MAPPING OF THE MAJOR STRUCTURES OF THE AFRICAN RIFT SYSTEM

Contract NAS 5-21748

Final Report

Principal Investigator
Dr. Paul A. Mohr

July 1974

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
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PREFACE

The ERTS-1 satellite imagery has facilitated a major advance in accurate mapping and better understanding of the African rift valleys. In this report, for the first time, a unified scheme of mapping of the whole rift system, from Malawi to Ethiopia, has been accomplished. The structures revealed by the ERTS imagery are discussed in the light of known ground truth for the northern half of the African rift system (with which the author is more or less familiar); the southern half will be discussed in collaboration with East African geologists at a later date, but the maps are presented here.

The ERTS-revealed structures confirm the likelihood of a drift of Arabia away from Africa and impose constraints on the drift vectors. Numerous features have been newly recognized from the imagery: the gently curvilinear plan of virtually all the African rift valleys, the pervasive but not overriding degree of influence of Precambrian structures on rift faulting, the deep structural control of many rift volcanic centers, the occurrence of several unsuspected calderas both in the rifts and on the plateaus, and massive cauldron subsidence phenomena previously unknown to eastern Africa.

Lithological mapping in eastern Africa can be greatly refined using the ERTS imagery, and new or revised subdivisions of the Precambrian appear possible and, in some places, necessary. Valleys excavated in the Ethiopian highlands by Pleistocene glaciers are newly recognized.

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ILLUSTRATIONS

SHEETS

1:1 million-based sheets are collected at the back of this book for ERTS-mapped structural lineaments for the following areas:

Sheet	Area
1A	13 to 19°N, 41 to 48°E
1B	16 to 20°N, 35 to 39°E
2	12 to 16°N, 36 to 45°E
3	8 to 12°N, 35 to 43°E
4	4 to 8°N, 33 to 41°E
5	8 to 12°N, 43 to 51°E
6	3 to 8°N, 41 to 49°E
7	0 to 7°N, 28 to 35°E
8	0 to 4°N, 33 to 41°E
9	0 to 4°S, 26 to 33°E
10	0 to 4°S, 33 to 40°E
11	4 to 8°S, 26 to 33°E
12	4 to 8°S, 32 to 39°E
13	8 to 12°S, 26 to 34°E
14	8 to 16°S, 33 to 40°E

MAPPING OF THE MAJOR STRUCTURES OF THE AFRICAN RIFT SYSTEM

P. A. Mohr

1. INTRODUCTION

This report deals in outline with the results of the author's mapping of African rift structures from ERTS-1 satellite imagery. It should be noted that refinement and interpretation of the maps will continue beyond the production of this report.

ERTS-1 imagery has been used to map the outstanding lineaments of the African rift system, from latitude 20°N to latitude 20°S. Lineaments, defined in the next section, have been identified as far as reliable ground-survey data are available; otherwise, their nature is left unresolved on the plotted 1:1 million sheets (reproduced at small scale in this report). Additionally, some outstanding lithological features on the ERTS imagery have been mapped, and this work can be greatly extended.

Only the northern sector of the African rift is discussed in this report, although maps are presented for the entire system. This restriction is due to the author's familiarity with ground-based geology in Ethiopia and parts of northern East Africa: It is felt that other geologists are better qualified to interpret the ERTS maps of the southern sector of the African rift system (Figure 1). Even the brief discussion of the Yemen given here is included only because, to the author's knowledge, no one else will be interpreting the ERTS imagery of this important area in the near future. The mapped sheets are summarized, unified and updated, in the small-scale maps for the northern sector (Figure 2) and the southern sector (Figure 3) of the rift system.

The northern sector, treated in this report, covers Ethiopia, Somalia, and Yemen, a region of considerable interest to plate-tectonic studies because it marks a transition

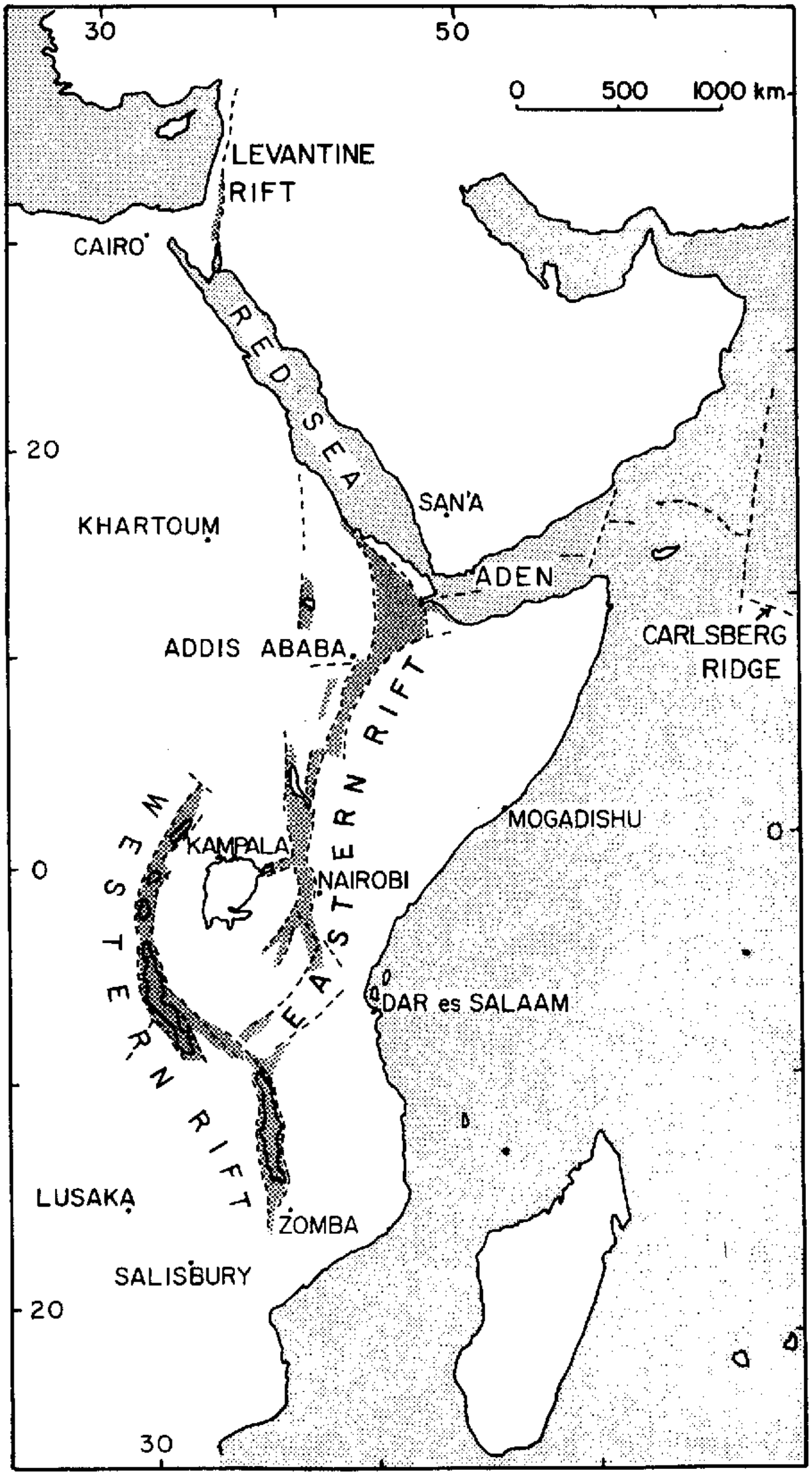

Figure 1. The East African rift system (rift valleys stippled).

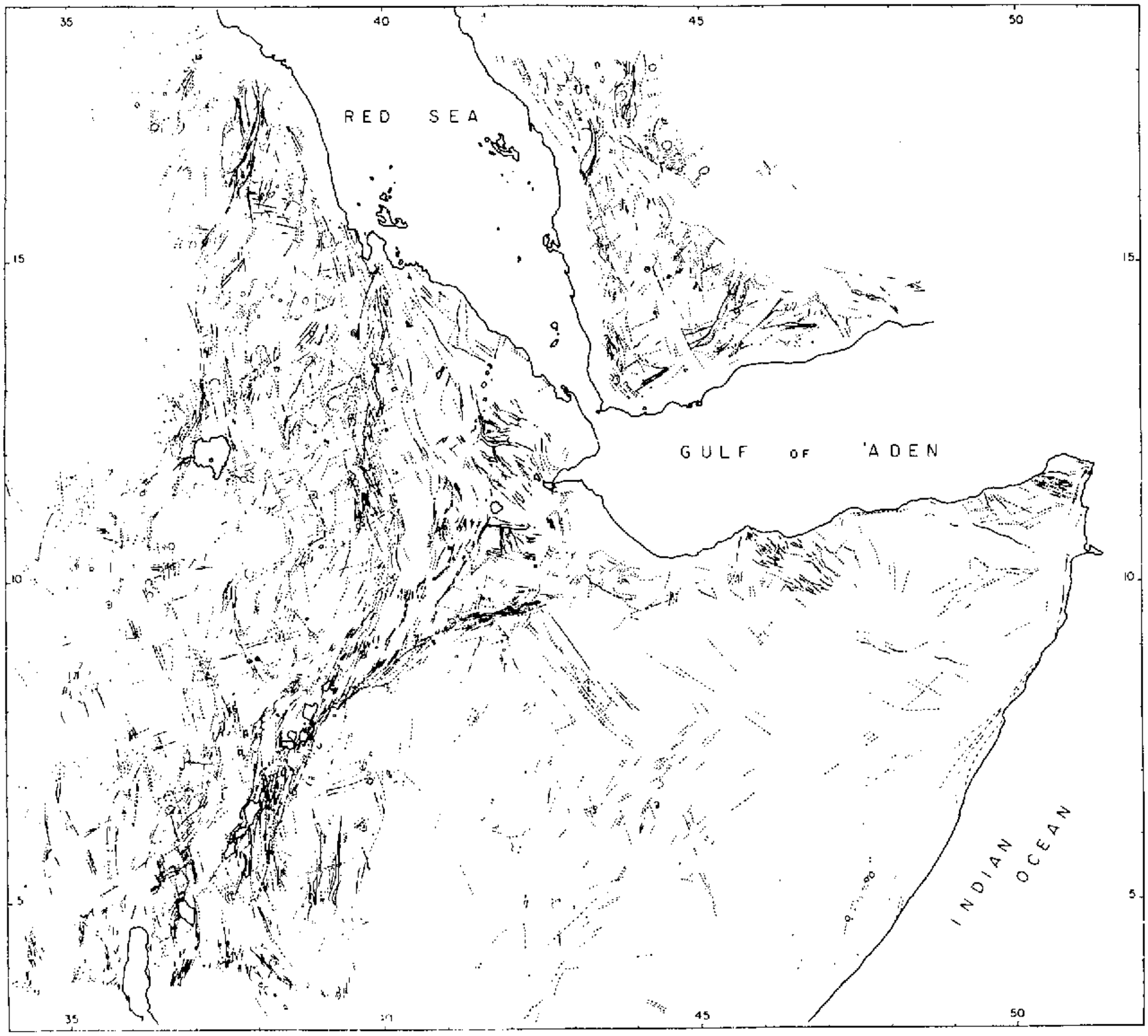

Figure 2. Structural map of Ethiopia, Somalia, and Yemen, based solely on mapping from ERTS-1 imagery, at 1:1 million scale. Thicker traces mark Cainozoic faults with visible displacements (the trace is dashed for fractures with uncertain or no apparent displacement; the latter include lineaments). Thinner traces mark major structural lines in the Precambrian basement. The downthrown side of faults is ticked, where known, and arrows indicate the sense of motion on transcurrent faults.

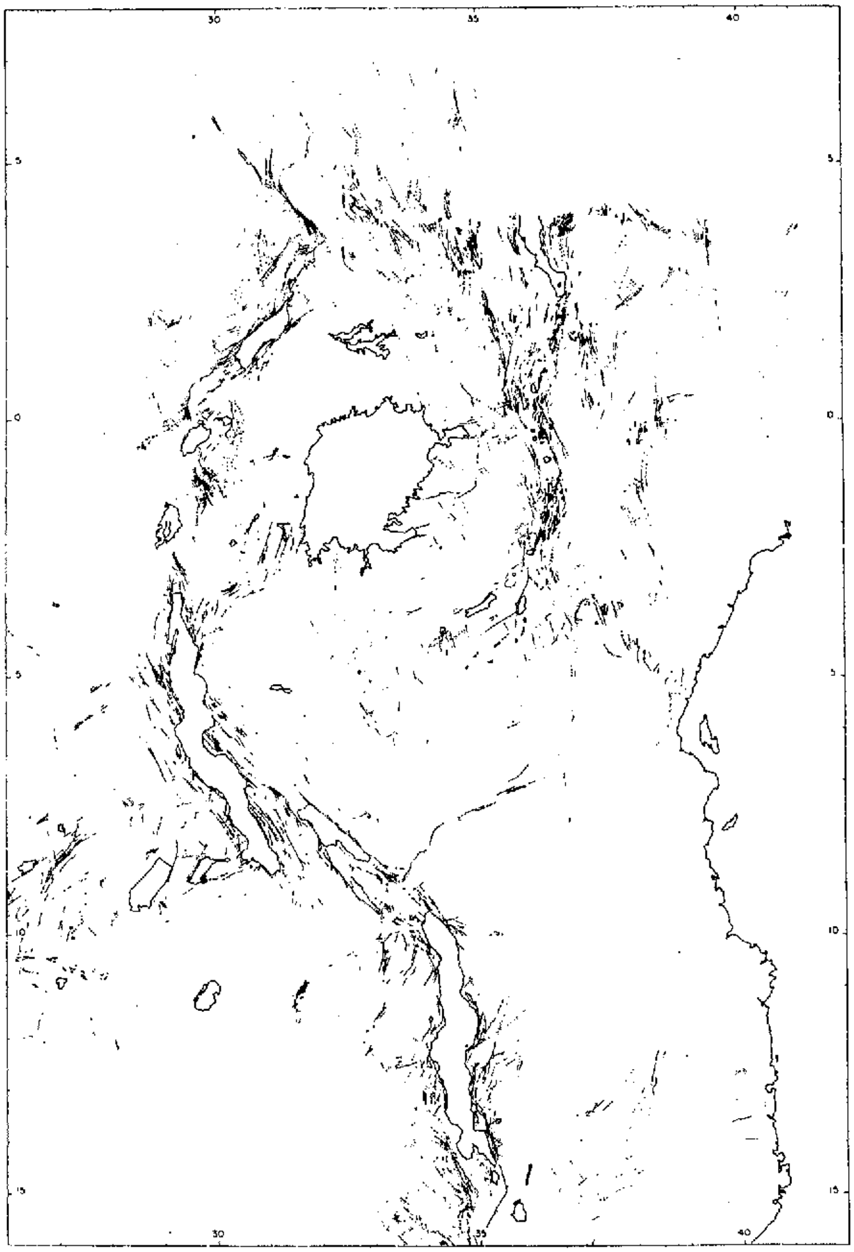

Figure 3. Structural map of East Africa and some adjacent areas, based solely on mapping from ERTS-1 imagery, at 1:1 million scale (see caption to Figure 1 for further details). Persistent cloud cover has prevented mapping of the Lake Kivu area, of southeastern Tanzania, and of parts of central Kenya, northern Mozambique, southeastern Malawi, and Ruwenzori.

from oceanic to continental rifts, with the greater part of the transition area being subaerial rather than submarine. This transition area encompasses the Afar triple junction, on which converge the spreading lines of the Red Sea, Gulf of Aden, and African rifts. The elevated existence of Afar is an anomaly within the sea-floor spread basins of the Red Sea and Gulf of Aden: Mohr (1970) considers that Afar consists essentially of new crust but that it was generated in relation to crustal extension over the whole width of the transitional area rather than at single, oceanic-type axes; and, thus, the volcanic products forming the Afar crust have a distinctive petrology. Schilling (1973) reckons, from geochemical data, that a mantle plume underlies the Afar region, and this helps account for the excessive igneous activity required to build up and maintain Afar above sea level during the Cainozoic. However, with the resumption of sea-floor spreading in the Red Sea 5 to 4 m.y. ago (Girdler and Styles, 1974), a like mechanism of crustal genesis now seems to have been imposed on the northern sector of Afar, at least (Tazieff et al., 1972).

The fascinating and controversial problem of Afar and its converging rift systems cannot be divorced from a structural consideration of the intervening "plates," here notably uplifted in several episodes (Baker et al., 1972) to form the Ethiopian, Somalian, and Yemeni plateaus. The plateau rocks are, of course, sialic and bear witness to a structural and lithological history extending back at least as far as the late Precambrian. A knowledge of the major structural features of the plateaus is essential to a full understanding of the evolution of the northern sector of the African rift system.

Six 1:1 million sheets cover the Horn of Africa and Yemen, and the ERTS-revealed lineaments have been plotted on these. Ground control has been taken from all available published sources, supplemented in the case of Ethiopia by the author's own researches. Yet, it must be emphasized that such control is inadequate or even nonexistent for large tracts of the mapped region, and there is still scope for major discoveries in rift tectonics (e.g., Zanettin and Justin-Visentin, 1973; Mohr and Potter, 1973).

Bannert (1972, 1973) has analyzed Afar tectonics as shown on Apollo space photography, a source now to be supplemented by data from Skylab. It would be interesting to compare the results of mapping from space photography with that from ERTS-1 imagery and investigate the reasons for any differences, but this is a large topic that awaits attention.

2. LIMITATIONS OF THE METHOD

The prime value of ERTS imagery to structural geology is the regional scale on which structural features can be sought, identified, and mapped (Short, 1973). It then provides a regional framework for all means of structural and tectonic analysis and for corrections to previous analyses, and facilitates the mapping of volcanic centers, related flows, and faults. Lithological mapping is possible in some areas, but not in others, seemingly according to the degree of soil and vegetation cover.

The types of structural features that can be identified on ERTS imagery, for the purposes of regional mapping, have already been discussed elsewhere (Mohr, 1973a). Linear features, termed lineaments, are the most striking structural features on the ERTS imagery of eastern Africa. Lineaments may separate tonally contrasted surfaces or be marked by intermittent, aligned topographic features. They can frequently be related with ground-identified faults, lithological contacts, metamorphic grain, jointing, or geomorphological features, and may range in length from a few kilometers to subcontinental dimensions. Many lineaments are subtly expressed, and many were unknown to aerial photographic or ground studies: Such lineaments lack apparent displacement and their nature remains problematical (Isachsen et al., 1973), but may reflect basement elements buried under deep cover (Allen et al., 1973). A few ERTS-identified "lineaments" may prove to be spurious as structures. The importance of structural lineaments cannot simply be related to the intensity of their expression on the ERTS imagery: Shackleton (in Hepworth, 1967) notes that it is the "common experience [of photogeologists] that dislocations of trivial importance can give rise to conspicuous lineaments, while major strike faults or slides, especially if pre-metamorphic, might be invisible." This perceptive but pessimistic viewpoint is, in the author's opinion, valid in some instances but certainly not in the general case. Furthermore, what may be termed "Shackleton's paradox" itself invites enquiry.

Evidently, a field check of lineaments is required, followed by an attempt at a genetic classification. A study of ERTS-revealed lineaments of the Colorado plateau (Goetz et al., 1973), correlated with ground-based studies, shows that these lineaments range from very strongly developed sets of joints to vaguely developed, almost indefinite groups of short linear features, which together portray a possible structural grain. Some conspicuous lineaments reflect stratifications in metamorphic terrain (a fact exemplified for the Precambrian of eastern Africa), but elsewhere reflect zones of strong fracturing. Steffensen (1973) notes that the distinction between lithological and fracture lineaments on ERTS imagery can be difficult, although the latter are commonly arranged in parallel sets. The author concurs from his own experience that fracture lineaments in normally faulted terrain usually display an unmistakeable clarity and linearity compared with lithological boundaries, at least in terrain of fairly strong relief and where lithological dip is not near vertical.

Space-photographic interpretation of the structural geology of the Red Sea and Gulf of Aden region, by Abdel Gawad (1970), has been strongly criticized or qualified (see the discussions following the cited paper). If it is indelicate to hint that we object to our personal geological preserves being opened, without consultation, to public exposure from space techniques, yet we must agree that a reversed argument may hold: With realistic resources, ground surveys are unlikely to lead to a conclusive regional interpretation of continental geology (see reply to discussions, by Abdel Gawad, 1970, p. 40) – that is, unless they are backed by satellite imagery or photography. Hepworth (in discussion of Abdel Gawad, 1970) makes a professionally apposite and concise summary of the problem: "Space photography [and imagery] is a tool <u>additional</u> to aerial photography, geological and geophysical mapping, and is not an exclusive source of conclusive answers." There is "pressure to present [space photographs] as a revolutionary new method which would justify the enormous expenditure which it took to produce them." Nevertheless, this report attempts to show the invaluable contribution that space studies can make to regional structural geology.

ERTS-1 imagery cannot distinguish among different types of faults or, except for major transcurrent faults, the amount of displacement along them. Neither can it easily distinguish sequential ages of different fault trends. By lacking the capability for stereoscopic emphasis, it cannot be used to identify regional vertical upwarps, except those from long-term secondary effects such as canyon erosion. These are matters for ground-based surveys. The virtue of ERTS-1 imagery is that it provides in map form the regional tectonic pattern of the Earth's crust as expressed at the surface.

3. GEOLOGICAL SUMMARY

A brief summary of the known geology of the Horn of Africa is given here, to provide a basis for the more detailed discussions that follow.

3.1 Stratigraphy

The Precambrian, or "Basement" rocks of the Horn of Africa are divided by Kazmin (1971) into median "Archaean" blocks separated by "Upper Proterozoic" eugeosynclinal belts, the whole comprising part of the Mozambique Belt of eastern Africa. The Archaean blocks are approximately 500-km across and trend NNE across the Horn; they are composed essentially of granitic gneisses, typically of amphibolite facies but occasionally of granulite facies, disposed in broad, gently dipping synclinoria and anticlinoria. Radiometric ages are all younger than 740 m.y. (Rogers *et al.*, 1965), indicating remobilization during the late Precambrian.

The Upper Proterozoic sequence can be divided into a lower series of metavolcanic rocks and an upper series of greenschist facies shales, arkoses, and limestones. The greater proportion of these rocks was deposited in shallow water, and the volcanics are notable for their tendency to become more silicic with time (Beyth, 1972). Late-syntectonic diorites, granodiorites, granites, pegmatites, and mineralized quartz veins (intruded in that order) characterize the synclinal axes and shear zones of both the Archaean and the Upper Proterozoic. Radiometric ages indicate an early Paleozoic termination to this magmatic activity (Rogers *et al.*, 1965). The thickness of the Precambrian sequence in the Horn is at least 3500 m.

Tillites and other glacial rocks rest with profound unconformity on the Basement metamorphics of Tigray (north central Ethiopian plateau). They could be either Upper Carboniferous or Upper Ordovician in age; the latter is preferred by Dow *et al.* (1971), despite the magnitude of the basal unconformity and also the upward passage, without evident disconformity, into the early(?) Jurassic Adigrat Sandstone formation. Small sediment-filled valleys lie preserved beneath the Adigrat Sandstone in the Abbay basin and are tentatively assigned a late Paleozoic age (Mohr, 1963a).

The Mesozoic of the Horn of Africa and of the Yemen was marked by a marine transgression (starting in the Liassic) and ensuing regression (starting in the Tithonian) that left shallow-water sandstones, shales, limestones, and gypsiferous evaporites over most of the region. The typical sequence, from bottom to top, is transgressive sandstones, shales, limestones, shales and gypsum, and, finally, regressive sandstones. The total thickness varies from a few hundred meters on the fringes of western Ethiopia and eastern Yemen, to 2000 m on the present Ethiopian and Somalian plateaus, increasing to 4500 m or more toward the Red Sea and present-day Afar and also toward the Indian Ocean coast in Ogaden (Geukens, 1960; Jepsen and Athearn, 1962; Holwerda and Hutchinson, 1968). The suggestion is one of a proto-rift trough subsiding within the transgressed platform. Following regression, the newly emerged regions of the Horn were subject to intense lateritization during an as yet ill-defined period in the Cretaceous–Paleocene.

Cainozoic marine sedimentation continued from the termination of the Mesozoic in the eastern Horn and eastern Yemen, until ended by abrupt uplift during the Upper Eocene. Oligocene and subsequent marine sedimentation have occurred within the Red Sea basin, with the notable precipitation of 3000 to 7500 m of halite during the Miocene (Hutchinson and Engels, 1972); thick halite deposits of Pliocene–Quaternary age occur in northern Afar, a sub-sea-level region now isolated from the Red Sea. Coastal Tertiary sediments, dominantly clastic, occur along the downwarped margins of the Gulf of Aden and sectors of the Indian Ocean.

The evolution of the Ethiopian–Yemen swell and its transecting rift valleys during the Cainozoic has been accompanied by profuse volcanism and subordinate instrusive activity. The earliest lavas, and related sills and laccoliths, are found interbedded with the youngest Mesozoic sediments in regions close to the present-day rift valley. Away from the rift, the Mesozoic sediments and the overlying flood basalts are separated by a progressively more emphatic unconformity.

The stratigraphy of the Ethio-Yemen volcanics has recently been subject to major revisions, and no consensus yet exists. Blanford coined the terms Trap Series for the flood basalts of the Ethiopian plateau and Aden Series for the volcanics of the rift valley, the latter essentially postdating the formation of the rift. The Trap Series was further subdivided into two groups (Blanford, 1869; Dainelli, 1943), but this subdivision now appears difficult to sustain, despite its retention by the Geological Survey of Ethiopia (Kazmin, 1973).

The Trap Series ranges from a thickness of a few hundred meters to a maximum of over 3000 m in north central Ethiopia (Simien Mts.) (Mohr, 1967a) and along the margins of the rift valley and Afar. The lavas are dominantly alkali olivine basalts and hawaiites, but tholeiites are known (Gregnanin, 1969; LeBas and Mohr, 1970); they were supplied chiefly from fissures now preserved as dikes along the warped rift margins (Mohr, 1971a). A major unconformity exists within the flood basalts of the east central Ethiopian plateau (Mohr and Rogers, 1966; Zanettin and Justin-Visentin, 1973). Silicic lavas and ignimbrites of Upper Oligocene—Lower Miocene age are intercalated near the top of the flood-basalt succession. Large shields were built up on the plateau either contemporaneously with or immediately subsequent to the fissure-fed lavas. Radiometric ages indicate that the shields are of Miocene—early Pliocene age.

In central and southern Ethiopia, the Trap Series is unconformably overlain by Miocene—Pliocene pantelleritic ash-flow tuffs (Mohr, 1968a) that seem to have originated from caldera volcanoes at the rift margins. Equivalent Miocene alkali granites are now exposed on the floor and margins of Afar (Brinckmann and Kürsten, 1969; Black et al., 1972a). The subsequent volcanic history of the rift and Afar has been localized and complex (Bannert et al., 1970; Barberi et al., 1972; DiPaola, 1973): In northern Afar, quasi-oceanic tholeiites are continuing to be erupted along a line of crustal extension; in central and southern Afar, the Neogene Afar Series stratoid basalts (with late-stage mugearites and alkali trachytes) are locally superimposed by Pliocene—Pleistocene rhyolites and Quaternary fissure basalts; in the main Ethiopian rift, the axial zone of most recent faulting is marked by dormant pantellerite centers (often with a caldera) and localized fissure basalts.

Intimately associated with the rift volcanics is a sequence of Pliocene—Quaternary freshwater sediments (Taieb, 1969, 1971) in central and southern Afar and the main Ethiopian rift. These sediments are particularly concentrated in tectonic depressions within the rift floor. In northern Afar, the marine sediments are succeeded by freshwater and terrigenous sediments (Beyth, 1972; Bannert et al., 1970).

3.2 Tectonics

Precambrian tectonics are not yet well known: As mentioned above, Kazmin (1971) has subdivided the Precambrian of the Horn into a pattern of parallel, old, and relatively rigid blocks separated by deformed belts of late Precambrian sediments. The sediments and volcanics of these deformed belts now form broad synclines and anticlines, trending between NNE and NNW. An interesting structure from the northwestern margin of Afar with the Ethiopian plateau has been described by Kazmin and Garland (1973): A meridionally trending horst within the Precambrian of Tigray (the Atsbi horst of Beyth (1972)) is bordered by recumbent-folded late-Precambrian sediments. West of the horst, slates and dolomites are tightly folded and overturned to the east (i.e., dips are westward), whereas east of the horst, conglomerates and greywackes are overturned to the west. This indicates the existence of a resistant block subject to east–west compression late in the Precambrian, a concept supported by the thinning of sediments over the horst. Kazmin and Garland conclude that block faulting of the Afar margin began in the Precambrian. However, in detail (see below, discussion on Sheet 2), the Cainozoic faulting of the Afar margin does not follow the Atsbi horst, and it seems that no convincing case can be made for a Precambrian origin to the Afro-Arabian rift system (King, 1970; Mohr, 1973a).

Important Mesozoic tectonism is indicated by the riftward thickening of the sedimentary rocks of this age. Upper Jurassic faulting, trending NW–SE and upthrown NE, has been described from Tigray (Beyth, 1972), and from the same region some gentle folding about east–west axes was noted by Mohr and Gouin (1967). By the end of the Mesozoic, warping of the rift margins became sufficiently strong that abundant basaltic magma began to reach the surface: The warping was related to swell uplift of the plateaus, which occurred in pulses (Baker et al., 1972) with major episodes in the Upper Eocene, Lower–Middle Miocene, and late Pliocene–early Pleistocene. The preserved dike feeders along the rift margins show a conjugate pattern consistent with tension acting at right angles to the rift (Mohr, 1971a). The density of some dike swarms proves a minimum of 20% crustal extension due to the magmatic injection (Mohr and Potter, 1973).

The downwarping and fissure-basalt eruptions of the rift margins were followed by antithetic faulting across a broad zone, especially along the Afar margins. A marginal graben is commonly associated with the antithetic faulting, usually being situated on the plateauward side of the faulted zone. Synthetic faulting is notably developed along those sectors of the Afar margins farthest from the main Ethiopian rift: Also, volcanic extrusion has been much less where synthetic faulting has dominated over antithetic faulting. Both types of faulting are expressive of tension acting perpendicular to the rift (Abbate and Sagri, 1969; Black et al., 1972b). The antithetic faulting of the western margin of Afar tends to be concentrated into belts, which, although not coincident with the earlier dike swarms, often show identical trend even in conjugate detail. This suggests that the stress field for this region remained constant throughout continuing crustal extension during the Tertiary and, according to continuing seismic activity, into the Quaternary (Gouin, unpublished data; Mohr, 1971a).

The massive, stepped escarpments of the main Ethiopian rift were probably faulted in the early Pleistocene, close to the time of the floor-belt faulting of Afar. These faults dropped the graben well inside the dike-intruded, warped margins of the proto-rift trough. Severe, late Pliocene–Quaternary crustal extension has affected the floor of Afar and the main Ethiopian rift, matching resumption of sea-floor spreading in the Red Sea (Girdler and Styles, 1974). This extension resulted in belts of horst-graben and ratchet faulting, from which a horizontal extension of about 25 km can be demonstrated across the width of central Afar, acting NE–SW, perpendicular to the Red Sea trend of the faulting (Mohr, 1972a). It has not yet been possible to identify an earlier (Upper Eocene–Lower Oligocene) episode of tensional faulting in Afar matching the first stage of Red Sea floor spreading (Girdler and Styles, 1974), although a closer examination of the Afar Series flood basalts might make this possible. The preserved Afar floor fault belts and the tensional episode that produced them are tentatively related to the important late Pliocene–Pleistocene phase of swell uplift in Ethiopia (Baker et al., 1972).

Intersections and abutments of fault belts in central Afar, apparently pene-contemporaneous in their development, raise problems as to the nature of the stress field(s) that produced them (Mohr, 1967b; Tazieff, 1971). However, the work of Black et al. (1972b) in southeastern Afar demonstrates that rapid and radical changes in stress-field orientation have occurred there during the Pliocene–Quaternary, accompanied by changes in the composition of associated magmatism. These rapid changes, uncharacteristic of the plateau margins of Afar, may be related to the proximity of the new and actively developing Gulf of Tajura depression. Nevertheless, tectonic modeling by E. Cloos (in Badgley, 1965, see Figures 4–16) shows that abutment of two perpendicular fracture sets can be produced by a single rotational shear, and the tectonics of Afar should be examined in this light.

Within the main Ethiopian rift, only one belt of young, extensional faulting (the Wonji fault belt) affects the rift floor. The belt varies in the intensity of its development and progressively displaces from the western side of the rift floor to the eastern side, proceeding northward along the rift valley. The nature of these displacements has been described as due both to abrupt transverse shears (Mohr, 1967b) and to en echelon development (Gibson, 1969; Gibson and Tazieff, 1970); but in both the rift valley and Afar, the real pattern rarely conforms to these preconceptions! Bifurcations, bilateral displacements, and curvilinear or gradual displacements are features of different sectors of the rift system in the Horn of Africa.

In the main Ethiopian rift, dormant trachyte-pantellerite caldera volcanoes are situated on the Wonji fault belt, at fairly regular intervals of 30 to 40 km, and the fault belt is commonly offset near where a volcano occurs. The Wonji fault belt extends north from the rift valley, across southern Afar as far as Lake Abbe. In so doing, it undergoes some large dextral offsets, of which the Ayelu–Amoissa offset is the most notable (Mohr, 1967b).

The existence of proto-transform faults, and their possible extension into the bordering sialic plateaus as transform directions, is disputed (Mohr, 1967b; Gibson and Tazieff, 1970). Faults, dikes, and tight monoclines, within and perpendicular to the western margin of Afar, have been mapped, but whether they are minor accidents or of some structural significance is not yet known.

Important Cainozoic structures occur on the plateaus. Along the length of northern Somali, the plateau rim overlooking the Gulf of Aden is faulted NW–WNW parallel to the spreading axes of the Gulf of Aden. The same trend is shown by the

Marda lineament, where NW–SE tectonism was associated with basaltic magmatism in the late Mesozoic–Paleogene (Gouin and Mohr, 1964; Shachnai, 1973). On the Ethiopian plateau, the Tana graben is a meridionally trending, asymmetric structure of Pliocene–Quaternary age: Before the ERTS-1 imagery, its connection, if any, with the rift system to the east was unknown (Mohr, 1967b). Extensive fault systems, sometimes associated with earlier zones of warping and dike injection, occur in the middle and lower Abbay basins and in the Omo basin (Baker et al., 1972); they are predominantly of main rift trend, but transverse structures are occasionally important, as in the case of the Addis Ababa–Ambo faulting.

4. DISCUSSION OF MAPPED SHEETS

4.1 Sheet 1: 16 to 20°N, 35 to 47°E

4.1.1 Yemen

Geological interpretation of ERTS imagery of Yemen has already been presented (Mohr, 1972b), and here an outline synthesis will be given. The geology of Yemen is very much relevant to that of the African rift system for, before sea-floor spreading and plate separation across the present Red Sea and Gulf of Aden, Arabia was tucked in close as part of the African continent. Ground knowledge of Yemeni geology is restricted to reconnaissance traverses (Geukens, 1960).

The structural framework of the Precambrian basement in Yemen is generally one of broadly folded metamorphic rocks cut by near-circular intrusions. Synclinoria and anticlinoria can be recognized, for example, near the Red Sea margin between latitudes 16 and 18°N (Brown and Jackson, 1960) and near the Gulf of Aden margin between longitudes 45 and 47°E. At the latter locality, the Precambrian structures are closely parallel with the superimposed Cainozoic structures (Greenwood and Bleackley, 1967), whereas inland of the NW-trending Red Sea margin, the Precambrian structures are trending NNE on average. This NNE trend is matched on the opposing, western side of the Red Sea trough in Ethiopia (Beyth, 1972; see also discussion of Sheet 2). Considerable detail could be extracted from the ERTS imagery concerning the fold structures and major lithological elements of the Yemeni basement.

Lineaments, forcibly expressed on the ERTS imagery, traverse Precambrian terrain in Yemen without apparently effecting any major crustal displacements. Jointing hardly seems the correct term to apply to such features, which can extend for lengths of more than 100 km; nor, except for short, linear sectors, can they be hinge lines. Prominent examples of these lineaments occur in northeastern and south-eastern Yemen. In southeastern Yemen, their trend curves from ENE (in the west) to northeast before being obscured under sand cover at latitude 15°N.

Some of the Precambrian lineaments have undoubtedly been rejuvenated in the Cainozoic extensional tectonism of the region, since structural parallelism has been observed, for example, along the Iyadh and Ataq fault zones bounding the Azzan graben (Greenwood and Bleackley, 1967), between longitudes 47 and 48°E, and also along the Dhala fault zone at longitude 45°E. These three fault zones trend NW–WNW (Greenwood and Bleackley (1967) apply the term "Red Sea" trend to this orientation of the zones, but this presumes a genetic association that is not yet proved). Beydoun (1970) has matched the Azzan graben with the similarly trending Asseh graben of northern Somali (see discussion of Sheet 5). The structural significance of such a matching, if valid, is important, for it indicates that the original lines of crustal weakness predate the initiation of drift in the Eocene (Girdler and Styles, 1974; cf. the Middle–Upper Miocene age taken by Beydoun). As the topographically preserved faults of the two gräben indisputably postdate the Eocene, a Precambrian age is implied for the original, common fractures.

The ERTS imagery reveals the two main types of Cainozoic tectonism in Yemen. First, coastal monoclines along the margins of the Red Sea and Gulf of Aden are characteristic, though not uninterrupted, features of these margins. Antithetic faulting within the warped zones is prominent along the Gulf of Aden margin, where, however, the orientation is suited to sun-shadow emphasis on the imagery. The coast monocline at Jizzan, on the Red Sea margin at latitude 17°N (Coleman et al., 1972), is virtually impossible to distinguish on the ERTS imagery, emphasizing the fact that ERTS data need to be integrated with air and ground data before a full interpretation can be made.

Second, some large, single normal faults, or a narrow zone composed of several such faults, have trends not obviously related to the Red Sea and Gulf of Aden tectonism. In northern Yemen, the Jebel Barach fault extends southeastward for 150 km from the northern side of the Sa'da graben (Geukens, 1960; Mohr, 1972b). This fault is upthrown to the northeast and is not a continuous linear but is offset in several places with connecting, transverse fault segments. The trend of the J. Barach fault can be projected to meet the Iyadh fault of the Gulf of Aden margin. Thus, the Red Sea trough can be envisaged as widening out symmetrically at its southern end about the present spreading axis: The J. Barach–Iyadh fault line is mirrored by the Ethiopian plateau–Afar margin, although the latter has undergone a more fundamental and continuing development (Tazieff _et al._, 1972; Mohr, 1967b).

Some prominent fault zones trending NE–ENE in Yemen may be reactivated Precambrian structures. Thus, an unnamed fault zone extends northeastward from 13°N, 44°E and, in so doing, passes from Paleogene Trap Series terrain in southwestern Yemen, across the Dhala fault, to Precambrian terrain in eastern Yemen. This fault zone appears to have acted as a hinge for the margin warping of the Gulf of Aden, as well as a line for vertical, block displacements (Brown, 1970; Mohr, 1972b). Farther north, and running parallel to this fault zone, are the Dhama–Reda and Sirwah–Marib fault zones of eastern Yemen (Geukens, 1960), both associated with Quaternary basaltic volcanism. The Sirwah–Marib fault zone likewise marks a line of major block displacements, without any evidence for transcurrent movements. These fault zones exercised a tectonic control on the fields of Tertiary flood-basalt deposition (Mohr, 1972b) and thus were active during the Paleogene. The flood basalts filled the downthrown side to the extent that there is now no marked topographic expression of the block faulting.

The Dhala fault (Greenwood and Bleackley, 1967) runs NNW and immediately east of the axis of the Yemeni highlands. A zone of smaller, parallel faults, about 35 km across, may be associated with the Dhala fault, which then forms the eastern boundary of the zone. The zone notably extends through the Quaternary volcanic field of San'a. If, as Greenwood and Bleackley (1967) maintain, the Dhala fault is a line of major displacement of crustal blocks with downthrow to the west, then it is interesting that the topography is now higher to the west. Evidently, Tertiary flood lavas filled the depression on the downthrown side of contemporaneous block faulting, and uplift and tilting of the Yemeni plateau during the Neogene have placed the downthrown, lava-stacked block at a higher elevation than the upthrown Precambrian block farther east. This phenomenon is also known, for example, from the southern end of the main Ethiopian rift (Mohr and Gouin, 1968).

The cross-cutting relationship of the Dhala fault to the NE-trending fault zones described above indicates a mosaic pattern of crustal-block tectonics in the evolution of Yemen, a pattern that may be older than its strong, Cainozoic expression.

Pleistocene–Holocene alkali olivine basalts occur sporadically along the axis of the Yemen highlands, parallel to the margin of the Red Sea (Kabbani, 1970; Gass, 1973). The largest area of such young basalts in Yemen occurs as a 1500-km^2 field northwest of San'a. Mohr (1972b) noted that this lava field is associated with NNW-trending fractures, of both pre- and post-lava ages, but possibly also with an intersection of this Red Sea trend by a weak NE–SW lineation belt parallel to the fault zones farther south.

4.1.2 The Eritrean plateau (north of latitude 16°N)

The northern part of the Eritrean plateau is perhaps more properly considered as a feature of the Red Sea margin, rather than as the northern promontory of the Ethiopian swell. The plateau here is formed of Precambrian metamorphic and igneous rocks, the surface of which was deeply lateritized in the late Mesozoic (Dainelli, 1943). No Tertiary basalts occur (or at any rate, are preserved) on the lateritites, such as typify the highlands of the Ethiopian swell, to the south.

West of the Baraka valley, the southern end of the Red Sea Hills exposes NNE–ENE-trending lineaments, evidently representing the Precambrian metamorphic grain, crossed by subordinate and distinctive east–west lineaments. Prominent circular features, 10 to 15 km in diameter, are numerous within this terrain. Ground surveys of the Red Sea Hills farther north (Ruxton, 1956; Lotfi, 1963) identify a metamorphic terrain, chiefly schists and slates, intruded by batholithic granite and, later, dikes. Near the end of the Precambrian, an episode of ring granite-syenite intrusion with minor associated volcanism occurred, and it is these intrusions that are conspicuous on the ERTS imagery. Detailed examination of this imagery is being done by Professor J. R. Vail (University of Khartoum).

East of the Baraka valley, on the Eritrean plateau proper, some of the most remarkable features of the entire ERTS imagery of eastern Africa are expressed. These comprise a system of narrow (c. 5 km), gently curvilinear belts, trending, on the average, SSW and extending from the Red Sea coast for at least 300 km to across the Baraka and Gash (Mareb) valleys (Mohr, 1972b). The SSW–NNE trend is paralleled by the fold axes of metamorphic terrain both in the Red Sea Hills, to the north (Lotfi, 1963), and in Tigray province, Ethiopia, to the south (Arkin *et al.*, 1971).

In more detail, the belt system can be described as extending from the Red Sea coast near latitude 18° 10'N, in a direction of S30°W. Proceeding initially along the Ayet valley, the system is joined by a tributary, meridional belt at Jebel Hamoet (longitude 38°E). The system then runs as two closely spaced, parallel belts along the Adóbaha valley to latitude 17°N, where the belts begin to diverge gradually. A major "tributary" belt again comes in from the NNW at this divergence. After diverging to about 25 km, the belts approach and merge at latitude 16°N. Thence, the single belt is only intermittently exposed farther southwest, owing to increasingly thick alluvial cover; and the last clear expression of the system on the ERTS imagery occurs in the Gash valley near Aycota (latitude 15° 15'N).

The nature of the belt system is not yet certain, lacking focused ground surveys. Gherardi (1951) described a series of isoclinally folded, argillaceous schists striking NNE–SSW in a stretched S-plan, and although Gherardi places this rather vaguely in the "Western Lowlands" of Eritrea, he may have signified what has now been identified from the ERTS imagery. The schists, dominantly chloritic and sericitic, have near-vertical foliation dips that are generally directed westward. The schists include concordant, intercalated lenses of crystalline limestone and some basic intrusions with "silicified" margins. Similar narrow, nearly vertical foliated schist zones appear to be a feature of the Red Sea Hills (Lotfi, 1963) and the Asir Highlands north of Yemen (Brown and Jackson, 1959). Whether or not these narrow schist belts are associated with the cataclasites mentioned by Andreatta (1941) remains to be shown, but the belts are evidently zones of severe deformation, picked out by subsequent erosion. No transcurrent displacements are identifiable.

The east–west lineaments noted in the southern Red Sea Hills are paralleled by lineaments near the southern margin of the region covered by Sheet 1. Such lineaments become more profuse farther south (see Sheet 2).

4.2 Sheet 2: 12 to 16°N, 36 to 42°E

The sheet covers the northern part of the Ethiopian plateau, between the Sudan plains in the west and the Afar depression in the east. It also includes northern Afar and the Danakil horst.

4.2.1 Precambrian terrain

Between 16 and 15°N latitude, the dominant lineaments belong to the Eritrean domain discussed under Sheet 1. Near-meridional strike lines mark the foliation of the regional, low-grade metamorphosed sediments and usually have a gently arcuate form. Quite different in appearance are some numerous, linear E–ESE lineaments. They occur north of a line joining Asmara and Agordat, and many have strong topographic expression that is presumed due to selective erosion. No displacements are evident along these lineaments. Vail (1970) and Whiteman (1971) briefly touch on the existence of east–west dikes and faults in the Red Sea Hills, and it possible that the same tectonic domain extends south as far as latitude 15°N.

Near 15°N latitude, the Precambrian structural trend sweeps around to the NE–SW trend typical of Tigray province. This is also the trend of the Adóbaha deformation zone (see discussion of Sheet 1), which crosses the Baraka river and then the Gash river at latitude 15°N, longitude 37°E, but then becomes concealed beneath the alluvium of the Atbara plains. Indeed, covering sediments tend to muffle expression of the NE–SW-trending basement strike in western Tigray, between longitudes 37 and 38°E. In the east, where the plateau has been most uplifted and eroded, the Precambrian structures are beautifully etched and emphasized on the ERTS imagery. By good fortune, this region has received relatively detailed ground-based survey (Merla and Minucci, 1938; Arkin et al., 1971; Beyth, 1972). Side-by-side synclinoria and anticlinoria of low-grade metamorphic schists are pierced by granodiorite bodies. The average dimensions of the clinoria are about 20-km wavelength and 5-km amplitude (Beyth, 1972), and they are exposed for 100-km length between the Trap Series cover to the south and the Adigrat outlier to the north.

About longitude 39°E, the Tsaee anticlinorium is flanked by the Chehmit synclinorium to the east and by the May Kenetal synclinorium to the west. These synclinoria plunge to the southwest (Merla and Minucci, 1938; Mohr, 1962), and in some sectors are bounded by faults of graben type (Beyth, 1972). North of the Adigrat outlier, the whole association has narrowed to about 15-km width and passes along the Red Sea escarpment, west of Massawa. The May Kenetal synclinorium contains granodiorite intrusions, 10 km or more across, with long axes parallel to the metamorphic strike. The western margin of this same synclinorium is superimposed by a line of the late-Tertiary Adua–Axum phonolite plugs (Prior, 1900).

Between the Chehmit synclinorium and the Negash synclinorium farther east, a zone of about 40-km width gives only weak expression to the Precambrian structures, although the Hauzien granite is prominent (Beyth, 1972). The Negash synclinorium, considered by Beyth to be an en echelon structure bounded by graben faults (this is not shown on the ERTS imagery), extends north as a very strong lineament, curving northeastward across the Afar escarpment zone to Alíd volcano, at latitude 15°N.

Jointing of two trends, 050 to 070° and 110 to 120°, is described by Beyth from the Precambrian of Tigray. Both these trends, especially the former, show up as a "grain" or even as distinct lineaments on the ERTS imagery. Their regional extent raises the question of their cause, a question that is deferred here until they are mapped in more detail.

There is no doubt that detailed mapping of the Tigray Precambrian, both its structures and its major lithology, can be effected from the ERTS imagery in conjunction with aerial photography and control from the ground.

4.2.2 Mesozoic sedimentary and Tertiary volcanic terrain

The Mesozoic sedimentary rocks and the Tertiary lavas contrast strongly on the ERTS imagery with the underlying basement and with each other, and thus their respective boundaries can be mapped. Earlier ground surveys of the Miocene basalts of the Asmara–Adi Quala region (Dainelli and Marinelli, 1912) and Adigrat–Adua region (Merla and Minucci, 1938), and of the Mesozoic formations of the Makale region (Arkin et al., 1971) are confirmed and can be made more precise.

Four important NW–WNW trending faults are known from the Makale Mesozoic terrain (Beyth, 1972, Figure 20). They are essentially pre-Tertiary in age, are upthrown to the northeast, and are paralleled by axes of gentle folds and some steep tilt planes (Mohr and Rogers, 1966). These faults show up weakly on the ERTS imagery, although their orientation is unfavorable to sun-shadowing: Only the Mekele and Chelekwot faults can be identified with certainty, and these not along the whole of their lengths as mapped on the ground.

Between Adua and Enda Selassie, west of Adigrat, a field of post-Trappean (Pliocene ?) phonolite-trachyte plugs shows up very clearly on the ERTS imagery. Some of the plugs are seen to be situated on alignments of the underlying Precambrian structures (NNE – SSW) and on Tertiary (?) ENE – WSW faults (see also Mohr and Rogers, 1966).

South of the Takaze river valley, a thick Trap Series succession comprises between 1500 and 3000 m of Paleogene flood basalts (Mohr, 1967a). Most notable here is the Lower Miocene volcanic center of Simien (13°20'N, 38°20'E), a 100-km-diameter shield whose summits culminate at 4543 m, the highest elevation in Ethiopia. On the eastern side of Simien, immediately west of the upper Takaze river, the synclinoria – anticlinoria of the Tigray Precambrian pass beneath the lava cover. The course of the Takaze river is strongly influenced by basement structures in this region, and lineaments of the same NNE – NE trend can be identified on the ERTS imagery as expressed through the Trap Series cover as far south as latitude 12°N on Sheet 2.

A striking feature on the ERTS imagery of Simien is the glacially excavated valley of the May Shaha; other valleys of Simien also show evidence of glaciation, notably the northeastward-draining Ataba valley. The May Shaha glacier at its maximum extent reached 40 km south from the head of the valley, excavating a valley 1700 m deep and about 12 km wide (Mohr, 1963b). Nilsson (1940) and Scott (1958) recognized the May Shaha as a glacially excavated valley, although this was contested by Minucci (1938) and Mohr (1963b). The ERTS imagery proves Nilsson and Scott to have been correct. The flow directions of the Simien glaciers appear to have been largely controlled by the regional southeasterly dip slope resulting from tilting from major NE – SW faulting. The existence of this faulting along the northwestern margin of Simien has previously been suspected but not confirmed from ground-based studies (Mohr, 1963b, 1967a). Now the enormous, near-vertical precipices of Simien are seen to be recession scarps in the resistant basalt pile, the amount of recession varying between 4 and 8 km.

The NE – SW faulting of Simien, probably of Middle Miocene age and associated with an uplift of the Ethiopian plateau (Baker et al., 1972), aligns with the Precambrian structures of May Kenetal and Tsaee (page 22). This provides a good example of the usage of ancient lines of crustal weakness by subsequent, and quite different, tectonism. The Simien scarp can be traced southwestward across the floor of the Tana graben (see below), before dying out near the eastern boundary faulting of this graben. Lineaments trending NNE within the Simien dome, as expressed on the ERTS imagery, may be dikes or dike swarms of this trend (Mohr, 1963b, 1967a); they are slightly but definitely oblique to the main scarp faulting. A weaker, NNW lineation in Simien parallels Neogene–Quaternary faulting in the Tana graben, to the west, and along the Afar escarpment to the east.

The Tana graben is an asymmetric, meridionally trending structure, 70 to 80 km wide, the geology of which is hinted at by Mohr and Rogers (1966). In essence, a strongly faulted and upwarped western margin to the graben faces a weakly and transversely faulted eastern margin. Trap Series alkali basalts-hawaiites form the margins and floor of the graben, are overlain by Quaternary olivine tholeiites and alkali rhyolites, and are pierced by trachyte and phonolite plugs. The young lavas blocked the graben drainage at its southern end, thus damming back the present lake; north of the lake, reversals in river drainage attest to northward tilting down of the graben floor (Mohr and Gouin, 1967).

The ERTS imagery reveals the regional extent of the Tana graben structures for the first time. Commencing east of Om Agher in the alluvial plain of the Takaze river (latitude 14 1/2°N), faulting runs first SSE, then south, curves SSW south of 13°N to form the western margin of the graben. However, SSE-trend faulting continues along the eastern margin of the graben, producing a gradual divergence that appears to terminate at the southern end of the lake, where a large, young volcanic field occurs. Precisely at latitude 13°N on the graben floor, a 20-km-diameter circular feature shows on the ERTS imagery, and ground survey has shown it to be a breccia-filled cauldron intruded by ring dikes (Hahn et al., private communication, 1974).

Although the faulting of the western margin of the Tana graben is shown by ERTS in precise detail, the warping is revealed only by fine lineaments presumed to mark antithetic faults (Jepsen, private communication, 1963). Between latitudes 12 and 12 1/2°N, the western margin of the Tana graben is formed by NNE faults, upthrown west, intersected by subordinate NNW faults. The WNW lineaments mapped from aerial photographs by the writer (Mohr and Rogers, 1966) fail to show up on the ERTS imagery. This may be because they are small-scale joints (possibly also some dikes) too narrow to show up from 900-km distance with 75-m resolution.

East of Lake Tana, the graben margin is formed by weakly expressed, apparently discontinuous, NNW-trending lineaments that can nevertheless be traced for a further 100 km to the north. A narrow, mesa-like strip of the Trappean plateau surface is preserved 20 km northeast of the lake, curving from NW–SE in the northwest to ESE in the southeast. Faults cannot be definitely identified with the western scarp of this mesa on the ERTS imagery, but there could be a link with the faulting of the western margin of Simien, farther north (page 24). This implies that the Menna basin, east of Gondar, was formed by Middle Miocene(?) upfaulting and tilting (down to the east) of a semicircular tract of terrain, some 80 km in radius. The eastern sector of this basin is traversed by rather strongly expressed NNE–SSW lineaments, projecting south from the Precambrian clinoria of Tigray across the Tertiary basalt terrain: Their projection farther south, onto the region covered by Sheet 3, aligns with a 90-km-long sector of the Abbay valley.

4.2.3 Northern Afar and Danakil horst

The margin of the Ethiopian plateau with northern Afar, topographically determined by Miocene–Quaternary faulting, shows up with variable emphasis on the ERTS imagery. It should be noted that the quality of this imagery is generally excellent. Where marginal gräben are developed (13°50' to 14°40'N; 12°55' to 13°10'N; 12°00' to 12°50'N), sun shadow clearly reveals the eastern margins of the gräben, and high illumination, the western margins. Both margins can be found further emphasized by erosion gullies perpendicular to the fault scarps. But other sectors reveal rather indeterminate and apparently disconnected structures—for example, the sinistrally offset link between the Afar margins at latitudes 14°40' and 15°00'N (see Mohr, 1967b, pp. 19-21).

A review of the structures of the Afar margins, as reinterpreted from ERTS imagery, has been given elsewhere (Mohr, 1974), supplemented by ground-survey data (Beyth, 1972; Black et al., 1972b; Abbate et al., 1968; Mohr, 1971a; Mohr and Rogers, 1966). In the margin sector covered by Sheet 2, the Neogene–Quaternary faulting swings from NNW in the north to NNE, south of latitude 14°N, and then back to NNW a little north of latitude 12°N. This gently curving plan is superimposed on an older pattern of dextrally offset sialic blocks, oriented NNW–NW (Tazieff et al., 1972). These two superimposed structural styles can probably be equated with the two episodes of Red Sea floor spreading (Girdler and Styles, 1974).

The NNE-trending sector of the Afar margin faulting is parallel to Precambrian structures occurring farther west on the Ethiopian plateau. One of these structures, forming the Negash synclinorium–Atsbi horst boundary (Beyth, 1972; Kazmin and Garland, 1973), projects to the NNE as a lineament, which intercepts the Afar floor tectonism exactly at the dormant caldera of Alíd. This points to deep tectonic control of sites of rift silicic volcanism in Ethiopia; other possible examples include the calderas of the Dubbi volcanic lineament (Mohr, 1967b) and the Ma'alalta and Dabbayra volcanoes of westernmost Afar.

Application of space photography to geological mapping of the floor of Afar has been made by Bannert (1972, 1973), and ERTS mapping of the same region is in progress by Dr. P. Kronberg (Clausthal Technische Universität). Here, it must suffice to say that detailed mapping of the major volcanic formations of Afar appears feasible (Bannert, 1972, 1973) from the ERTS imagery alone; furthermore, the Miocene granites and the Pliocene–Quaternary graben sediments can be identified and mapped. Likewise, the fine faulting of the Afar floor can be mapped on a unified basis.

The major structures of the Afar floor, north of latitude 12°N (Sheet 2), are predominantly oriented NW–NNW. This is the orientation of the long axes of the Erta-ali, Alayta, and Tat-ali basalt shields and of the active/dormant volcanic centers situated on them. However, both the Alayta and Tat-ali shields contain structural elements curving off to the southwest; in the case of Tat-ali, they occur along a projection southwestward from important lineaments in the Danakil horst, to the northeast. This may again be an influence or hangover from earlier basement tectonic control. The NW-trending belts of concentrated faulting in north-central Afar adapt to a more complex pattern in eastern Afar (Mohr, 1967b, 1968b). Here, curved gräben suggest the influences of crustal nuclei and of rotational and longitudinal shear (Barberi et al., 1972; Mohr, 1968b, 1971b).

The ERTS imagery shows the Danakil horst to be limited west by a more pronounced lineament than would be expected from the mere overlap of graben sediments onto a tilted block (Holwerda and Hutchinson, 1968; Hutchinson and Engels, 1970, 1972). This margin lineament is powerfully expressed between latitudes 14 1/2 and 13 1/2°N, and its direct association with patches of basalt lavas suggests it is a fracture line. To the south, the margin of the Danakil horst against Afar appears to offset eastward, but this may be due to burial of the main fracture line beneath younger sediments. The offset fault line intercepts the NNE–SSW Dubbi volcanic alignment at the calderas of Nabro and Mallali.

Within the Danakil horst, numerous faults of Red Sea trend are visible and are identified with the extensional faults described by Brinckmann and Kürsten (1971). However, a major zone of deformation traverses the horst in a north–south direction, along longitude 41 1/4°E. The zone is not marked by any faults on the geological map of Brinckmann and Kürsten (1970), although offshoots to the southwest appear as transverse faults impinging on the horst margin. The nature of this deformation zone across the horst is uncertain, but may be a Precambrian structural zone that has been reactivated since deposition of the Mesozoic marine sediments. Moreover, its lack of imprint by the NW–SE extensional faults occurring to either side of it suggests that the reactivation occurred in the Paleogene and that it has been resistant to subsequent crustal movements.

The indisputable presence of transverse faults, both on the Danakil horst and on the Ethiopian plateau margins of northern Afar, raises two questions. What is their place in the pattern of regional strain release in Afar; and, are there any such faults continuing from the margins into the floor of Afar, that is, from continental to neovolcanic crust? The first question has been answered by Dainelli (1943), and in more detail by Mohr and Rogers (1966) and Mohr (1971a), in terms of the transverse structures of the Afar margins being subsidiary, and sometimes compressive, elements in the strain field of Afar, a field that is dominated by the least compressive stress. This stress direction is approximately NE–SW in the Afar region and, of course, has been responsible for the NW–SE tensional faulting.

Do transverse faults exist on the floor of Afar? This has been answered in the multiple negative by Tazieff and coworkers (e.g., Tazieff et al., 1972). While no transverse lineaments continuous across the width of northern Afar can be detected on the ERTS imagery, shorter lengths are observed: Examples of such NE–SW lineaments occur in the vicinity of the western end of the Gawa graben (eastern Afar), as faults controlling the form of Musli caldera in central Afar, and a nearly 100-km lineament runs N50°E from Dabbayra volcano to the Affara-dara granite in western Afar. Furthermore, some of the transverse lineaments of the Afar margins appear to extend into the Tertiary sediments fringing the Salt Plain, possibly indicating the initiation of transform directions (Vogt, 1973).

4.3 Sheet 3: 8 to 12°N, 35 to 43°E

This sheet covers the central part of the Ethiopian plateau, the northernmost part of the Somalian plateau inclusive of the Aisha horst, southern and central Afar, and the northern end of the main Ethiopian rift.

4.3.1 Precambrian terrain

Most of the terrain west of longitude 36 1/2°E exposes Precambrian basement. Precambrian rocks are also exposed in the extreme east, on the Somalian plateau (Gortani and Bianchi, 1937), but over such narrow and restricted areas that large-scale structures cannot be deduced from the ERTS imagery.

The Precambrian rocks exposed in Illubabor, the lower Abbay and Didessa valleys of Wollega and Gojjam, and west of the Tana graben are ascribed by Kazmin (1971) to the same "Upper Proterozoic" mobile belt as is exposed farther north in Tigray and Eritrea (Sheet 2). In fact, the structures of the Precambrian of west-central Ethiopia are only weakly expressed on the ERTS imagery. No belts of clinoria can be recognized, except for a small area west of Gore, and extensive lineaments of the regional NNE trend are few. Ground observations confirm that this NNE trend corresponds to the foliation and often to the lithological strike (Desio, 1940; Mohr, 1962; Quinn, 1963). Lineaments trending NNW are dominant in the Didessa valley and in the Mandi and Wombera districts. West of Lake Tana, the regional lineaments trend NE–SW.

The weak expression of the lineaments of west-central Ethiopia could arguably be related to a deeper lateritization and more dense vegetation cover than exists in

Tigray and Eritrea. But immediately south of the Abbay river, between longitudes 36° and 37 1/4°E, strongly expressed Precambrian lineaments form a reticulate pattern, with two trends of N–NNW and ENE, respectively. The pattern remains expressed through patches of Tertiary volcanics. No ground data are yet available from this region, but the pattern itself is reminiscent of the Precambrian of the Red Sea Hills and of the Eritrean region north of Asmara–Agordat (Sheet 2). Circular features immediately north of the Abbay river can be identified with granitic intrusions mapped by Jepsen and Athearn (1961). Both east of longitude 37 1/2°E and west of 36°E, more typical NNE-trending lineaments characterize the Precambrian, indicating that the intervening region is somewhat singular. In summary, it would seem that subdivision of the Precambrian of Ethiopia, made possible from ERTS imagery, may well change existing ideas and should receive coordinated ground-survey investigations into structural, lithological, and economic geological provenances.

4.3.2 Mesozoic sedimentary and Tertiary volcanic terrain

Discussion here concerns the interiors of the Ethiopian and Somalian plateaus; the plateau margins are the subject of the following section.

The southern part of the Tana graben dominates the northwest corner of the region covered by Sheet 3. The eastern, more weakly expressed margin of this asymmetric graben appears to peter out on crossing the Abbay river, southward into the Tala Mts. massif (see page 32). Faults of the transverse gräben east of Lake Tana (Mohr and Rogers, 1966) are also visible on the ERTS imagery.

The western margin of the southern sector of the Tana graben is of considerable structural interest, because of the remarkable and little understood transition from an east-facing escarpment, north of latitude 11°50'N, to a west-facing escarpment to the south of that line. At the latitude of Chelga (12 1/2°N), the east-facing escarpment is about 200 m high; and on both sides of the scarp fault lines, the Tertiary basalts dip gently westward (Mohr and Gouin, 1967). Farther south, the escarpment diminishes as a 10- to 12-km-wide zone of downwarping toward the graben is encountered, along the southwestern shores of Lake Tana. These features can be identified on the ERTS imagery, as can antithetic faults in the warped zone. The warped zone is traversed by an ENE-trending lineament at the southwestern corner of Lake Tana, along which a possible, small sinistral displacement may have occurred. This lineament crosses a broadly arcuate structure (see Sheet 3), likewise traversed by the zone of warping; and to the south the arc lineaments parallel the west-facing escarpment and are some 15 to 20 km west of it. This 15- to 20-km-wide zone seems to contain the warping; thus, the west-facing escarpment runs on the opposite side of the warped zone from the east-facing escarpment, farther north. In the south, the warping is directed inward to the foot of the escarpment. Until ground surveys are instigated, nothing can be stated as to the manner of crustal deformation at depth, but some additional observations are of interest.

First, the ERTS imagery shows that the west-facing escarpment lies on the same alignment as that of western Simien (see Sheet 2), suggesting a common origin due to regional westward uptilting. This uptilting would have preceded the formation of the present Tana graben. Second, Grabham and Black (1925) report that subhorizontal basalts of the west-facing escarpment can be equated with similarly disposed basalts on Mt. Belaya, some 60 km to the west. This equation belies the intervening zone of warped trachyte lavas and tuffs, raising obvious and unanswered questions.

The west-facing escarpment, recessed like the Simien escarpment from the original faults, terminates at latitude 11°N near the limit of extent of the Tertiary volcanic cover on the Precambrian basement. The escarpment is paralled to the west by the zone of faulting and dikes that passes NE–SW through the Belaya volcanic center (Jepsen and Athearn, 1961). The northern sector of the Belaya zone marks an approximate westerly limit to the sharp upwarping of the Tana graben shoulder, northwest of the lake.

The floor of the Tana graben, south of the lake, is rather featureless on the ERTS imagery except for patches of Quaternary basalts, whose relative ages are expressed in their albedo: The younger flows are darker. The young basalts of the Burie region, farther south on the northern rim of the Abbay canyon, surprisingly fail to show on the ERTS imagery (cf. Jepsen and Athearn, 1961). Some NE–ENE lineaments cross the Tana graben floor, south of the lake, and can be traced into plateau lineaments that extend as far as the Afar margin, to the east.

Between the Abbay river and the Afar escarpment, the Tertiary flood lavas of the Ethiopian plateau show a flat, depositional surface, which ERTS imagery reveals is preserved over 30 to 40% of this region; river drainage has excavated canyons in the remaining portion. This surface lies at 2400 to 2600 m, now tilted up eastward toward the Afar margin. It has been attributed to termination of a Tertiary, post-volcanic erosion cycle by Desio (1940) and Merla (1963); but in the absence of firm evidence for any angular discrepancy between the surface and the lava bedding, a depositional origin is preferred (Dainelli, 1943; Mohr, 1966a).

The central part of the Ethiopian plateau, covered by Sheet 3, shows numerous lineaments that are, however, rarely expressed strongly. This corresponds with the known lack of topographic displacement across most of them. Three main trends are discernable: NNW, NNE, and ENE. The NNE trend is parallel to the faulting of the Ethiopian rift, farther to the east, and is the predominant lineament direction south of about latitude 10 1/2°N. Faults of this trend turn off from the NNW-trending Afar margin in the Dessie region (Gouin and Mohr, 1964, Figure 4). Some NNE faults in the Mesozoic sedimentary rocks of the Abbay basin are not expressed in the overlying Tertiary flood basalts: This is suggestive of a very early phase of Ethiopian rift tectonism.

North of latitude 11°N, NNW-trending lineaments are common on the Ethiopian plateau. However, important lineaments of this trend occur farther south, most notably the faulting along the Guder valley, which has been associated with late-Tertiary warping and small extrusions of Quaternary basalts. Some of the ERTS lineaments may also mark the Guder dike swarm (Mohr, 1971a). The Guder lineaments are, perhaps coincidentally, on the alignment of the Tana graben eastern margin faulting: The intervening volcanic highlands of central Gojjam reveal no connecting lineaments. Immediately south of the Ambo fault (see page 33), the Guder lineaments pass via the young volcanic shields of Wonchi and Boti (Smeds, 1964), to die out some 40 km farther on near ENE–NE lineaments. Both Mts. Wonchi and Boti are crowned by calderas within which maars have been formed: Two maars in the Boti caldera are aligned NW–SE, oblique to the Guder lineaments. Some 175 km west of the Guder valley, NNW lineaments run along the Didessa valley and are again associated with patches of Quaternary basalt.

Lineaments that trend ENE are weakly but persistently developed over the whole central Ethiopian plateau region, and some extend into the Afar margins in the east. Faulting of this trend forms the north-upthrown Ambo faults, west of Addis Ababa. The uniqueness of this important faulting within the plateau prompts the idea that it represents the northern boundary of an aulacogen (Burke and Whiteman, 1973), but the relatively small angle with the main Ethiopian rift faulting is not conducive to this hypothesis. Nevertheless, as noted by Baker et al. (1972), the structural style of deformation of the plateau rocks changes on crossing the Ambo faults: South of the faults, the flood basalts are tilted and roughly peneplaned, and there are no planar, depositional surfaces of the type characteristic of the Abbay basin region.

In the southeastern corner of Sheet 3, the interior of the Somalian plateau is revealed to be largely featureless, as far as lineaments are concerned. The difference from the Ethiopian plateau is very noticeable in this respect. Only in the extreme east are significant lineaments encountered: These trend NW–SE and the strongest of them marks the Marda volcano-tectonic line (Gouin and Mohr, 1964; Shachnai, 1973). The Marda line is considered by Gouin and Mohr to be a late-Mesozoic and Tertiary line of west-upthrown faulting and related basaltic volcanism, but Shachnai considers that the line is the erosional expression of a massive, tilted sill of basalt. The linearity of the trace on the ERTS imagery indicates that tear faulting may have had some role in the formation of the Marda line. The Marda and associated NW-trending lineaments fail to intersect the Afar margin structure, but a young volcanic field on the floor of Afar, immediately below the plateau escarpment, lies on a NW projection of the Marda line (Mohr, 1967b).

4.3.3 The rift and Afar margins

The Afar–plateau structural margins, as expressed on the ERTS imagery, have been discussed elsewhere (Mohr, 1974). In summary, for the region covered by Sheet 3, the Ethiopian plateau–Afar margin trends NNW in the north and NNE in the south and continues farther south with the same NNE trend as does part of the main Ethiopian rift. The Somalian plateau–Afar margin curves in a wide sweep from northeast in the south (where it leaves the Ethiopian rift) to east–west in the east. Some of the more interesting details bear emphasis, in view of the continuing debate over the nature of Afar (Tazieff, 1973; Mohr, 1972a).

The typical structure of the Afar margin is that of an antithetically faulted monoclinal warp, with a marginal graben intervening between the warp and the undeformed plateau to the west. As far as the southerly limit of the NNW-trending faults, on the region covered by Sheet 3, this kind of structure holds, with forceful development of the Menebay–Hayk and Borkenna marginal gräben. The eastern boundary faults of the Menebay–Hayk graben show small offsets, possibly compatible with longitudinal dextral shear. Transverse, ENE-trending lineaments intersect the NNW-trending Afar margin between latitudes 11 and 12°N, and ground-based surveys show that at least some of these are faults (Mohr and Rogers, 1966). Two SSW-trending belts of lineaments turn off from the Afar margin in this sector, at Waldia and Dessie, and thus presage the change farther south to a regional NNE–SSW trend for the Afar margin itself.

The Ethiopian plateau–Afar margin assumes a NNE–SSW trend south of latitude 10°N. The change from the NNW-trend, north of this latitude, is made rather abruptly through a complex structural zone dominated by curvilinear faults in a strong downwarp (Gouin and Mohr, 1964). The southernmost, NNE-trending sector of the margin is singular in lacking any marginal graben development, and synthetic faulting gradually dominates over antithetic faulting southward. The faulting is arranged en echelon such that the faults nearest Afar traverse the floor of the main Ethiopian rift and, continuing SSW, enter the eastern marginal structures of the rift. Upthrows are to the east and are of the order of only a few tens of meters. Two of these traversing fault zones are utilized by the active, Holocene Wonji fault belt (Mohr, 1960, 1967b; Gibson, 1969); one passes through the Boseti volcanoes and the other, some 25 km to the west, through Gadamsa caldera (Thrall, 1974). Thus, as is well known from ground surveys, the Wonji fault belt is offset en echelon, but the ERTS imagery reveals that the en echelon segments are reactivated sectors of older fault lines that are continuous across the rift.

The Addis Ababa structural embayment (Mohr, 1967b) results from a 60-km right-offset in the major throw on synthetic faults of the margin of the Ethiopian plateau, coupled with the presence of a gentle downwarp toward the rift. No transverse lineaments are observed on the ERTS imagery to be limiting the northeast and southwest margins of this embayment (cf. Mohr, 1967b). The imagery confirms the embayment to be transected by 20- to 25-km-separated lines of NE–NNE synthetic faulting (Mohr, 1973b). South of the embayment, the rift margin faulting is taken up again along the Guraghe escarpment, a major synthetic fault against the upwarped shoulder of the rift. This fault is faced, on the rift floor, by antithetic faulting, resulting in a marginal graben (Gouin and Mohr, 1967), which can be identified on the imagery. Prolongation from the Guraghe faulting northeastward across the Addis Ababa embayment passes via Zuquala volcano and the Bishoftu explosion craters (Mohr, 1961, 1967c), but no connecting lineament is clear on the ERTS imagery.

The youngest faulting of the floor of the rift, comprising the Wonji fault belt, has a right en echelon pattern (Gibson, 1969). The ERTS imagery emphasizes this for the Boseti–Gariboldi–Fantali–Ayelu fault zones, but it must be noted that apparent left en echelon displacements occur to form the Asella–Gadamsa–Koka fault zones. Thus, the attribution of these en echelon fault patterns to longitudinal rift shear becomes difficult to sustain. Furthermore, Gibson's identification of sigmoidal faults as a pattern characteristic of the Ethiopian rift floor, in the sector where it funnels out into southern Afar, is complicated here by the identification of linear, NNE-trending faults traversing the floor of the rift (see page 34).

The southern margin of Afar, against the Somalian plateau, forms a narrower zone of structural deformation than does the western margin (Mohr, 1967b). Sheet 3 shows the essential fault lineaments, previously mapped from aerial photography and ground traverses and from preliminary ERTS studies (Mohr, 1967b, 1974). Where the Ethiopian rift funnels out, the southern margin of Afar is initially formed by a very narrow zone of large, stepped faults, commencing at a dextral offset near latitude 8°N (Mohr, 1960, 1973a). A second such offset occurs at Mt. Gugu (latitude 8 1/2°N), where adjustment is made through curvilinear faults, which are themselves subject to small dextral offsets. The margin faults trend NE–SW; and to the northeast, the margin widens, and antithetic faulting of downwarped flood lavas indicates a similar structural style to the western margin of Afar. However, no marginal gräben are developed. There is a tendency for faults to turn off to the NNE from the margin at rough spacings of about 25 km. The NE–SW faulting of the margin persists eastward to longitude 41°E, near Afdem, and is backed to the south by a strongly lineated zone: The nature of these lineations is not yet known, but may be a strike feature of downwarped Tertiary lavas.

An abrupt break in the structural trend of the southern margin of Afar occurs near longitude 41°E, east of where an ENE–WSW trend is taken up. This change of orientation cannot be related to any intersection by extraneous lineaments, although those with megavision might be inspired to note that projecting the NNW–SSE Ethiopian plateau–Afar margin from Dessie southward across Afar would make an intercept near the southern margin break.

In the Dire Dawa–Harar region (longitude 42°E), detailed ground surveys have been made by Greitzer (1970), Black et al. (1972b), and Shachnai (1973). Both the main structural lines and the lithological boundaries of the various Cainozoic lava formations can be confirmed from the ERTS imagery, and a more precise revision is possible. Black et al. worked out a lithological-tectonic succession, which, though locally variable, can be generalized as follows:

3. E–ESE faulting, affecting formations B3 and B4.

2. NNW–NNE faulting, mostly upthrown east, and affecting formations R1, R2, and B2.

1. E–ENE faulting, upthrown north, and affecting formations B(asalt)1 and R(hyolite)1.

Fault episodes 2 and 3 are clearly shown on the ERTS imagery, but 1 either is too weak or has been overprinted by the near-parallelism of 3. The importance of NE–NNE lineaments separating structural subprovinces on the Aisha horst, in the southeastern corner of Afar, is confirmed on the ERTS imagery, although no transcurrent displacements have yet been identified along them (Roberts and Whitmarsh, 1969; Black et al., 1972b).

Synthetic faulting of southward-tilted blocks characterizes the southern margin of Afar in the Dire Dawa region, but some antithetic faulting and minor gräben are present in some sectors (Teilhard de Chardin, 1930; Mohr, 1971a; Canuti et al., 1972). As noted above, the important Marda lineament of the Somalian plateau impinges on the Afar margin near longitude 42 1/2°E. Here the floor of Afar is covered with young basalt fields (B3 and B4), and aligned cinder cones are associated with east–west faults. Even more significant, there is a sharp reduction in the magnitude of the margin structures, east of the impingement with the Marda line. This is where the Aisha horst abuts the Somalian plateau, and the weakness of the structures separating these two blocks points strongly to their long-standing unity, contrary to the plate-tectonic scheme of Mohr (1972a). The ERTS data therefore not only constrain plate-tectonic interpretations, but show the continuing influence of the Marda line on Neogene tectonism of the southern margin of Afar, despite the apparently extinct tectonism of the line itself. The Marda line lies on a southeastward projection of the eastern limit of the sialic blocks of the western Afar margin, suggesting it was active during the late Eocene–early Oligocene (Girdler and Styles, 1974).

4.3.4 Southern Afar

The NW–SE trending fault belts of northern Afar (Sheet 2) continue south of latitude 12°N into central Afar (Mohr, 1967b). They extend southeast to the Lake Abbe–Gulf of Tajura region, with magnificently clear expression on the ERTS imagery, but are abruptly curtailed south of latitude 11°N. This curtailment seems to be related to the terminus of behind-block extension from the counterclockwise rotation of the Danakil horst, and a limit is also provided by the transcurrent faults of the Aisha horst. This conforms with the requirements of plate tectonics (Mohr, 1972a).

South of latitude 11°N and west of longitude 41 1/2°E, the structures of the Afar floor are completely dominated by the prolongation of NNE–NE main Ethiopian rift faulting (Taieb et al., 1972; Mohr, 1972a). The Wonji fault belt is identified as following the eastern bank of the Awash river as far north as Ayelu volcano (latitude 10°N), then being right offset to Amoissa caldera and the Issa graben, and continuing via Yangudi volcano to Gabillema volcano (Mohr, 1967b). Additionally, however, a second belt of east-upthrown faults runs parallel to the Wonji fault belt, at a distance about 25 km east of the Issa graben. The intervening region is here marked by young lava centers. This second fault belt runs for some 200-km length, southwestward from the west side of Lake Abbe to virtually the southern margin of Afar, and its eastern margin is marked by a zone of older, ratchet faulting and block tilting.

Both east and west of the Wonji and eastern fault belts, the floor of Afar is masked by sediments through which few lineaments are expressed. Transverse lineaments are decidely rare on the ERTS imagery (cf. Mohr, 1967b).

4.4 Sheet 4: 4 to 8°N, 33 to 41°E

This sheet covers the southern part of the Ethiopian plateau inclusive of the Omo basin, the main Ethiopian rift, and the western sector of the Somalian plateau and Ogaden.

4.4.1 Precambrian terrain

Precambrian rocks are exposed over extensive areas in the western and south-central parts of the region. In the west, the exposures form a narrow, NNW-aligned belt between Tertiary volcanic cover to the east and the alluvial sediments of the Akobo valley to the west. The ERTS imagery picks out curvilinear features of meridional trend, on which, at some localities, manifestly younger faulting has been superimposed. Ground control for this region is virtually nonexistent.

The southern margin of the Ethiopian swell exposes Precambrian rocks in a continuous tract extending to both sides of the Ethiopian rift valley. In the west, the Bako and Amar highlands show Precambrian rocks at elevations of up to 2750 m (J. M. Moore, private communication, 1973). On the rift floor, southwest of Lake Chamo, and also on the Amaro horst, Precambrian outcrops are extensive (Kazmin, 1971, 1972; Levitte et al., 1974). But the greatest area of such rocks occurs on the Somalian plateau, south of the Batu Mts. and between longitudes 38 and 40°E. Here, the Precambrian rocks are exposed in the Dawa Parma drainage system, west of a thick cover of Mesozoic marine sedimentary strata and east of a discontinuous strip of Tertiary volcanic rocks.

The ERTS imagery shows that faulting partly controls the overlap of the Mesozoic rocks onto the Precambrian of the Dawa basin. The main Precambrian lineaments run within 10° of north–south and are crossed by a subsidiary ENE group of lineaments that are expressed in the Mesozoic terrain. The detailed ground mapping of Chater and Gilboy (1970) shows a major fault separating different lithological types, roughly along meridian 39°E, and this can be seen on the imagery. Some of the mapped lithological units can also be discerned, especially granite gneiss, but the three major groups into which Chater and Gilboy divide the Precambrian of this region (see also

Kazmin, 1973) cannot be identified. Neither can the "important structure" of the Burjiji fold slide, some 15 km west of meridian 39°E, be regarded as having important emphasis on the imagery. The most powerful structure of this region, situated at the eastern margin of the area mapped by Chater and Gilboy but not apparently recognized by them, runs N05 to 10°E for nearly 150 km along meridian 39°17'E. In the north, it passes for a short distance into the Tertiary volcanic terrain of the Batu Mts.; in the south, it is buried under a thin cover of Quaternary lacustrine sediments. Kazmin (1973) indicates the fault as separating two types of Archaean gneiss, and Rogers et al. (1965) noted that there is a boundary at this longitude in Sidamo that separates younger, less metamorphosed rocks to the west from the more metamorphosed rocks to the east. Kazmin's map also shows a subordinate set of NW-trending fractures that cannot be picked out on the ERTS imagery; rather, there are lineaments of an ENE trend.

Lineaments are relatively few in the higher Precambrian terrain to the west and east of the Shakisso–Arero area, perhaps because of a thicker laterite and vegetation cover, although the cause may be geological according to the map of Kazmin (1973). South of the area, lineaments are very few in the Quaternary sedimentary cover, with the notable exception of a curvilinear one extending from west of Arero to west of Moyale. Precambrian rocks are again exposed on the WNW-trending Moyale ridge, upfaulted during the Cainozoic. The dominant lineaments are of meridional trend, and there could be a match with the Shakisso–Arero faulting, although this has yet to be proved (see page 39).

The accuracy of the geological mapping of Dodson and Matheson (1969) and of Walsh (1972) for the Kenya–Ethiopia border region and southward is strikingly confirmed by the ERTS imagery. Both Precambrian inselbergs and Tertiary lava patches can be easily discerned on the ERTS images of this semidesert terrain. However, faults and lineaments on the imagery are generally additional to those mapped on the ground.

4.4.2 Mesozoic–Cainozoic terrain of the plateaus

Except for a thin, undated sandstone beneath the Tertiary lavas of Sidamo and Gamu-Gofa, there are no rocks of Mesozoic age exposed on the Ethiopian plateau south of latitude 8°N. Tertiary lavas, often exceeding 1000-m thickness, cap most of the plateau and their succession has been exposed by the Omo river drainage system.

Ground-based surveys of the Omo basin are now in progress (Moore, private communication, 1973). For the region west of Lake Rudolf, published geological maps are available (e.g., Walsh and Dodson, 1969), while interpretation of ERTS images for the eastern hinterland of Lake Rudolf has been made by Johnson (1973).

The course of the Omo river, above the Gojeb confluence, is largely structurally controlled (Mohr, 1967b), and the ERTS imagery shows the presence of curvilinear fractures, convex to the east. Nevertheless, the imagery fails to show a concentrated zone of deformation along this narrow and deep valley: Erosional scarps can be identified on either side of the upper Omo. ENE lineaments are visible along the Gojeb valley, and some represent south-upthrown faults of this trend, observed on the ground (Mohr and Gouin, 1967).

Very few lineaments can be identified on the plateau watershed region between Gore and Maji (meridian 35 1/2°E, between latitudes 6 and 8°E), perhaps in part due to afforestation. Horst-producing faults, east of Maji, are part of a gently curving zone of lineaments that pass from the Kibish valley in the south to Bonga in the north. Farther west, NW–NNW lineaments follow the trend of the Akobo valley: Powerful lineaments of NNW trend also extend from the Stefanie graben, and along the Guder valley, and may represent terminal, en echelon Red Sea tectonism within the Nubian plate.

In the Bako–Bulki region, between the lower Omo valley and the Ganjuli graben sector of the main Ethiopian rift, some of the known large faults, bounding NE–SW horst and gräben (Schottenloher, 1938; Merla, 1963), show up well on the imagery, though others, not necessarily of opposite throw and illumination, are difficult to discern. The lineaments of this area form a pattern slightly convex to the west, as on the west side of the Omo, near Maji. Indeed, there is a regional pattern of west-convex lineaments across the Ethiopian plateau, at latitude 6 to 6 1/2°N, arranged fanlike, with projected focus at the north end of Lake Rudolf.

The extensive deformation of the Ethiopian plateau has been emphasized previously (Mohr, 1962, 1967b): It is certainly not a case of a mobile rift zone confined between rigid, undeformed plateau blocks. Thus, the wide zone of horst-graben development in the Bako–Bulki area is witness to major crustal extension acting outside the rift valley.

South of Bako, the horst-graben trend is replaced, in largely Precambrian terrain, by a reticulate network of lineaments reminiscent of some central Abbay and Red Sea Hills areas (see pages 22 and 30). The NE–ENE set of lineaments may be related to the horst-graben faulting farther north: A prominent NW-upthrown fault extends from Mt. Nkalabong west across the Kibish valley. The perpendicular, NNW-trending set of lineaments can be identified, west of the Kibish valley, as west-upthrown faults along which relatively young basalts have been extruded. These faults can be traced northward into the Akobo valley. On the eastern margin of the area of meshed lineaments, directly north of Lake Stefanie, a NNW-trending graben, about 15 km wide, runs for some 60-km length to east of Bako. This (Dulei) graben contains a previously unreported(?) small lake at 5°25'N, 36°57'E. A 4.9-magnitude earthquake with the epicenter at 5.3°N, 36.8°E on January 7, 1973, was probably related to further development of this graben. To the south, the western margin faulting of the graben turns to a SSW trend and continues to Lake Stefanie, but the eastern margin faulting dies out near the small lake.

The southern fringe of the Ethiopian plateau is reached at the Kangen valley–Lotagipi swamp line. Between the Lotagipi swamp and the northern sector of Lake Rudolf, the geological mapping of Walsh and Dodson (1969) can in many instances be confirmed from the ERTS imagery, as regards both lithological boundaries and Cainozoic faulting. The imagery shows that the dominant fault trend is N–NNW, with upthrows to the west, but that there is NE–SW faulting, upthrown to the northwest in places, with adjusting faults connecting the two trends. West of the Lotagipi swamp, strong lineaments, some of which are undoubtedly young faults, are situated on the brief prolongation of the Uganda Escarpment (Baker et al., 1972) northward into Sudan.

Turning to the Mesozoic–Cainozoic terrain on the Somalian plateau, east of the Ethiopian rift, it is immediately evident that lineaments are conspicuous by their absence over large tracts in the east. The surface rocks there are essentially Upper Jurassic limestones, part of a Mesozoic sedimentary succession that thickens and dips gently to the east. Postdepositional tectonism has obviously been negligible, although the low rigidity of the sandstones, etc., compared with, say, Tertiary flood basalts, inhibits the expression and preservation of new or rejuvenated basement structures.

In the northern part of the region covered by Sheet 4, the Mesozoic sediments are capped by Tertiary flood basalts derived from the Sagatú Mts. farther west. The planar, high plateau surface formed by these basalts has been deeply incised by the Webi Shebeli drainage system (Savoja, 1932), and Precambrian rocks are exposed in the canyon bottom, east of longitude 40°30'E. The Sagatú Mts. form a NNE-trending ridge that shows up clearly on the ERTS imagery: The ridge is a 70-km-length linear feature running parallel to and about 40 km east of the main Ethiopian rift. Ground surveys show that the linear axis of the ridge is formed by dike swarms and aligned plugs. The dikes were intruded into a monoclinally warped zone bordering the proto-rift trough on its eastern margin (Mohr and Potter, 1973; Potter, in preparation). Deep valleys on Mt. Badda, at the northern and highest end of the ridge, can be seen on the imagery and on the ground as Pleistocene glaciated features.

Midway between the Sagatú ridge and the faulted rift margin lie the Pliocene trachyte centers of Chilalo, Kakka, and the Baltata caldera (this last recognized as such for the first time from the ERTS imagery). These three volcanoes, suppliers of a blanket of ignimbrites and lavas before the main faulting episode of the rift valley, are situated opposite the termini of the Sagatú ridge (Mohr, 1966b, 1968a), but no linking, transverse lineaments can be detected on the ERTS imagery. Weak ENE-trending lineaments occur on the trachyte shield of Mt. Kakka, but ground reconnaissances were unable to link these with any structural phenomenon.

South of the upper Webi Shebeli basin lies the Batu Mts. volcanic massif, the second highest (after Simien) on the Ethiopian swell. The ERTS imagery of this geologically unexplored region reveals that the Batu Mts. are the moderately denuded remnants of a Pliocene(?) caldera and its flanking flows. A larger (15-km-diameter) and older caldera, the Cawa caldera, occurs some 25 km northwest of Batu; it is situated on and elongated along a N20°E lineament at a possible intersection with a vague NW-trending lineament. The Batu Mts. and the extensive volcanic highlands to the southwest are traversed by numerous, prominent N65°E lineaments. Mapping of Upper Miocene dike swarms in the Batu Mts. (Mohr, 1971a; Megrue et al., 1972) has revealed three irruptive trends: a dominant one of N60°E (late Miocene basalts), subsequent N20°E basalt dikes, and final (Pliocene?) N65°W trachyte dikes. The ENE-trending lineaments are therefore presumably associated with dikes and observed young faulting (Mohr, 1971a), while the two intersecting trends at the Cawa caldera can be identified with the other two dike trends in the Batu Mts. Here, we have a good correlation between ground-based and ERTS-imaged data. However, the Quaternary basalts of the Dumal valley, south of Goba and newly indicated on the map of Kazmin (1973), cannot be identified on the ERTS imagery with certainty.

South of the Batu Mts., the Somalian plateau exposes Precambrian terrain, discussed above. The southern fringe of the plateau against the northern Kenya plains can conveniently be taken as limited by the Cainozoic faulting of the Mega–Moyali region. This faulting occurs in a zone some 20 km wide and trends NW–SE in the form of a horst; Mega is situated near the northeastern bounding fault of this horst, the geology of which has been reconnoitered by Mohr (1960). Young spatter cones of alkali basalt (with ultramafic nodules) are situated where short NNE-trending faults, identified from the ERTS imagery, intercept the horst faulting. The El Sod explosion crater (Mohr, 1960, 1961) lies on a north-northeastward projection of such faulting, 15 km northeast of Mega. These NNE-trending faults are upthrown east, in the same sense as the faults of the Kinu Sogo belt, east of Lake Rudolf (Baker et al., 1972; see page 45). The Mega–Moyali horst is bordered to the south by a NW–SE line of Precambrian granitic inselbergs (Dodson and Matheson, 1969), the parallelism of which can hardly be coincidental.

The Mega–Moyali horst dies out a little to the west of longitude 38°E (although it could be projected across the rift zone into the NW–SE lineaments of the Bako area on the Ethiopian plateau). A narrow belt of N–NNW faulting occurs west of the horst, close to longitude 37 1/2°E, and is superimposed with freshly preserved basaltic spatter cones. Although the NNW trend of the faulting is parallel, for example, to the eastern margin of the Stefanie graben, to the west, and to Precambrian lineaments in the Bur Oli region of the Mega–Moyali horst, the superimposed spatter cones show a tendency to be aligned NNE: This is the trend of the main rift faulting and suggests that magmatism is subject to a deeper control than represented by surficial tectonic features in some areas.

4.4.3 Main Ethiopian rift

The geology of the northern sector of the main Ethiopian rift has been mapped by Di Paola (1973) and, in part, by Mohr (1966b); the southern sector has been mapped by D. Levitte (unpublished data; Levitte et al., 1974). The overall structure of the main Ethiopian rift has been briefly described by Mohr (1960, 1967b) and Baker et al. (1972).

The ERTS imagery confirms to a large degree the mapping of the rift faults by Di Paola (1973) and corrects for distortion in the base maps used by that author. The limited resolution of the imagery means that the finer faulting of the rift valley, in particular that of the Wonji fault belt, cannot be identified in the detail possible from aerial photography. Nevertheless, the ERTS imagery picks out the major structures and presents a unified regional pattern not easily detected from ground-based surveys.

The imagery confirms the southward, gentle funneling of the rift, from a width of over 90 km at latitude 8°N to 60 km at latitude 6 1/2°N. The drainage pattern on the rift shoulders reflects the upwarping of these shoulders, probably at the time of faulting of the rift margins in the early Quaternary. Although stepped faulting of the margins is the rule, inward tilting and antithetic faulting occur at limited localities on both the eastern and the western sides of the rift. The reason for this local change in tectonic style is not known (Black et al., 1972b), but may be related to subsurface magnetic buoyancy in the case of antithetic fault style.

Although an axial line of young faulting is present in the main Ethiopian rift, at least north of latitude 7°N, the recent volcano-tectonic activity of the rift floor has been concentrated near the margins in the northern sector of the rift (Searle and Gouin, 1972). On the evidence provided by the ERTS imagery, en echelon development of the active Wonji fault belt is distinctly rare by comparison with the rift–Afar transition area (see Sheet 3): Only at the latitude of Shala caldera and, possibly, the old Awassa caldera, are there any such offsets (cf. Di Paola, 1973, who considers en echelon structures to be an essential feature of this sector of the rift). That the Wonji fault belt is able to be translated, proceeding southward, from the eastern to the western side of the rift floor, is at least in part due to the gently west-convex plan of the rift margin "envelope." A gently curvilinear plan appears to be a characteristic feature of almost all the African rift valleys.

Close to latitude 7 1/2°N, volcanic centers often with calderas are more common than in the north or south: Baltata occurs on the Somalian plateau, Shala in the rift, and Bobija (Mohr, 1960) and nearby smaller craters on the Ethiopian plateau. A possible, connecting transverse structural element was postulated by Mohr (1967b) to relate all these centers. This thesis is discounted by Di Paola (1973), although he admits the presence of transverse faults on the Ethiopian plateau side of the rift, visible on the ERTS imagery.

Lineaments are profusely developed in the Lake Margherita basin, with a dominating rift trend of NNE–N. North of the lake, this trend is obliquely traversed by NNW faulting lying, perhaps fortuitously, on a projection south from the Guder lineaments of the Ethiopian plateau. ERTS imagery of the Amaro horst, directly south of Lake Margherita, confirms the major faults mapped by Levitte et al. (1974): The powerful, curvilinear fault forming the singular western bound to the horst is seen to extend for nearly 100 km, while the eastern boundary faults curve to a southeasterly direction and may connect with a strong lineament extending via the El Sod maar (see page 43). The eastern margin of the rift, formed by the offset and antithetically faulted margin of the Galana graben, is well revealed on the imagery, but not the western margin, perhaps owing to the lack of illumination contrast in the densely forested area of the Ganjuli graben.

How does the main Ethiopian rift connect, if at all, with the northern end of the Gregory (Kenyan) rift? This is a question that ERTS imagery can help to answer, as the region concerned is barely explored. The imagery shows that the major faulting of the Ganjuli and Galana gräben, and the intervening Amaro horst, fail to pass south of the Sagan valley, at about latitude 5° N. Considering that crustal extension at latitude 6° N has been taken up not only in the rift structures of the Margherita basin, but also in the horst-graben faulting of the Bulki region farther west (see page 40), one expects, at least on the tenets of plate tectonics, to find equally powerful normal faulting south of latitude 5° N. Indeed, we do find thus situated the Stefanie and lower Omo graben or basin.

No en echelon offset from the main Ethiopian rift, through the Stefanie graben to the Lake Rudolf basin, is evident from the ERTS imagery (cf. Mohr, 1962b; Baker et al., 1972). The tectonics of the Stefanie graben are rather complex: The eastern boundary fault trends N–NNW, is upthrown and upwarped on the eastern side, and seems to have connecting faults with the powerful Kinu Sogo fault belt (also with easterly upthrows) to the south. The Kinu Sogo belt is the northernmost expression of the recent development of the Gregory rift, and thus the manner of connection, at least for

Quaternary tectonism, is indicated. The western margin of the Stefanie graben has a sawtooth plan: The rectilinear pattern of lineaments in the Precambrian terrain of the Bako area, immediately to the north, is almost exactly paralleled in the western margin faulting of the Stefanie graben, suggesting control of Cainozoic faulting by basement structural trends. The two sawtooth fault trends, NNW and ENE, both with westerly upthrows, are superimposed by some strong NNE-trending faults that make connection north with the Dulei graben. To the south these faults die out toward the NNW–SSE Derati-Shin fault forming the eastern margin of the Rudolf basin (Johnson, 1973).

In terms of the Quaternary fault pattern, therefore, the Gregory rift could be considered as continuing north via the Kinu Sogo fault belt to the Stefanie graben, and thence via the obliquely trending Dulei graben to the Bako-Bulki horst graben and even possibly up the middle Omo valley – this thesis was proposed by Mohr (1962). The main Ethiopian rift dies out at latitude 5°N, unless the Ririba fault belt at 4 to 4 1/2°N is regarded as a continuation. The writer therefore considers that there is a transposition of the zone of crustal extension, near latitude 6°N, although the term en echelon should be withheld in view of the complexities involved in the transposition. It would be useful to determine focal-plane solutions for earthquakes in all this region, to see whether transcurrent movement has a relatively more important role on faults oblique to the main rift trend (e.g., the Dulei graben), according to the plate-tectonic theory of behavior of rigid crustal blocks.

4.5 Sheet 5: 8 to 12°N, 43 to 51°E

This sheet covers the northern sector of the Somalian plateau and the coastal borders of the Gulf of Aden and Indian Ocean. In the south, it touches on the Ethiopian Ogaden, a flat, semidesert region floored with late Mesozoic–early Tertiary marine sediments. A summary geological synopsis for the northern part of this sheet has been given by Beydoun (1970).

4.5.1 Precambrian terrain

The only exposures of Precambrian rocks for this sheet form a generally narrow and discontinuous zone between the Gulf of Aden coast and the plateau escarpment.

Ground mapping has shown the presence of two contrasted suites of rocks: a more metamorphosed and presumed older suite, and greenschist-facies sedimentary rocks of presumed end Precambrian–early Paleozoic age. The latter suite outcrops between longitudes 47°15'E and 49°05'E, and at the former locality, the contact with the more metamorphosed suite can be observed, the nature of which remains disputed (Gellatly, 1960; Greenwood, 1961).

The ERTS imagery reveals lineaments only in the more metamorphosed suite, perhaps simply because of the greater degree of foliation. Thus south of Mait, at the boundary at 47°15'E, a NE–NNE lineation is developed in the more metamorphosed rocks to the west; but in the "younger," Inda Ad Series rocks to the east, lineaments of the same trend are barely discernible. The boundary between the two suites here, as mapped on the ground, is matched on the ERTS imagery by a tonal contrast (the greenschists are darker), but this contrast is not preserved away from the Mait region and so a geological significance for it is not yet established.

A large area of more metamorphosed and extensively intruded Precambrian rocks occurs in the Hargeisa area, at the western end of the Gulf of Aden coastal plain and east of the Aisha horst. The geology of the area has been described by Daniels et al. (1965), and the structural trends observed can be confirmed on the ERTS imagery, more especially west of longitude 44 1/2°E, where lineaments appear more strongly expressed. The lineaments are curvilinear with a tendency to parallelism to the NW–WNW trending Zeila coastline and Borama escarpment of the plateau. Of the intrusions mapped by Daniels et al. (1965), the more mafic, gabbroic ones stand out more clearly on the imagery, owing to tonal contrast and perhaps a more sparse vegetation. The boundaries of the gabbroic bodies can now be mapped precisely, by use of the ERTS imagery, but there are instances where Pliocene–Quaternary basalt fields in the Bulhar area are not easy to distinguish from the Precambrian gabbros.

In the vicinity of longitude 46°N, Precambrian lineaments trending between NNW and NE at the foot of the plateau escarpment are difficult to discern in dark imagery tones.

4.5.2 Mesozoic–Cainozoic terrain

Most of the Sheet 5 region is covered with thick Jurassic–Eocene marine limestones, gypsum-anhydrite, and sandstones. Structural deformation of these sedimentary rocks has been strongest along the fringes of the Gulf of Aden where even deep Precambrian basement is brought to the surface in the coastal plain. Thus, ERTS lineaments can be expected to be more numerous in the coastal plain sediments than in the subhorizontal, undeformed strata of the plateau, and this is, indeed, the case. Furthermore, the strong plateau uplift along the coastal fault zone and the ensuing erosional recession of the fault scarps have led to massive cliff exposures of the plateau succession. Lithological boundaries within these exposures are clearly revealed on some ERTS images (e.g., 1330-06394-5, in the Mait area; 1349-06454-7, in the Bihendula-Berbera area), in some instances because of morphological emphasis. On top of the plateau, the boundary between Lower Eocene limestone and gypsum formations is revealed in the differing patterns of impressed drainage, being more dendritic on the limestone (e.g., 1330-06401-5, in the Erigavo district). In all these instances, precise geological mapping should be possible from the ERTS images, though unfortunately, because of differences in illumination, albedo, or vegetation/soil cover, the lithological boundaries can be clear in one place but obscure in another (see Rowan et al., 1970).

The post-Precambrian structure of the northern Somali region is dominated by northward upwarping of the plateau toward the north-facing escarpment that overlooks a downwarped and faulted coastal zone, bordering the Gulf of Aden. The plateau escarpment is well developed between longitudes 44 and 46 1/2°E, close to parallel 10°N, and between longitudes 47 and 49°E, close to parallel 11°N. The intervening region is traversed by strong faulting of NW–WNW trend, dominantly upthrown northeast, that forms the Asseh graben. The faulting of this complex graben can now be accurately mapped in its entirety. East of longitude 49°E, the development of a near-coastal escarpment is again inhibited by a further zone of strong WNW-trending faults that extends east to the Indian Ocean coast, at longitude 51°E. The faulting is considered by Beydoun (1970) largely to predate the presumed opening of the Gulf of Aden, which new data push back to Upper Eocene (Girdler and Styles, 1974) rather than the once popular Middle Miocene. But the sharpness and lack of recession of most of the scarps indicates a Pliocene–Quaternary age, although, of course, rejuvenation of old fault lines is possible.

The ERTS imagery enables the existing fault maps of northeastern Somali (Somaliland Oil Exploration Co., 1954; Azzaroli, 1968; Beydoun, 1970) to be corrected and supplemented. This is notably so for a 40-km-wide belt of intense WNW-trending horst-graben faulting, southwest of Alula and Cape Guardafui. This extensional faulting may be some of the youngest such faulting in northern Somali and demonstrates that despite the occurrence of sea-floor spreading from the axis of the Gulf of Aden, a modicum of extension is still being taken up at the margin of the continent.

The faulting southwest of Alula becomes aligned, on a predrift fit of Arabia and Africa (Beydoun, 1970) with faulting of similar trend near Ras Fartak, on the southern coast of Arabia. In both instances, however, the currently expressed fault scarps are younger than the initiation of the Gulf of Aden; if the alignment is significant, it indicates the presence of older, controlling structures. The faulting southwest of Alula impinges in the east on NNE faulting that parallels the Indian Ocean coastline. This coastal faulting is not seen south of latitude 11°N. It can be noted that, in the past, the faulting of northern Somali has been classified according to near-parallelism with one of the three megastructures meeting at the Afar triple junction: thus NW–SE faults have been ascribed a "Red Sea" trend, ENE–WNW faults, a "Gulf of Aden" trend, and NNE–SSW faults, an "African rift" trend. Such ascriptions now appear misleading; thus the WNW-trending Asseh graben and the Alula faulting parallel the obliquely oriented spreading axes in the Gulf of Aden (Laughton et al., 1970) and have no evident relationship with the Red Sea.

In the interior of the eastern part of the plateau, two major WNW-trending morphological features have an evident degree of tectonic control, according to the ERTS imagery: These are the Darror and Nogal valleys, which debouche on the Indian Ocean coast. Both valleys appear to be gräben, with more strongly faulted margins preserved on their northern sides. The incursion of Oligocene marine sedimentation into the Darror graben indicates an early Tertiary initiation of this valley, confirmed for the Nogal valley, too, by the extensive erosional recession from not yet precisely located, old margin faults. Thus, these two gräben could have begun to form with commencement of Gulf of Aden spreading.

Returning to the western part of Sheet 5, WNW-trending Cainozoic faulting is again prominent in the Borama–Aubarri area and could be considered as a projection of faulting of the same trend in eastern Afar and the Gulf of Tajura, interrupted by the meridional structures of the Aisha horst (Sheet 3). However, unlike to the west of this horst, no impingement of the WNW faulting near Borama with the horst can be seen, owing to Quaternary sandcover on the flanks of the Tajura swell (Mohr, 1970). The several basaltic lava fields south of Bulhar cannot be associated with any fracture patterns revealed on the ERTS imagery. Such an association is expected, but again sandcover may have obscured the evidence.

In the southwestern corner of the area covered by Sheet 5, the southeastward extension from Sheet 3 of the Marda and related lineaments can be easily traced through the Dagabur–Dagmeda district, before passing to Sheet 6. The nature and age of these lineaments remain uncertain, but vertical displacements on them appear to be much less than for faulting of similar trend near the Gulf of Aden coast. It is of interest that the southward-displaced sector of the Somali escarpment between the Asseh graben and the Marda lineament is of the same length as the width of the southern Red Sea. This implies a clockwise rotation of the Somalia block (Baker, 1970), if an original continuity is presumed.

The dominant, Cainozoic structural grain of the northern Somali region may be said to be of WNW trend, with a much subordinate NE–ENE set of lineaments. The tremendous, Mesozoic downwarping of the Indian Ocean coastal margin ceased in the early Tertiary, and the region became subject to stresses from the development of the Gulf of Aden.

4.6 Sheet 6: 3 to 8°N, 41 to 49°E

This sheet covers southeastern Somali and the southern part of the Ethiopian Ogaden, west from the Indian Ocean coastline to longitude 41°E. Almost the entire region exposes Mesozoic marine sediments, with a cover of Eocene marine sediments in the northeast, and localized, small patches of Cainozoic lavas. Precambrian rocks are exposed only at the south central limit of Sheet 6. The structural geology of the region is essentially determined by the progressive downwarping, during the Mesozoic, of the continental margin. Sedimentation kept pace with subsidence and is reflected in the present flat, planar morphology that is traversed by the meandering Webi Shebeli and Juba rivers, originating farther west near the margin of the Somalian plateau with the main Ethiopian rift.

4.6.1 Precambrian terrain

Precambrian rocks of the Bur uplift touch on the southern limit of the area covered by Sheet 6 (Azzaroli and Merla, 1957; Beltrandi and Pyre, 1973). Daniels (1965) has made a photogeological study of the Bur inlier, including also the overlapping Jurassic limestones, and identifies two structural trends: NW–SE fold axes in the Precambrian gneisses and schists, and east–west faults. The latter, though largely confined to the Precambrian outcrop, in a few cases extend into the Jurassic rocks, where they show dextral displacements, and are associated with east–west axes of gentle folding.

ERTS imagery of the Bur region (including the rest of the inlier south of latitude 3°S) clearly contrasts the Precambrian and Jurassic terrains. The Precambrian has a lighter tone and a somewhat entrenched, dendritic drainage pattern; the Jurassic limestones show darker and lack any impressed drainage pattern. Structural lines on the ERTS imagery of the Bur uplift are twofold but do not correspond exactly with those of Daniels (1965). Broadly spaced (10 to 15 km) NNW-trending lineaments in the Precambrian may correspond to synclinal axes. Lineaments trending WNW in the eastern sector of the Jurassic escarpment, immediately to the north of the Precambrian outcrop, may represent either bedding-plane strike or possible faults.

4.6.2 Mesozoic–Cainozoic terrain

No strong lineaments, nor belts of lineaments, occur within the region covered by Sheet 6. If the Somalian plateau has been structurally deformed in a manner comparable with that of the Ethiopian plateau, then evidence is masked by the great thickness of Mesozoic sedimentary rocks (Baker et al., 1972). At least 3000 m of such rocks occur north of the Bur uplift, and south of the uplift, in the Kisimayo district, 2000 m of post-Lower Miocene sediments attest to local Tertiary tectonism of the continental margin, but these great thicknesses seem to have been deposited in response to subsidence by warping rather than by strong faulting.

The ERTS imagery reveals the presence across the Ogaden of persistent but weakly expressed NE–SW lineaments, from Lugh Ferrandi in the southwest to beyond

Galadi in the northeast and Gabredari in the north. These lineaments probably express the strike of gently dipping strata, such as is more clearly the case with outliers of Cretaceous limestone some 20 km west of Qellato. (N. B.: A small volcanic outcrop is marked here on the new geological map of Ethiopia (Kazmin, 1973), but cannot be identified on the ERTS imagery.) Along the coastal hinterland of the Indian Ocean, N–NE lineaments may mark ancient dune alignments and, in some instances, old shorelines. Beltrandi and Pyre (1973, Figure 6) indicate the existence of a Tertiary coastal fault system, but this is not identifiable with certainty on the ERTS imagery.

Some lithological boundaries within the Mesozoic–Eocene succession of the Ogaden show up sharply on the ERTS imagery. For example, in the Belet Wen–Mustahil area (see images 1187-06471-4/5), the superposition of Cretaceous sandstone on gypsum on limestone on Jurassic gypsum can be identified and mapped in detail.

Three interesting patches of Cainozoic lavas occur within the region covered by Sheet 6. The Tertiary olivine basalts, tinguaites, and pantelleritic ignimbrites of the Lugh Ferrandi area can be mapped in detail from the imagery, thus effecting appreciable revision of the map of Dainelli (1943). Quaternary basalts lie on the Mesozoic–Eocene sediments in the Wardere and Bulo Burti areas: Southeast of Wardere, two generations of basalt are discernible, the younger of which is much more restricted in occurrence and of very fresh character. Small basalt patches, known from ground reconnaissances south of Wardere and in the Bulo Burti area, cannot be identified on the ERTS imagery. However, the currently available imagery for the strip between longitudes 45 1/2 and 46 1/2°E, in these latitudes, is of poor quality.

No clearcut structural control of the Ogaden Cainozoic lavas is forthcoming from the ERTS imagery. However, a projection from the last clear traces of the Marda lineaments, at longitude 44°E, can be made southeastward to the Wardere volcanic field. Furthermore, the Wardere and Lugh Ferrandi occurrences are on a common NE–SW strike paralleling the coastal monocline. The Lugh Ferrandi volcanics also lie above the deepest sector of the Lugh–Mandera sedimentary basin (Beltrandi and Pyre, 1973). The Bulo Burti basalts may perhaps be associated with the presence of lineaments trending from the termination of the Marda lineaments, south-southeastward along the Fafan valley and then the lower Webi Shebeli valley.

Finally, the ERTS imagery permits an examination of the thesis of Beltrandi and Pyre (1973) that an "ancestral, pre-Jurassic trough or rift system" linked the Dar-es-Salaam coast with western Afar in virtually a direct line, during the Permo-Jurassic. This line passes through Sheets 4 and 6 along the 39 to 41°E meridian band, west of the Lugh Ferrandi volcanics. Neither on the geological map of Kazmin (1973) nor on the ERTS imagery is there any definite evidence pointing to the existence of this "Abyssinian trough." As noted previously (Sheet 4), the Batu Mts. volcanics are sited on prominent ENE-trending lineaments, although their position lies on the postulated trough also.

5. CONCLUSIONS

1. ERTS imagery of eastern Africa and Yemen has provided a most valuable tool for regional mapping of the lithology and structures associated with the African rift system.

2. The overall structural pattern of the African rift system is seen in its unity for the first time, including previously unmapped regions in parts of Ethiopia, Yemen, northeastern Somali, and southeastern Sudan.

3. Distinction can be made on the imagery among the strike of folded, metamorphosed basement, normal faults, and lineaments of various types.

4. Accurate, small-scale lithological mapping is possible for many areas, but is difficult or occasionally impossible for others. The distinction is at least partly related to soil and vegetation cover, but the cause needs further investigation.

In the Red Sea Hills of northeastern Sudan, a desert region, the geology is very clearly expressed, with the younger, ring granites being strongly emphasized. Major subdivisions of the Precambrian of Ethiopia, based on reconnaissance ground surveys, are not picked out on the ERTS imagery, but regions with grossly different fracture patterns are revealed. Lithological types are rarely distinguishable in the Precambrian, except in northern Somali, where the boundary between the older gneisses and the younger Inda Ad Series does show a tonal contrast.

In the Mesozoic—Eocene sedimentary sequence of northern Somali and eastern Ethiopia, lithological boundaries can be very sharply etched on the imagery, especially in river valleys or along major fault escarpments. Some rock formations can be distinguished by the type of superimposed drainage pattern.

Outcrops of Cainozoic lavas lying on basement or sedimentary rocks are usually clearly delimited. Where they lie on older lavas of similar petrographic type, their boundaries are difficult to distinguish unless the younger lava is very recent.

5. The ERTS imagery enormously facilitates regional structural mapping. In nongneissose ("Proterozoic") Precambrian terrain, synclinoria and anticlinoria can be identified, as well as major faults. Metamorphic foliation strike is emphasized in some narrow schist belts, notably the newly recognized, 300-km-long Adóbaha belts of northern Eritrea. The overall Precambrian structural grain in the Horn of Africa and Yemen is oriented close to a meridional trend: Transverse lineaments can be identified in many places, and in some areas are strongly developed (e.g., southern Eritrea, southern Yemen, central Abbay basin). These lineaments can be identified with ground-mapped joints in northern Ethiopia and are revealed to persist individually over unexpectedly long distances. In Yemen, extensive Precambrian linears are neither faults nor joints and may have acted as hinge lines.

The detailed fault pattern of Afar is beautifully revealed on the imagery of this desert region, and the results of ground and air-based surveys are generally confirmed and can be extended. The Afar marginal gräben, the floor fault belts, annular gräben, and the Wonji fault belt all show well. So do all the volcanic craters and calderas, some of which are now seen to be sited on tectonic nodes. Alíd volcano, in northernmost Afar, is revealed to lie on the intersection of young, Afar floor faulting with a Precambrian fault line. Transverse lineaments are identified on the floor of Afar, but are not abundant compared with the Afar margin lineaments. The Danakil and Aysha horsts, immediately east of Afar and important elements in the plate tectonic evolution of the Afar triple junction, are shown on the ERTS imagery to be affected both by longitudinal extensional faulting and by near-transverse faulting. The Dubbi volcanic lineament, trending NNE across the Danakil horst, is confirmed to extend into the floor of northeastern Afar. The Aysha horst appears, according to the imagery, to be separated by no major structures from the Somalian plateau; it has also resisted impress by WNW-ESE faulting to the northwest and southeast.

The main Ethiopian rift can at last be uniformly and completely mapped by use of the ERTS imagery. The plan of the rift shows a gently curvilinear form, convex to the west, and within the continuous envelope of its marginal faults, the Wonji fault belt of the rift floor shows dextral and a few sinistral transpositions. These transpositions are not always strictly en echelon, for in some sectors the faulting is continuous at an acute angle, right across the rift from one margin to the other. The faulting of the main Ethiopian rift fails to extend south of latitude 5°N but is on a direct projection with the northernmost faulting of the Kenyan rift valley, near latitude 4°N. Crustal extension in southern Ethiopia has been taken up west of the rift, in the complexly faulted Stefanie graben and horst-graben faulting of the middle Omo valley.

Structural deformation of the Ethiopian plateau is confirmed on the ERTS imagery to have been more severe than for the Somalian plateau, but thick sedimentary cover on the latter must be allowed for. The margin structures of the Tana graben, developed in the northern part of the Ethiopian plateau, can now be accurately mapped; they appear not to extend either north or south into Red Sea or rift-valley structures. The Tana graben traverses an old, large escarpment of NE–SW trend, facing northwest, which ERTS imagery reveals may have originated from late-Miocene(?) faulting and regional tilting up to the northwest. In the southern sector of the Ethiopian plateau, there is a fanlike spread of curvilinear faulting north from Lake Rudolf, convex to the west. The entire Ethiopian plateau is marked with ENE-trending lineaments, whose nature awaits elucidation.

On the Somalian plateau, a major belt of old, fault lineaments forms the Marda volcano-tectonic line, trending northwestward to the southwestern corner of the Aysha horst. The northern escarpment of the plateau, overlooking the Gulf of Aden, is offset some 100 km at the Asseh graben in the same, sinistral sense as the Sheba spreading axes within the Gulf; this graben and similar young faulting at the very tip of the Horn can now be accurately mapped and seem to be related to extensional strain acting outside the Gulf of Aden spreading lines.

6. Basement control of the rift structures is evident from many localities, although ERTS imagery suggests that the overall rift pattern is a new impress on the crust. In Yemen, Precambrian lineaments have acted as hinge lines and means of egress for basaltic lavas during the Cainozoic. In the central Ethiopian plateau, lineaments expressed in the Tertiary flood basalts can be projected into and, in some instances, are directly connected with adjacent Precambrian structures. Basaltic spatter cones can form alignments that are oblique to the surficial faulting, for example, in the Ririba valley of southern Ethiopia, which suggests a deeper seated tectonic control that should be noted in studying the regional plan of the rift valley. The complex, sawtooth plan of the Stefanie graben faulting matches the reticulate mesh of lineaments in the Precambrian terrain to the northwest. The ERTS imagery therefore reveals that

rejuvenation of old structures is a common phenomenon, on the local scale, in the Cainozoic development of the African rift system.

The ERTS imagery also shows several instances of tectonic control of the site of volcanism. These include volcanic centers of north and western Afar, the newly identified Batu and Cawa calderas of the Somalian plateau, and isolated patches of lava in the Ethiopian Ogaden.

7. Geomorphological studies could be greatly extended from the present work, which reveals, for example, the precise limits of the planar, flood-basalt surface of the central Ethiopian plateau. Glaciated valleys are recognized on the higher summits of Ethiopia.

8. On the scale of plate tectonics, the ERTS imagery has revealed new constraining features (for example, concerning the position of the Aysha horst) and additional major transcrustal fracture zones (for example, the Jebel Barach–Iyadh zone, mirroring the western margin of Afar about a Red Sea–Bab el Mandeb axis).

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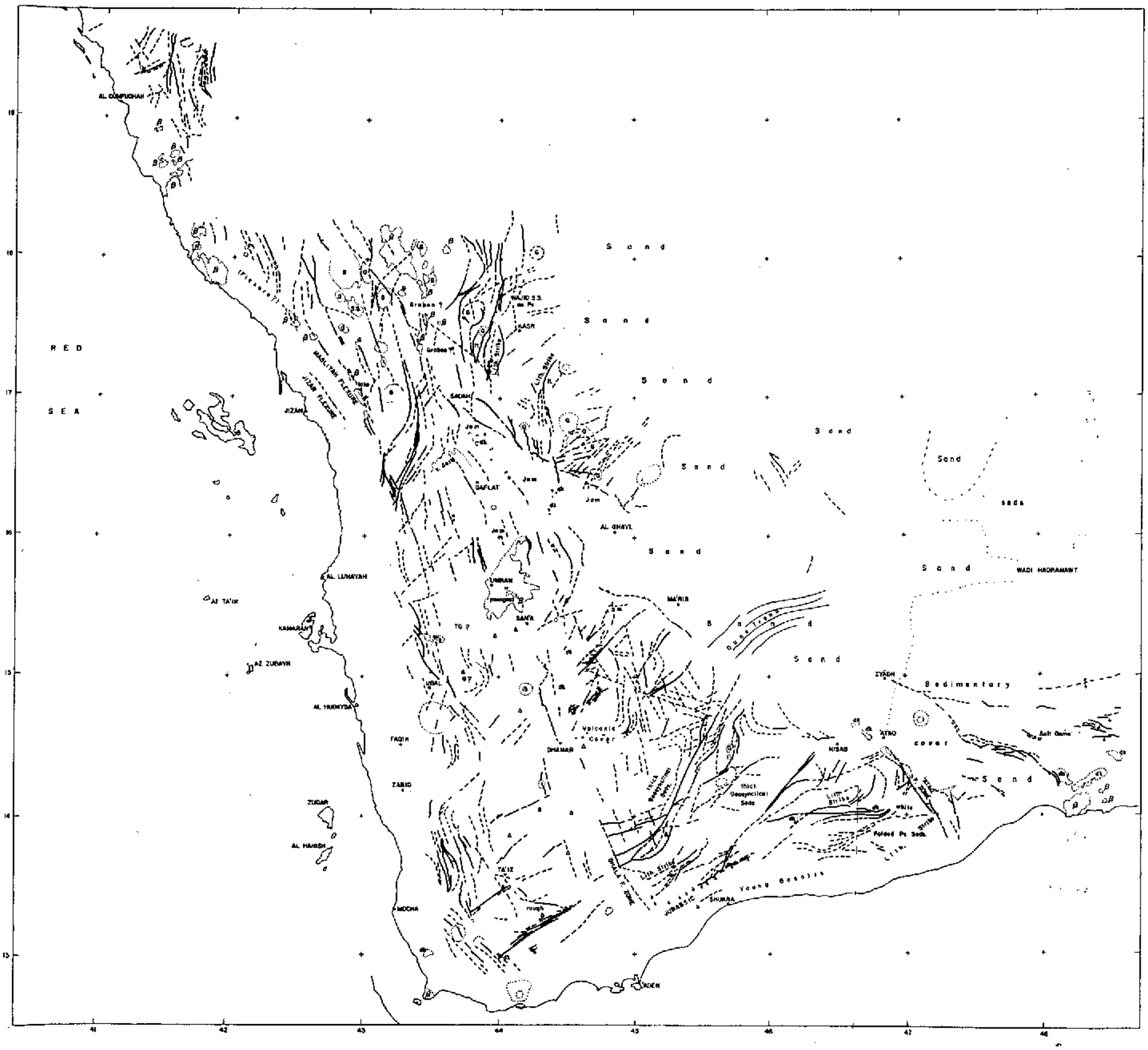

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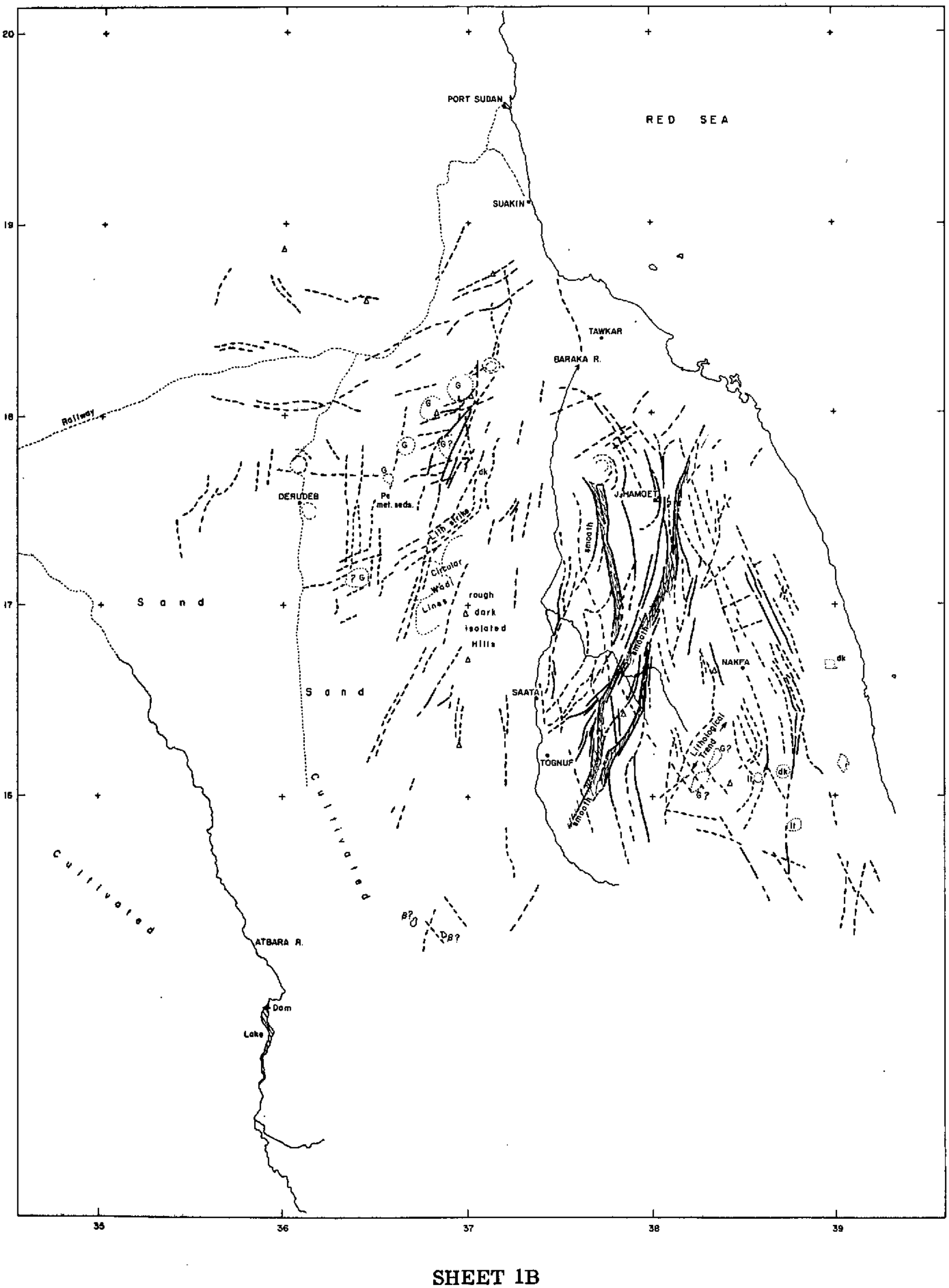

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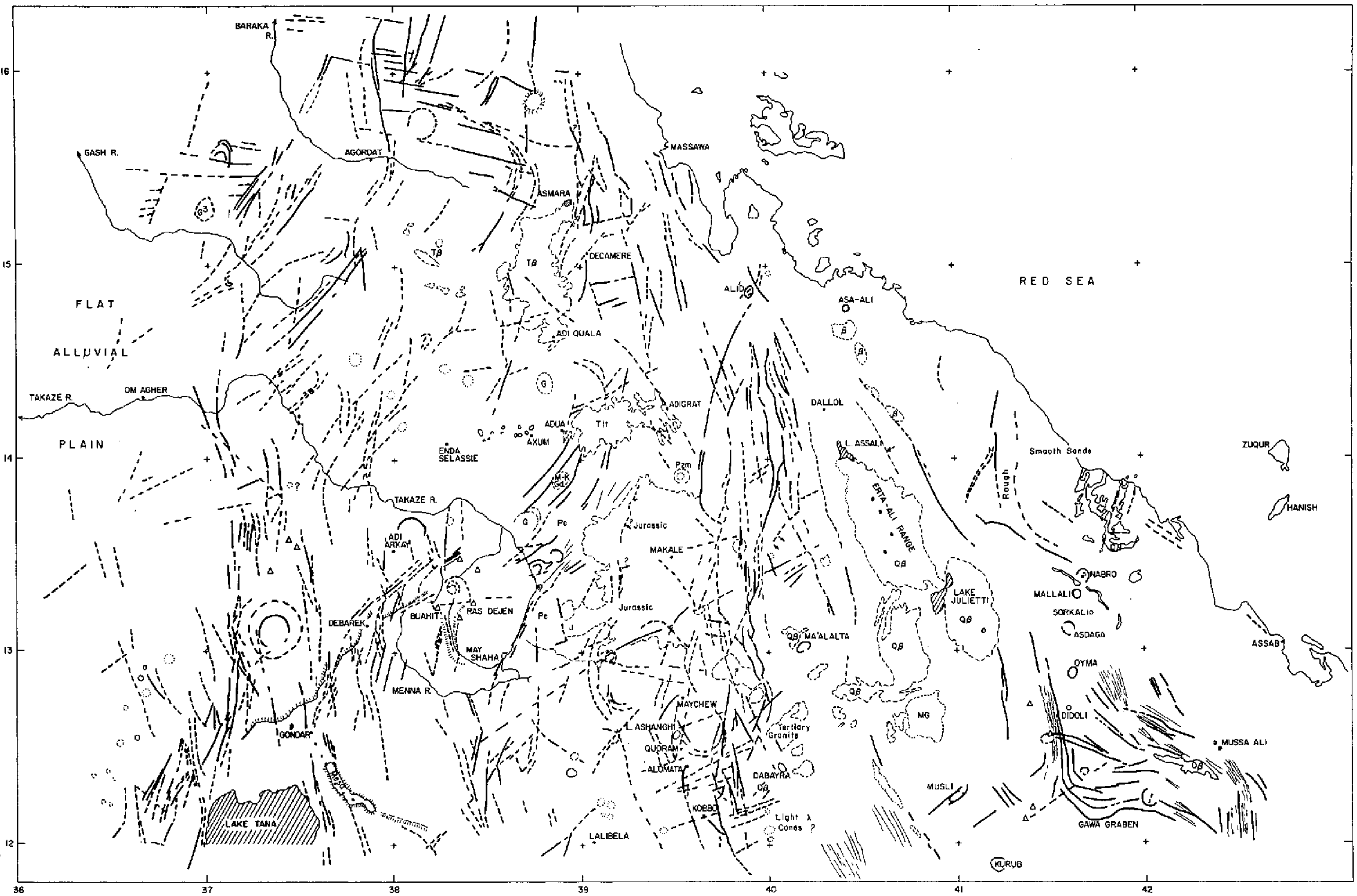
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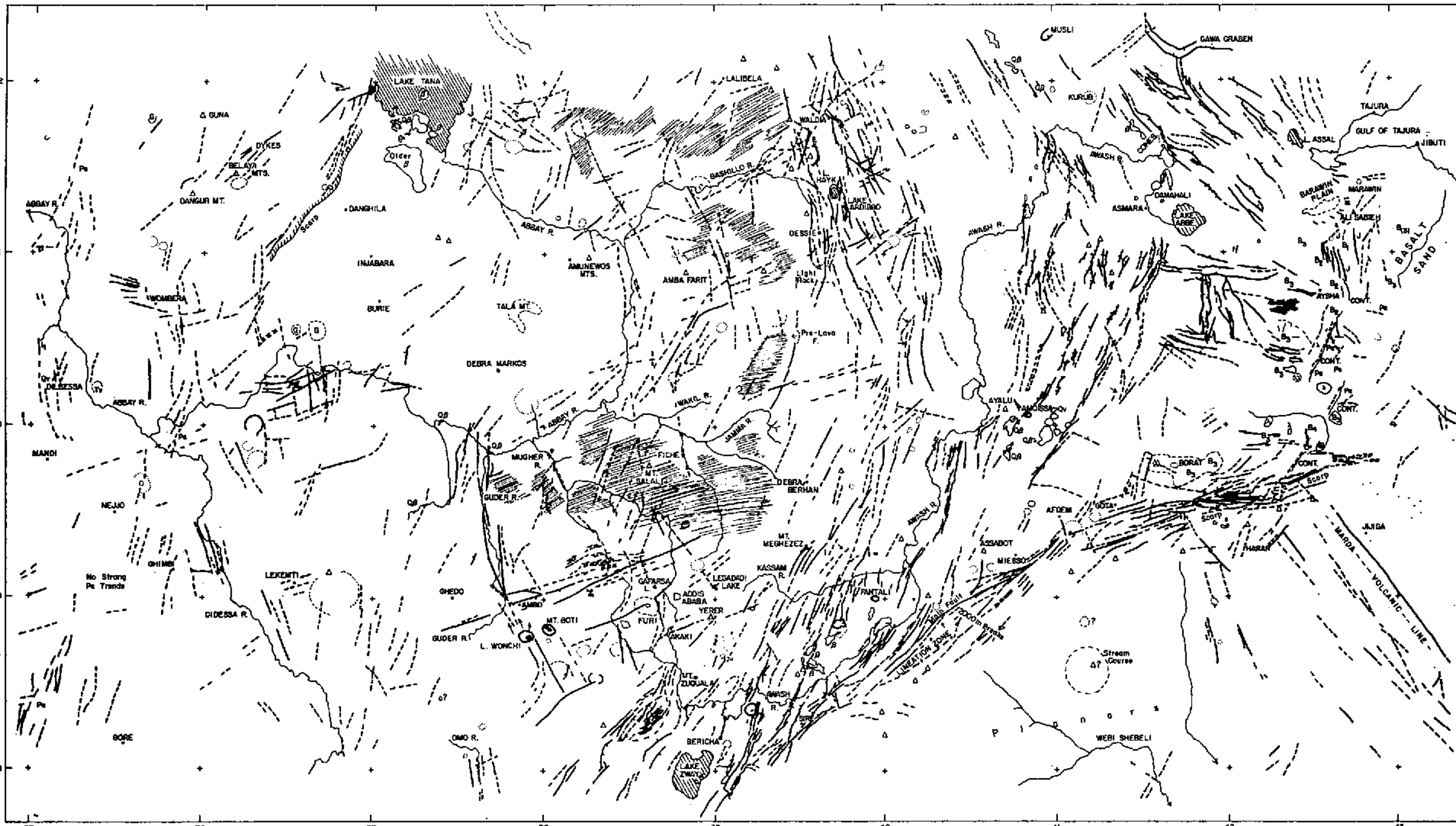
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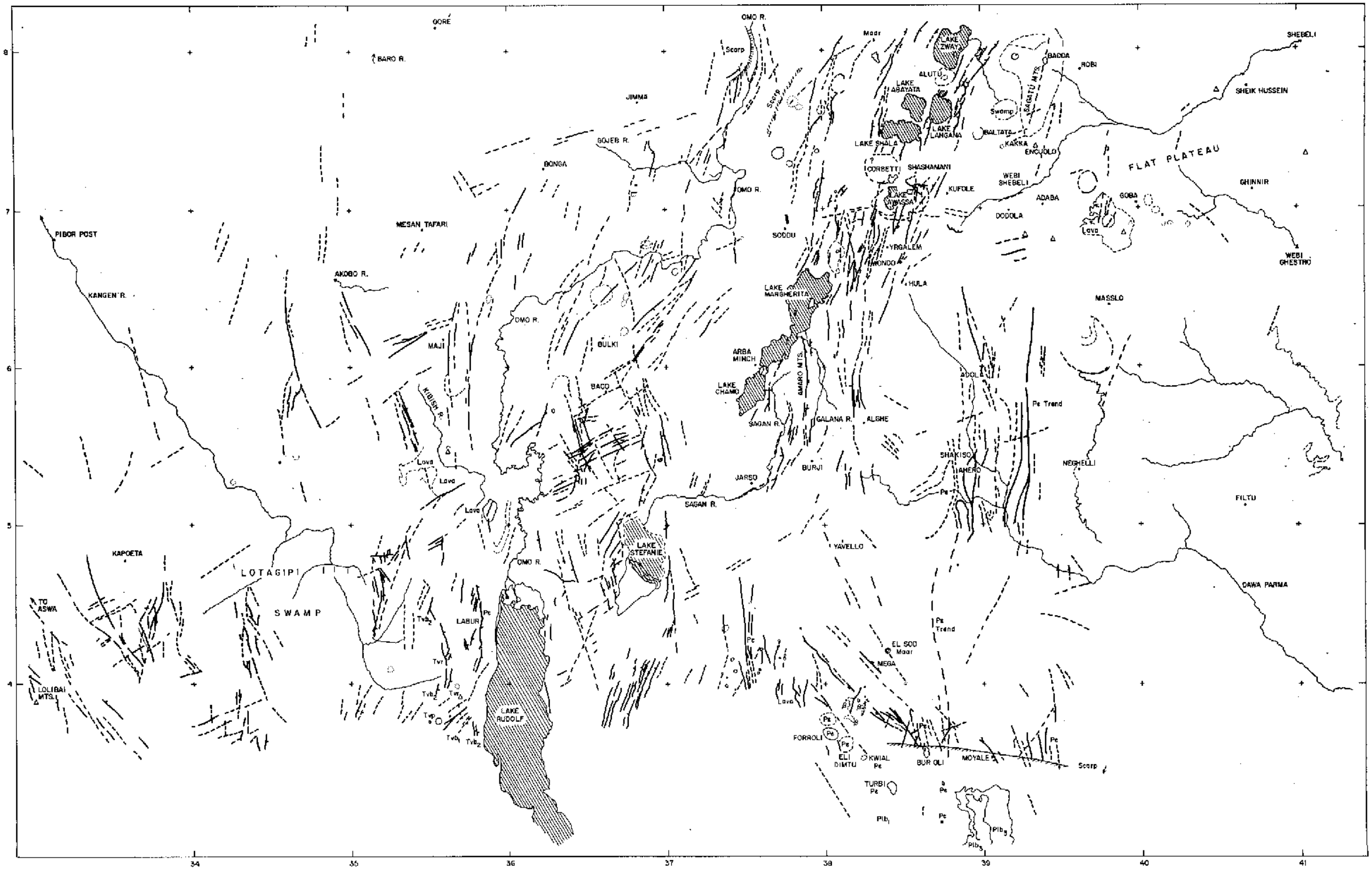
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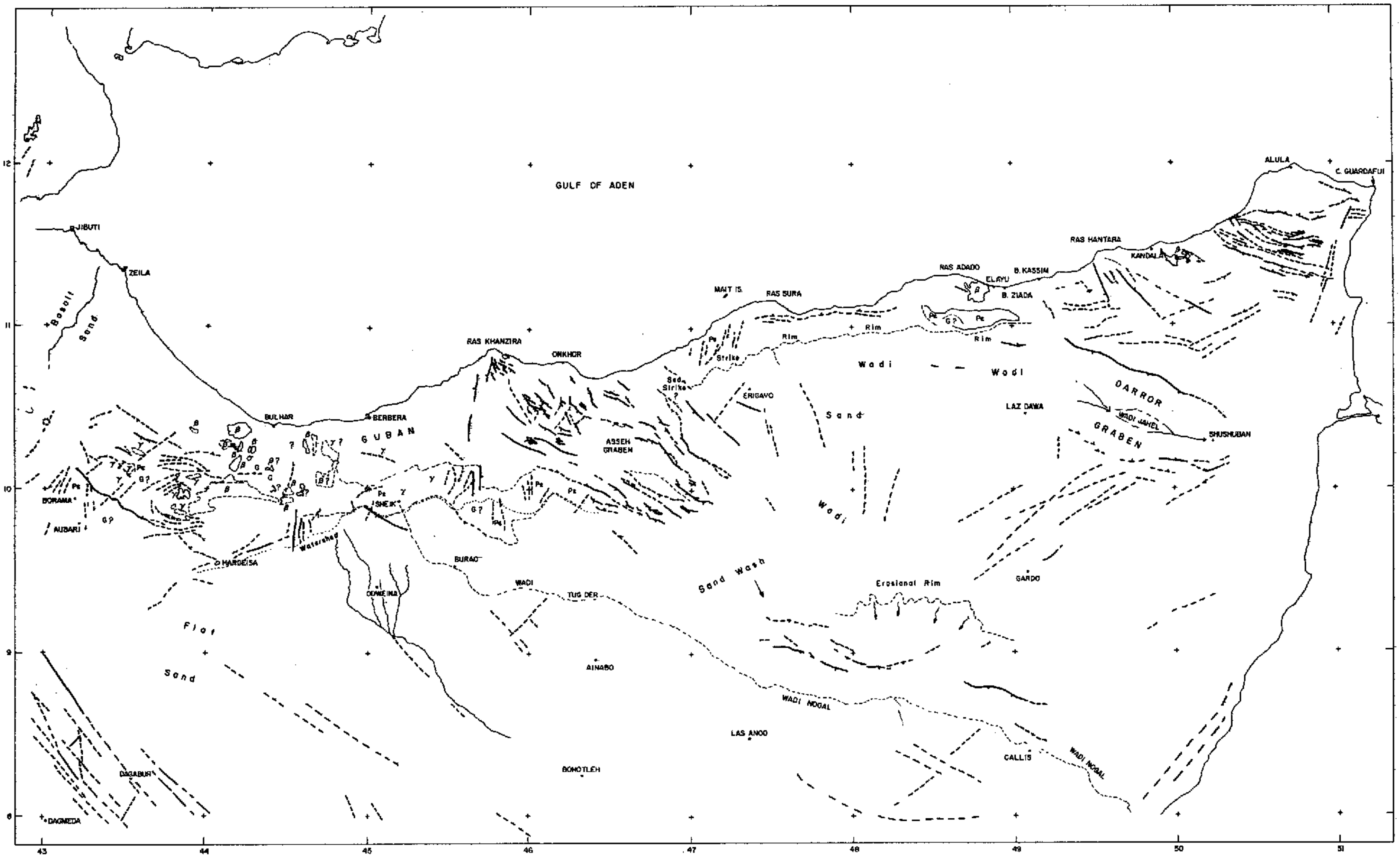
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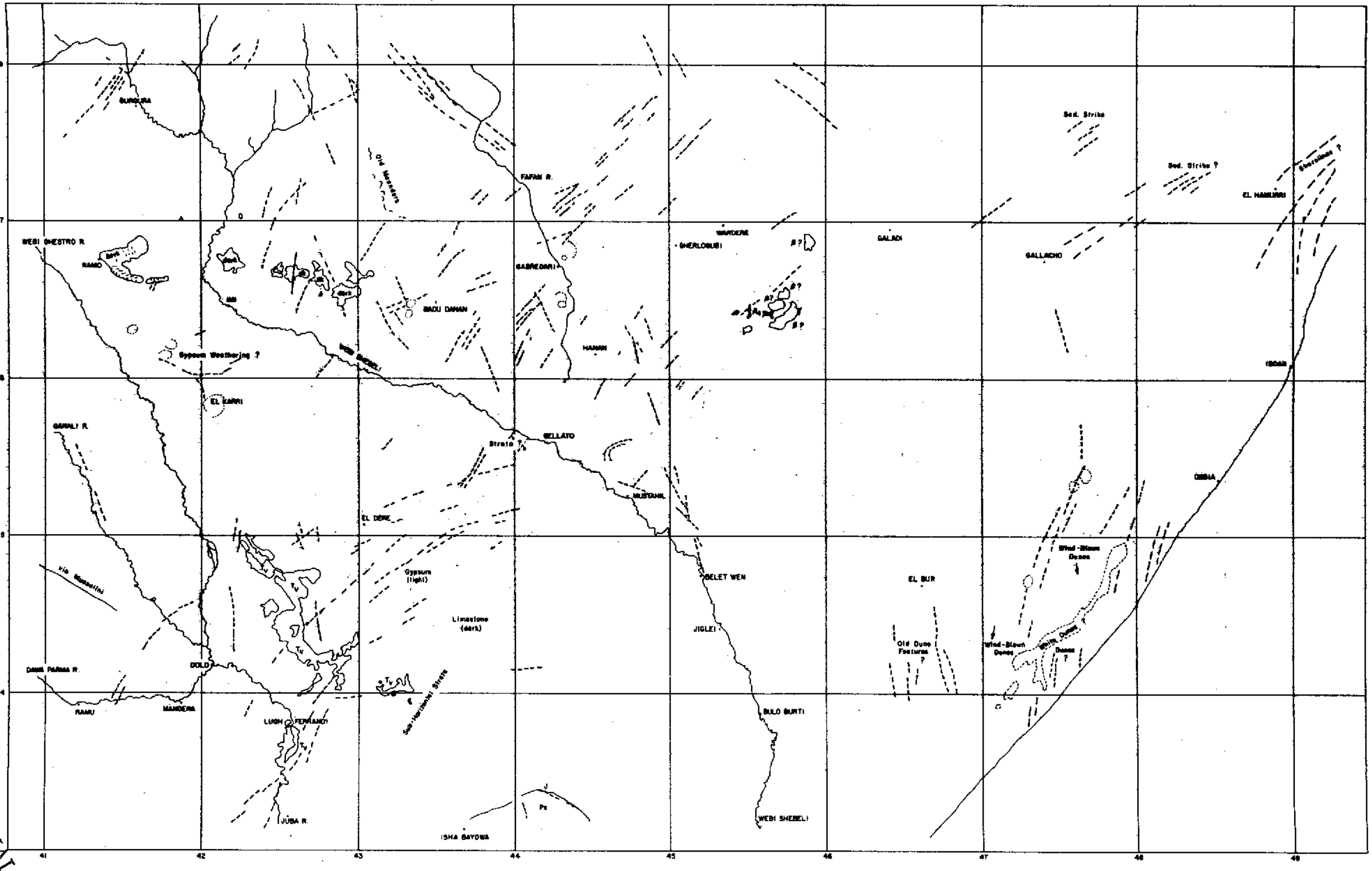
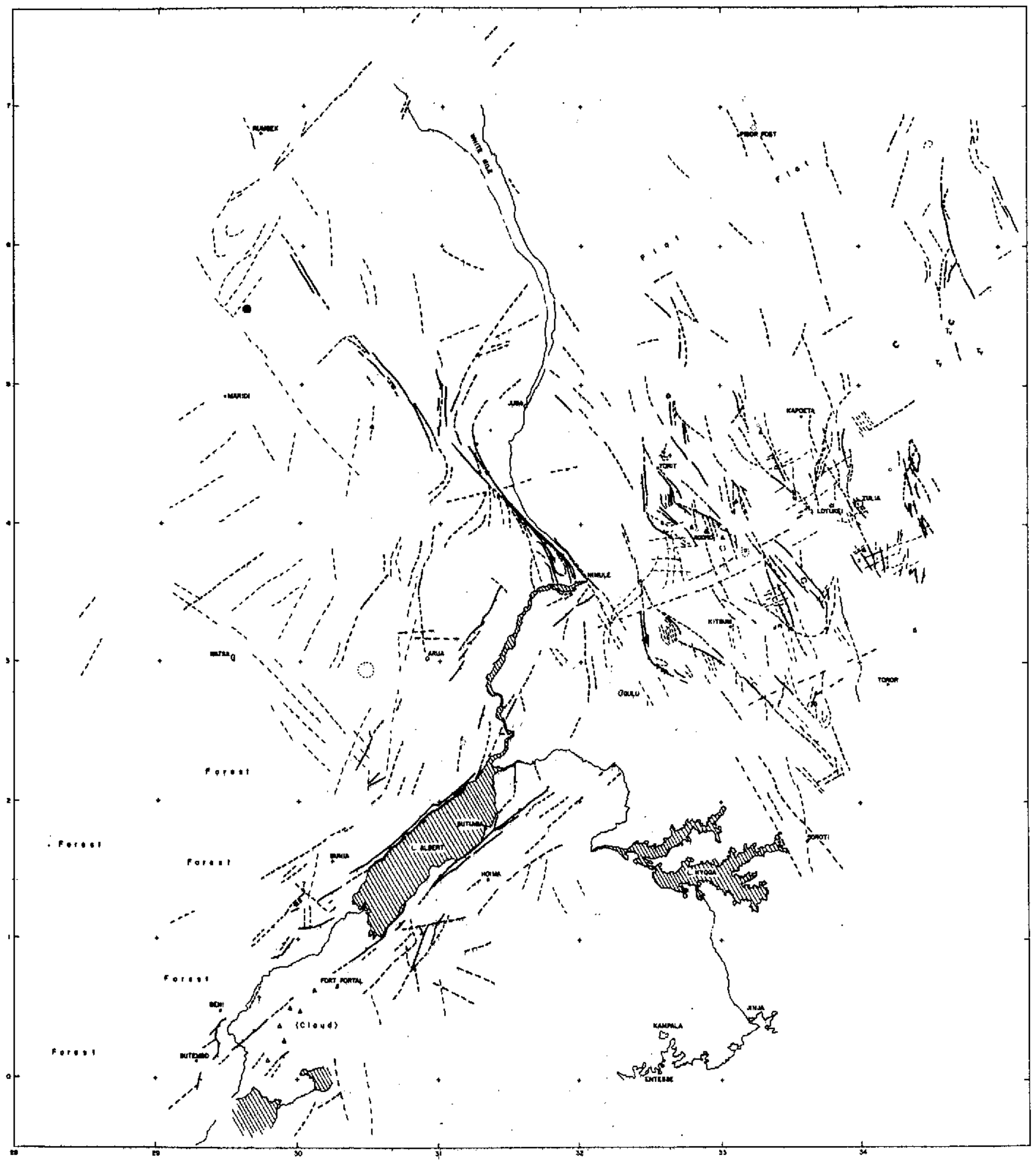
RAS SURA
ERIGAVO
ASSEH
GRABEN
BORAMA
AUBARI
HARGEISA
Watershed
SHEIK
BURAO
ODWEINA
WADI
TUG DER
Flat
Sand
AINABO
LAS ANOD
BOHOTLEH
DAGABUR
DAGMEDA
WADI NOGAL
CALLIS
GARDO
Erosional Rim
Sand Wash
Wadi
Sand
Rim
LAZ DAWA
DARROR
GRABEN
WADI JAHEL
SHUSHUBAN
RAS ADADO
ELAYU
B. KASSIM
B. ZIADA
RAS HANTARA
KANDALA
ALULA
C. GUARDAFUI
Strike
12
11
10
9
8
43
44
45
46
47
48
49
50
51

SHEET 5

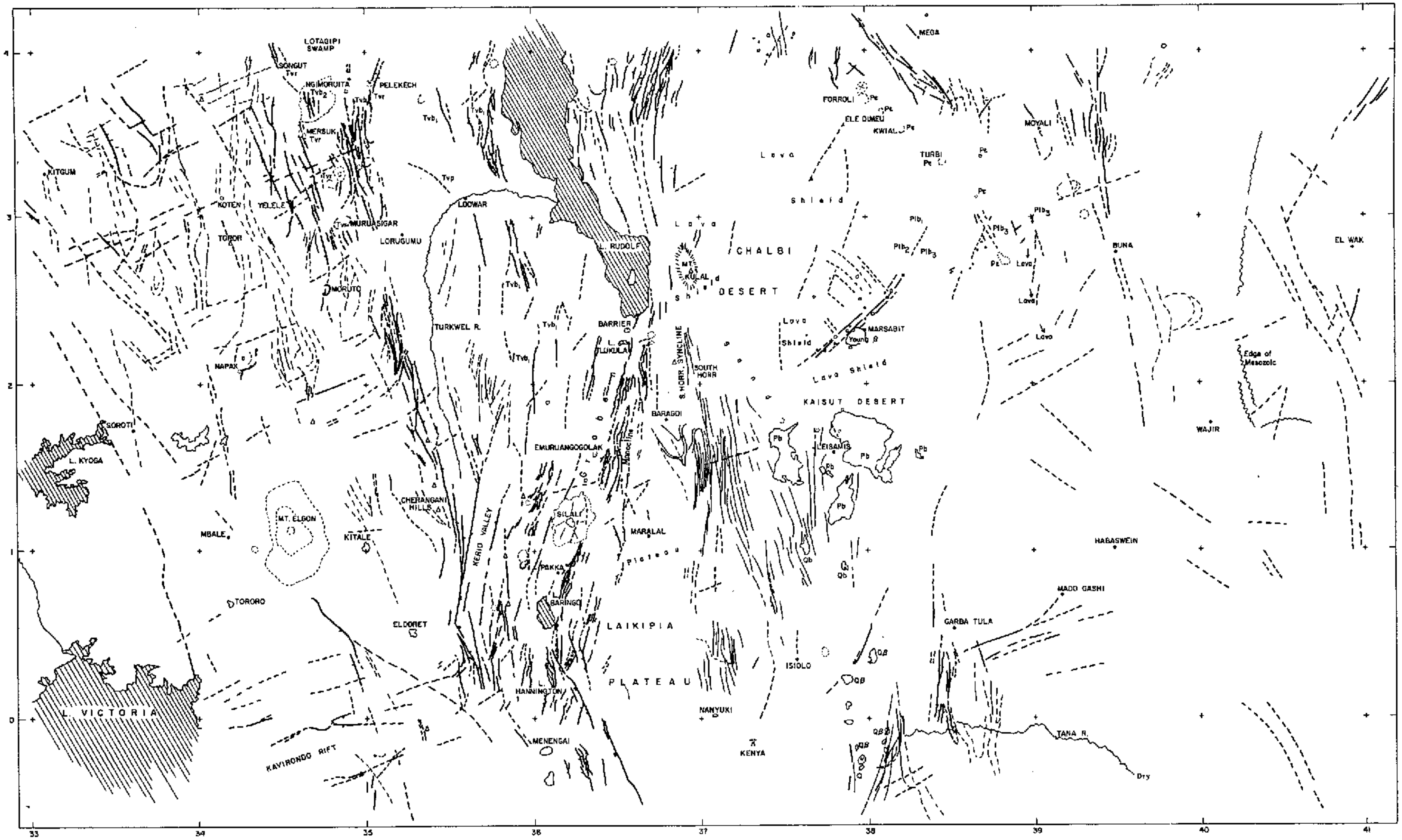


SURGURA
Old Meanders
FAFAN R.
Sed. Strike
Sed. Strike ?
EL HAMURRI
WEBI GHESTRO R.
RAMO
WARDERE
SHERLOGUBI
GALADI
GALLACHO
SABREDARI
BADU DANAN
HANAN
Gypsum Weathering ?
WEBI SHEBELI
ISOAN
EL KARRI
GARALI R.
BELLATO
Strata ?
MUSTAHIL
OBBIA
EL DERE
BELET WEN
EL BUR
Gypsum (light)
Limestone (dark)
Wind-Blown Dunes
Old Dune Features ?
JIGLEI
Wind-Blown Dunes
Dunes ?
DAWA PARMA R.
DOLO
RAMU
MANDERA
LUGH FERRANDI
Sub-Horizontal Strata
BULO BURTI
JUBA R.
ISHA BAYDWA
WEBI SHEBELI
41
42
43
44
45
46
47
48
49

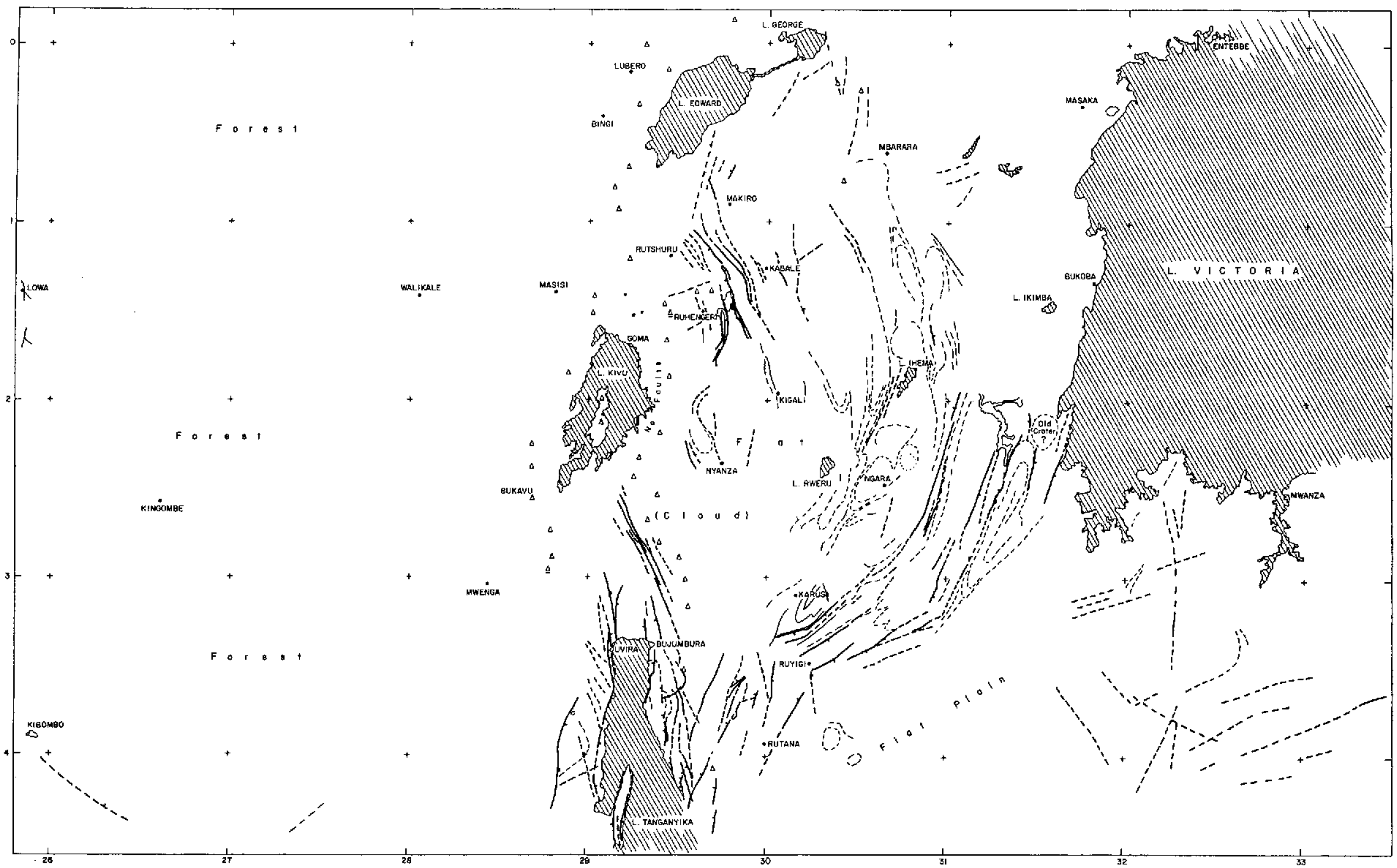
SHEET 6


RUMBEK
PIBOR POST
MARIDI
JUBA
WHITE NILE
NIMULE
TORIT
KAPOETA
KITGUM
ARUA
GULU
TORORO
Forest
BUNIA
L. ALBERT
BUTIABA
HOIMA
L. KYOGA
SOROTI
FORT PORTAL
BENI
(Cloud)
BUTEMBO
KAMPALA
JINJA
ENTEBBE

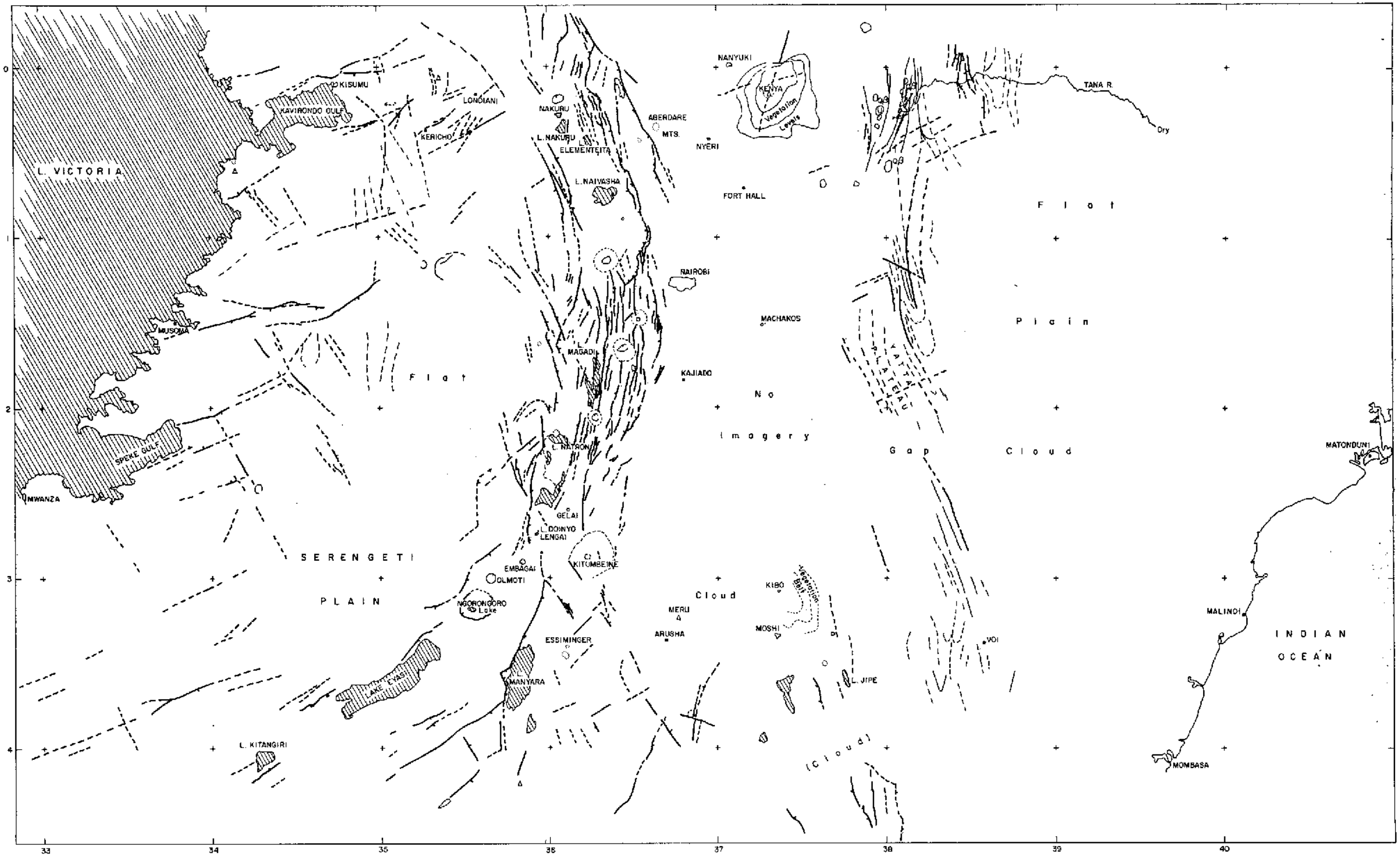
SHEET 7


LOTAGIPI SWAMP
SONGUT
NGIMORUITA
PELEKECH
MERSUK
KITGUM
KOTEN
YELELE
MURUASIGAR
TOROR
LORUGUMU
MORUTO
LOKWAR
L. RUDOLF
MT. KULAL
CHALBI
DESERT
TURKWEL R.
BARRIER
L. LOKULA
S. HORR. SYNCLINE
SOUTH HORR
NAPAK
SOROTI
L. KYOGA
BARAGOI
EMURUANGOGOLAK
CHERANGANI HILLS
MT. ELGON
MBALE
KITALE
KERIO VALLEY
SILALI
MARALAL
PAKKA
TORORO
ELDORET
BARINGO
LAIKIPIA
PLATEAU
L. HANNINGTON
L. VICTORIA
KAVIRONDO RIFT
MENENGAI
NANYUKI
KENYA
MEGA
FORROLI
ELE DIMEU
KWIAL
TURBI
MOYALI
Lava
Shield
MARSABIT
KAISUT DESERT
LEISAMIS
BUNA
EL WAK
Edge of Mesozoic
WAJIR
HABASWEIN
MADO GASHI
GARBA TULA
ISIOLO
TANA R.
Dry
33
34
35
36
37
38
39
40
41

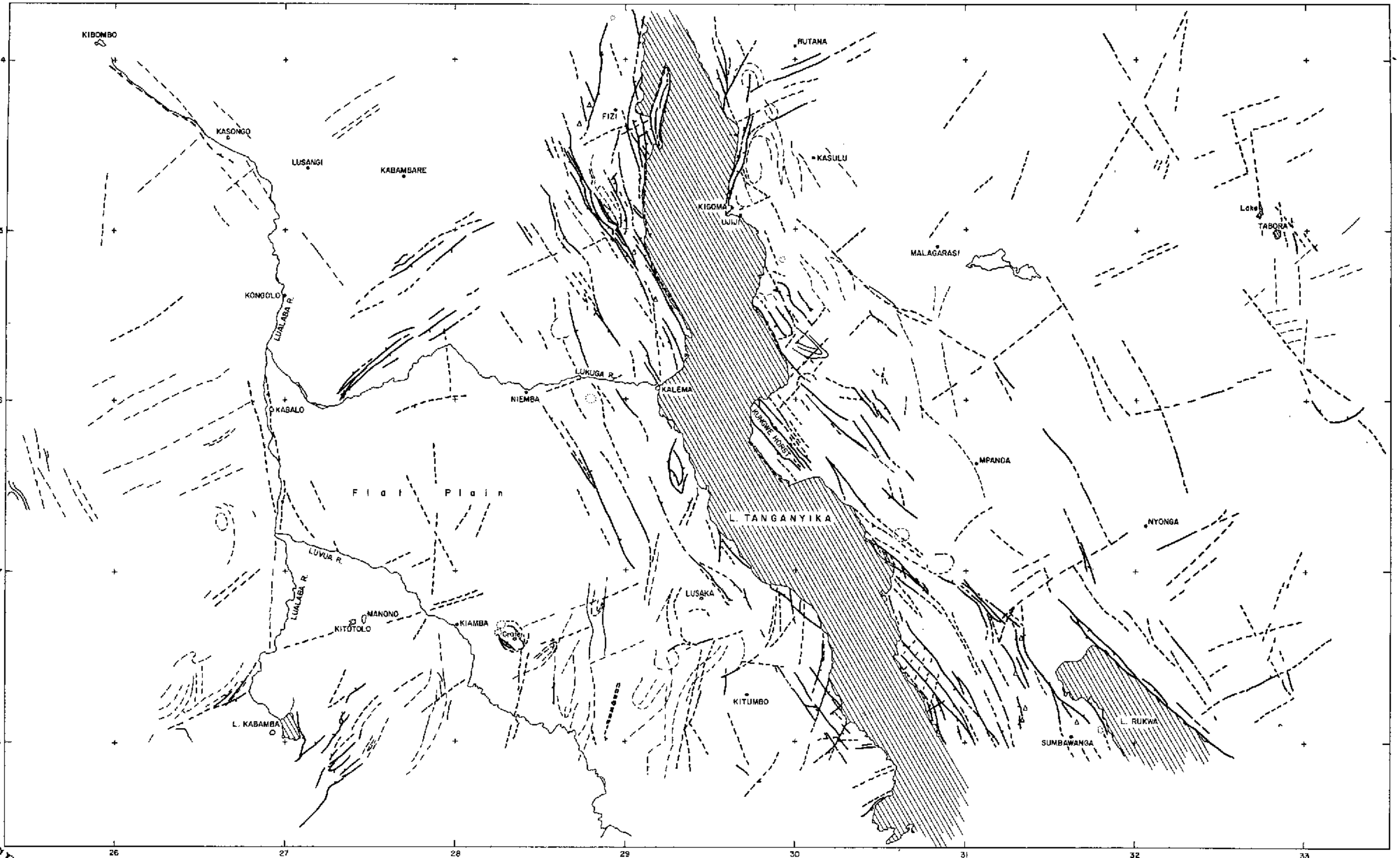
SHEET 8


L. GEORGE
ENTEBBE
LUBERO
L. EDWARD
BINGI
MASAKA
Forest
MBARARA
MAKIRO
RUTSHURU
KABALE
BUKOBA
L. VICTORIA
LOWA
WALIKALE
MASISI
L. IKIMBA
RUHENGERI
GOMA
L. IHEMA
L. KIVU
KIGALI
Old Crater ?
Forest
Flat
NYANZA
L. RWERU
NGARA
BUKAVU
MWANZA
KINGOMBE
(Cloud)
MWENGA
KARUSI
Forest
UVIRA
BUJUMBURA
RUYIGI
Flat Plain
KIBOMBO
RUTANA
L. TANGANYIKA
0
1
2
3
4
26
27
28
29
30
31
32
33

SHEET 9


L. VICTORIA
KISUMU
KAVIRONDO GULF
LONDIANI
KERICHO
NAKURU
L. NAKURU
ELEMENTEITA
L. NAIVASHA
ABERDARE MTS.
NANYUKI
KENYA
NYERI
FORT HALL
TANA R.
Dry
NAIROBI
MACHAKOS
MUSOMA
MAGADI
KAJIADO
Flat
No Imagery
Gap
Cloud
Flat Plain
YATTA PLATEAU
SPEKE GULF
MWANZA
L. NATRON
GELAI
L. DOINYO LENGAI
KITUMBEINE
EMBAGAI
OLMOTI
NGORONGORO Lake
SERENGETI PLAIN
ESSIMINGER
MERU
ARUSHA
KIBO
MOSHI
Vegetation Belt
L. JIPE
VOI
LAKE EYASI
MANYARA
L. KITANGIRI
(Cloud)
MATONDUNI
MALINDI
INDIAN OCEAN
MOMBASA
33
34
35
36
37
38
39
40
0
1
2
3
4

SHEET 10



KIBOMBO
KASONGO
LUSANGI
KABAMBARE
FIZI
RUTANA
KASULU
KIGOMA
UJIJI
MALAGARASI
Lake
TABORA
KONGOLO
LUALABA R.
LUKUGA R.
KALEMA
NIEMBA
KABALO
KUNGWE HORST
MPANDA
Flat Plain
L. TANGANYIKA
NYONGA
LUVUA R.
LUALABA R.
MANONO
KITOTOLO
KIAMBA
Crater
LUSAKA
KITUMBO
L. KABAMBA
L. RUKWA
SUMBAWANGA
4
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6
7
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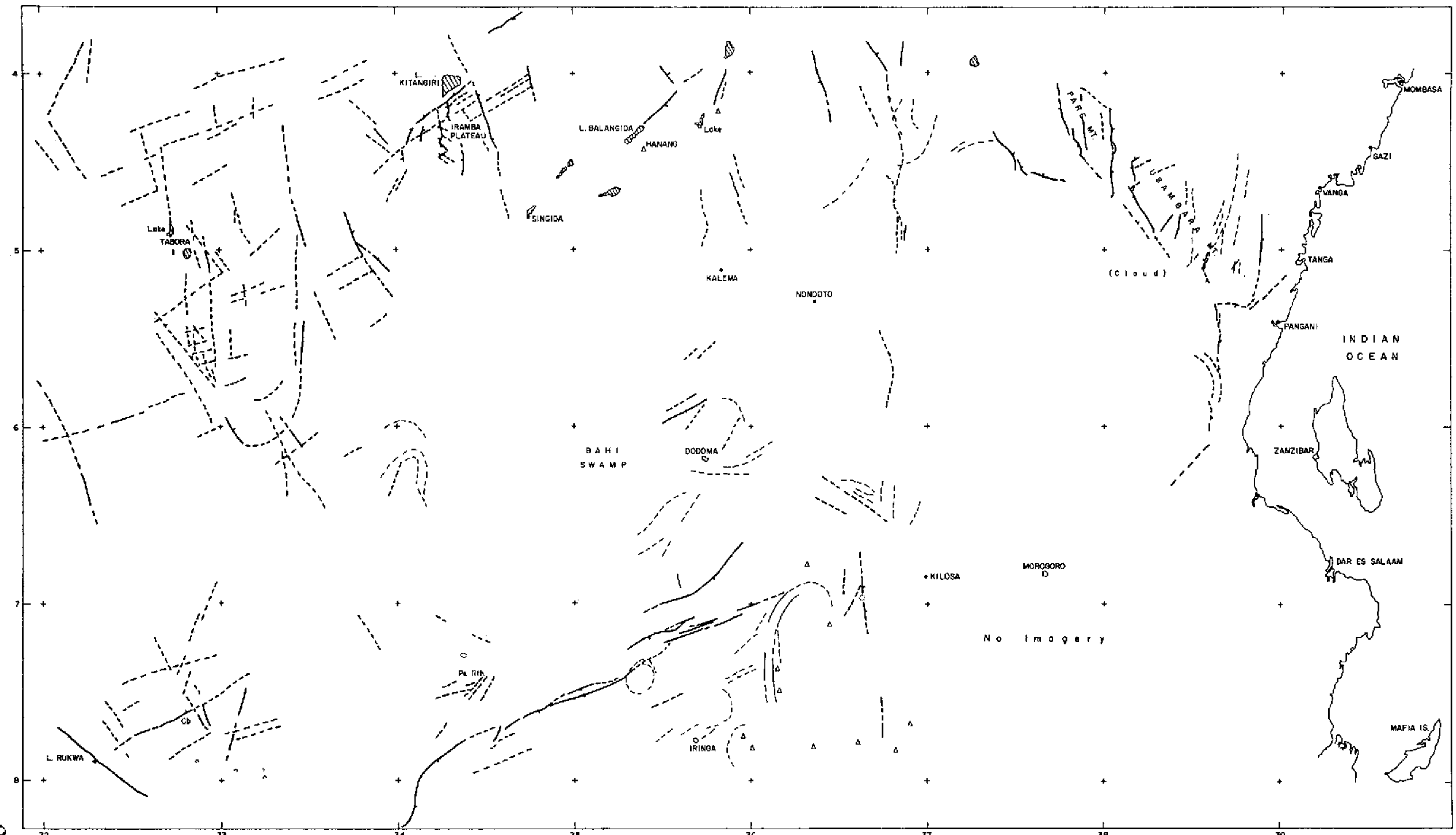
31
32
33

SHEET 11


L. KITANGIRI
IRAMBA PLATEAU
L. BALANGIDA
HANANG
Lake
SINGIDA
Lake
TABORA
KALEMA
NONDOTO
PARE MT.
USAMBARA
(Cloud)
MOMBASA
GAZI
VANGA
TANGA
PANGANI
INDIAN OCEAN
ZANZIBAR
BAHI SWAMP
DODOMA
KILOSA
MOROGORO
DAR ES SALAAM
No imagery
Ps lith
Cb
L. RUKWA
IRINGA
MAFIA IS.
4
5
6
7
8
32
33
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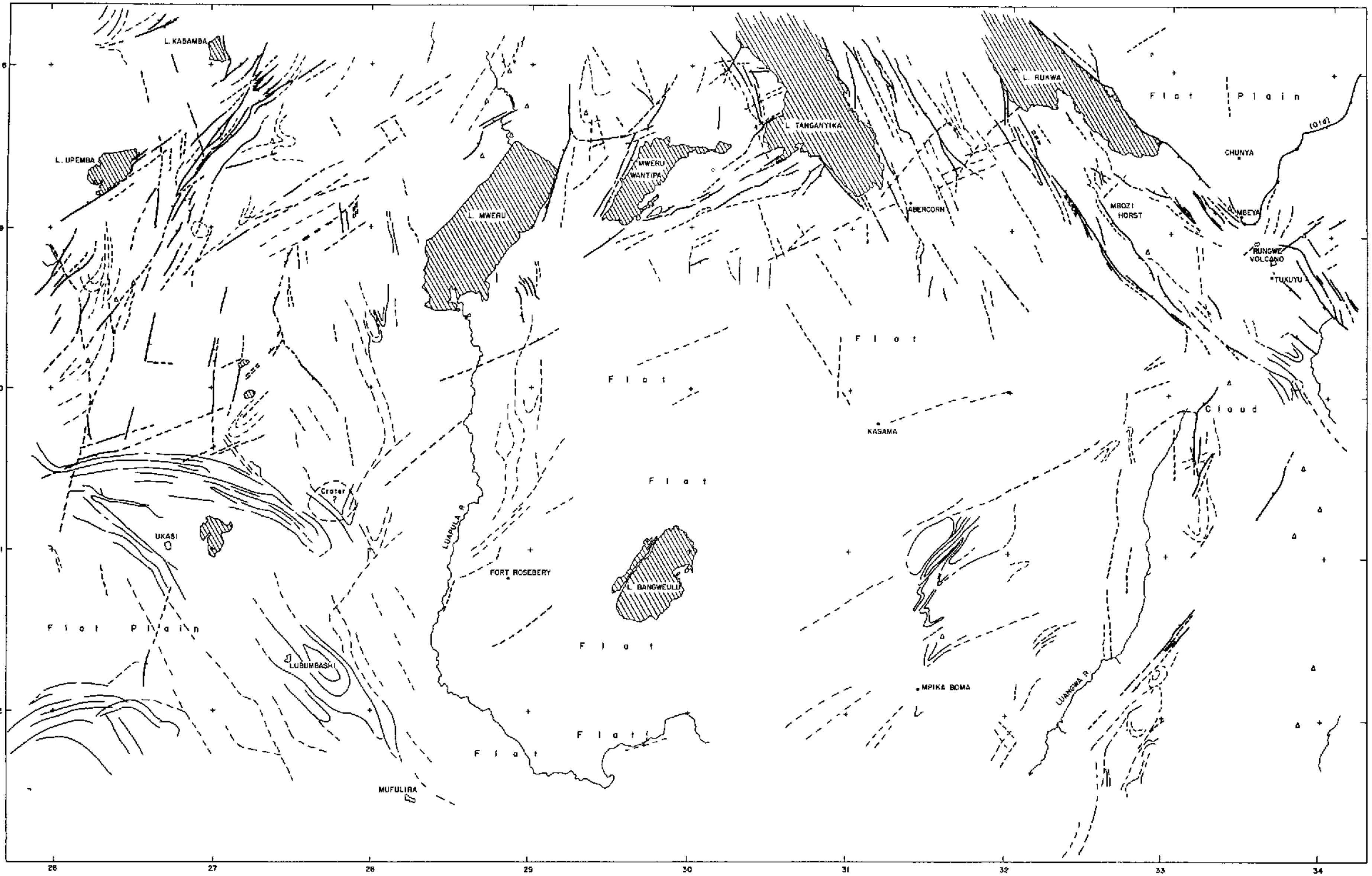
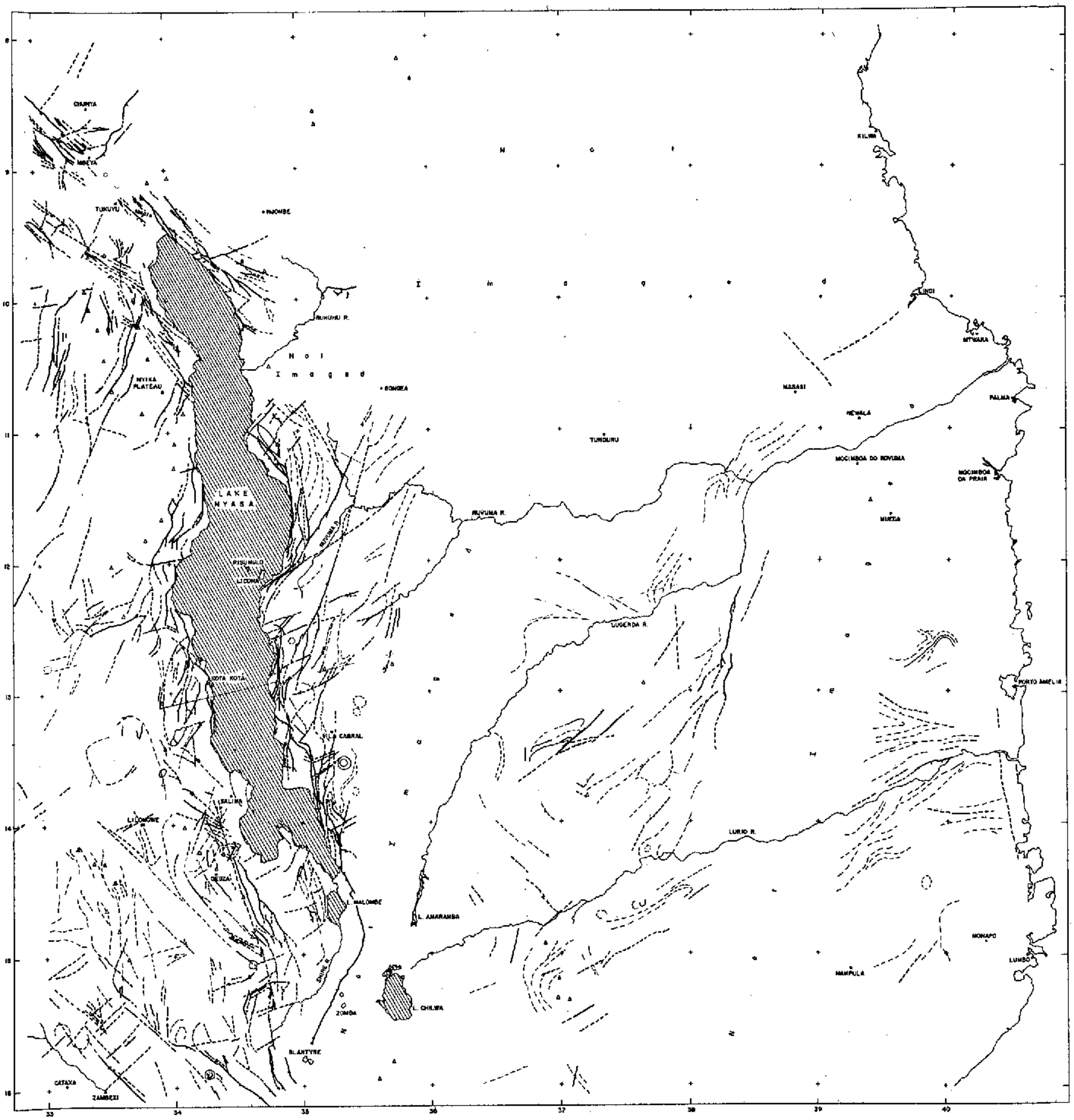
35
36
37
38
39

SHEET 12



L. KABAMBA
L. UPEMBA
L. MWERU
MWERU
WANTIPA
L. TANGANYIKA
ABERCORN
L. RUKWA
Flat Plain
(old)
CHUNYA
MBEYA
MBOZI
HORST
RUNGWE
VOLCANO
TUKUYU
Flat
KASAMA
Cloud
Crater
?
UKASI
LUAPULA R.
FORT ROSEBERY
L. BANGWEULU
Flat Plain
LUBUMBASHI
MPIKA BOMA
LUANGWA R.
MUFULIRA
8
9
10
11
12
26
27
28
29
30
31
32
33
34

SHEET 13


LAKE NYASA
RUVUMA R.
LUGENDA R.
LURIO R.
L. CHILWA
L. AMARAMBA
L. MALOMBE
BLANTYRE
ZOMBA
LINDI
MTWARA
PORTO AMELIA
MONAPO
TUNDURU

SHEET 14

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