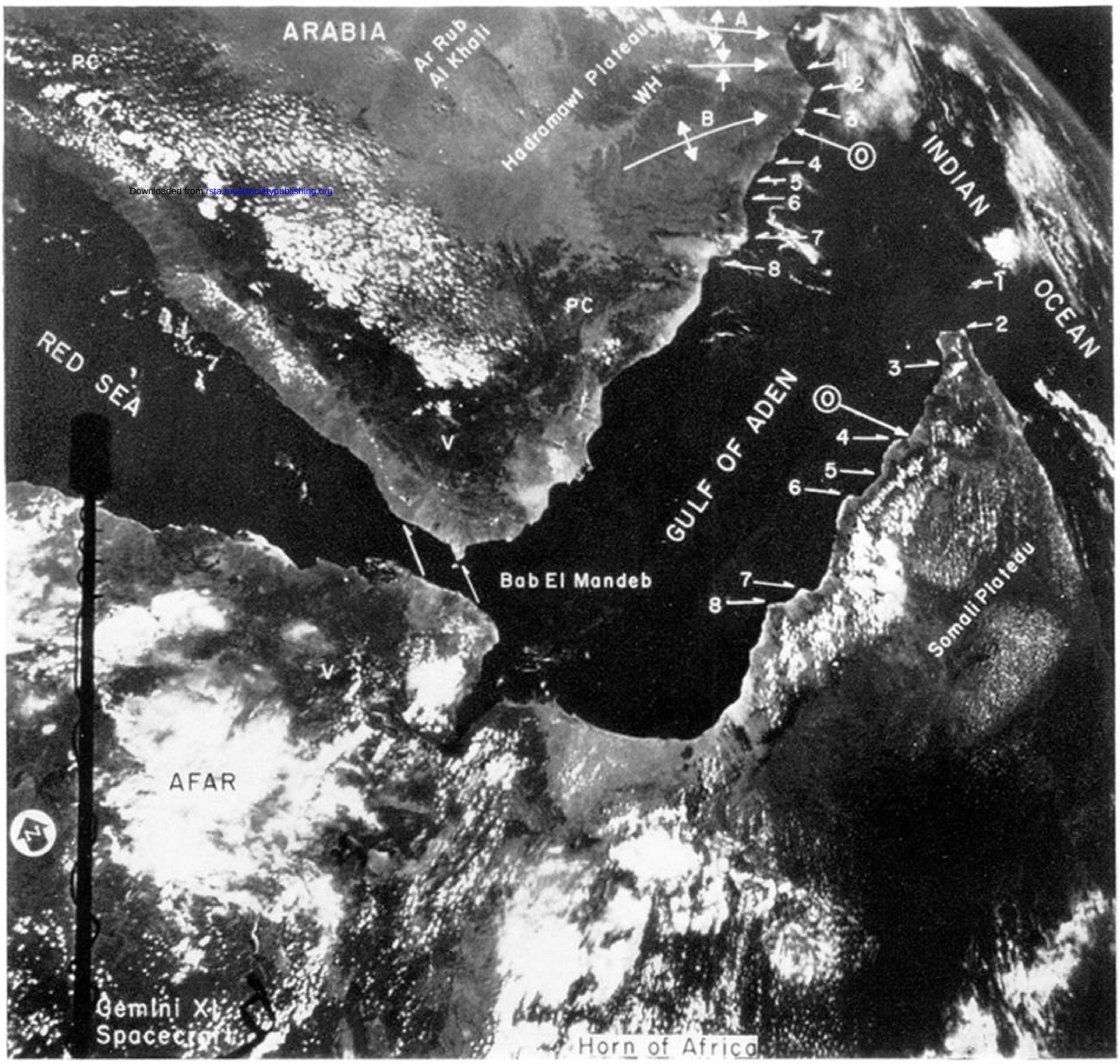


■ trendline
F ⟶ fault trace
——— outline of (Nf) approx.

FIGURES 3, 4 and 5. For legends see facing page.

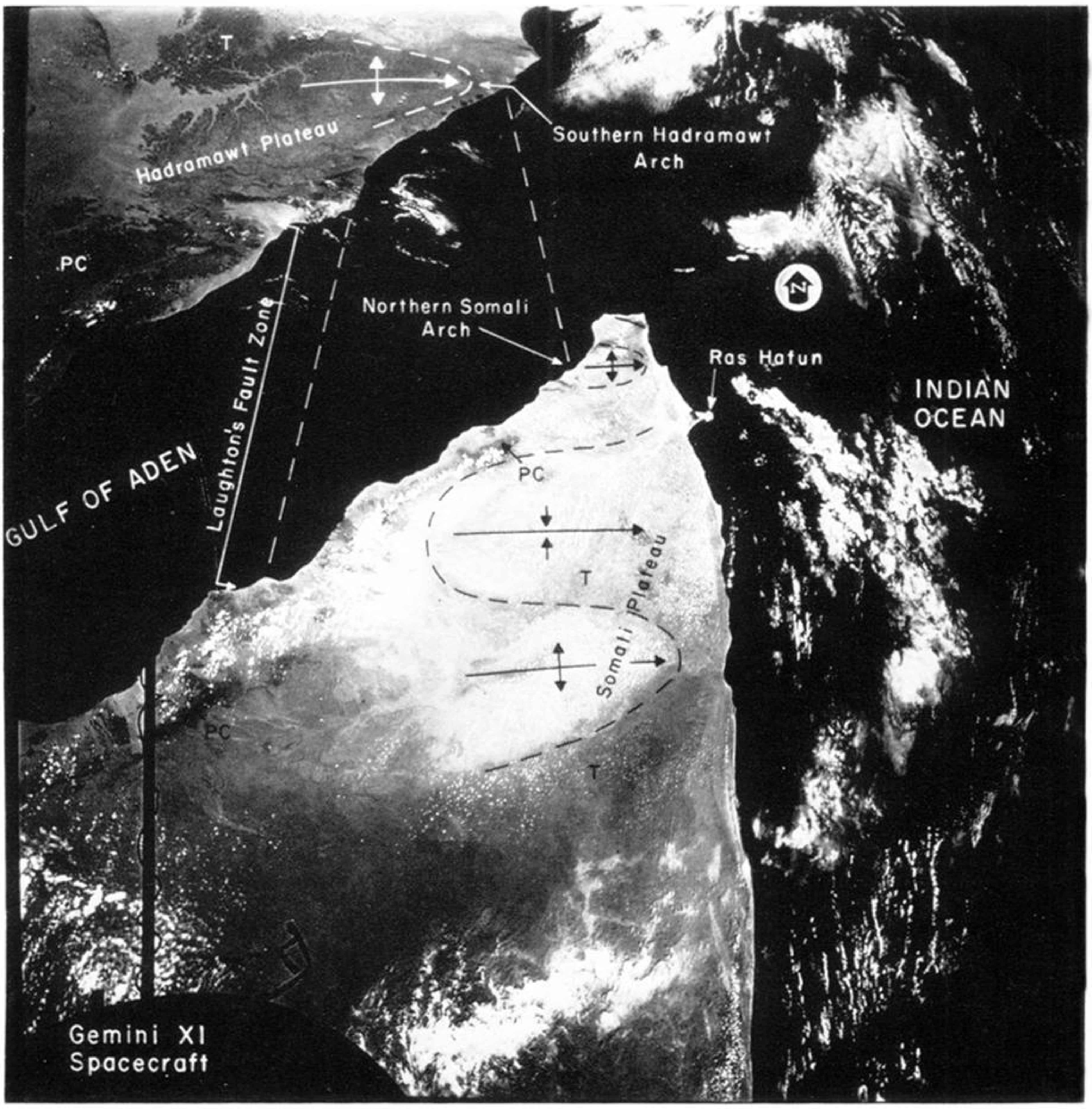
6



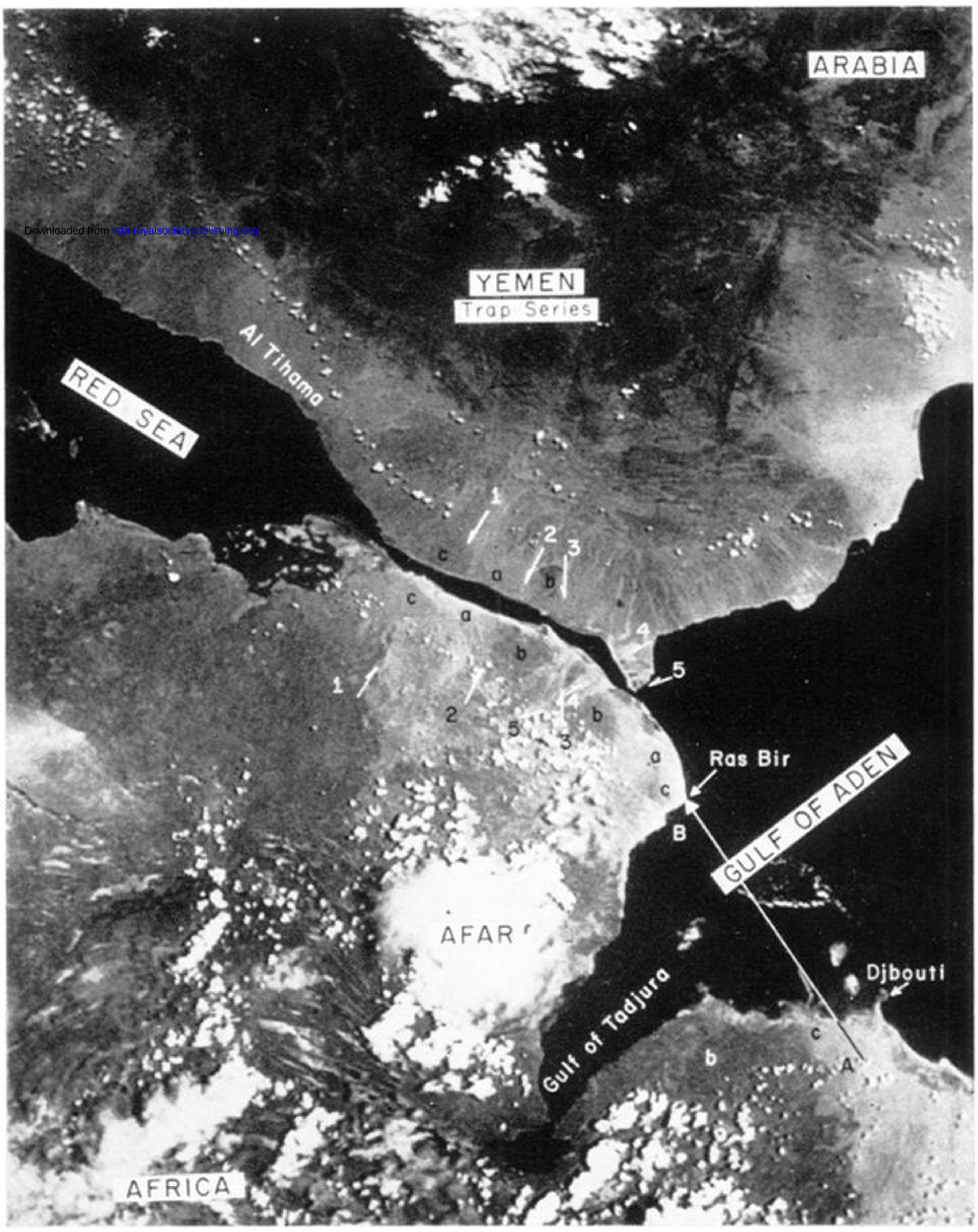


FIGURES 6 and 8. For legends see facing page.

9



11



FIGURES 9 and 11. For legends see facing page.