Paper G 12

# STRUCTURAL GEOLOGY OF THE AFRICAN RIFT SYSTEM: SUMMARY OF NEW DATA FROM ERTS-1 IMAGERY

P. A. Mohr, *Smithsonian Astrophysical Observatory, Cambridge, Massachusetts*

## ABSTRACT

ERTS imagery reveals for the first time the structural pattern of the African rift system as a whole. The strong influence of Precambrian structures on this pattern is clearly evident, especially along zones of cataclastic deformation, but the rift pattern is seen to be ultimately independent in origin and nature from Precambrian tectonism. Continuity of rift structures from one swell to another is noted. The widening of the Gregory rift at its northern end reflects an underlying Precambrian structural divergence, and is not a consequence of reaching the swell margin. Although the Western Rift is now proven to terminate at the Aswa Mylonite Zone, in southern Sudan, lineaments extend northeastwards from Lake Albert to the Eastern Rift at Lake Stefanie. The importance of en-echelon structures in the African rifts is seen to have been exaggerated.

## INTRODUCTION

Unified mapping of regional structures of the African rift system (Figure 1) on a scale of 1:1 million has been completed except for a few persistently cloud-covered areas. The mapping has been done by direct tracing from 18-cm square black-and-white prints (spectral bands 5 and 7). Incorrect indication of coordinates on some images has been adjusted for using the USAF Operational Navigation Charts, and distortion from a precise 1:1 million scale has been allowed for by arithmetical scaling.

The results of the mapping have been charted on fifteen 100 x 50cm sheets, and they include Precambrian strike, Cainozoic faults, and lineaments of an uncertain nature. In some areas, young lava shields, calderas, cones and craters, and lithological boundaries have additionally been recorded. The area mapped covers nearly 5 million sq.km, and obviously it has been impossible to give full attention to fine detail, fascinating though this can be on the best ERTS images.

River courses and lake shorelines in eastern Africa are accurately seen for the first time, though due to uncertainties in satellite position the precise coordinates of mapped features can be subject to as much as 2-3 minutes of arc error in some areas.

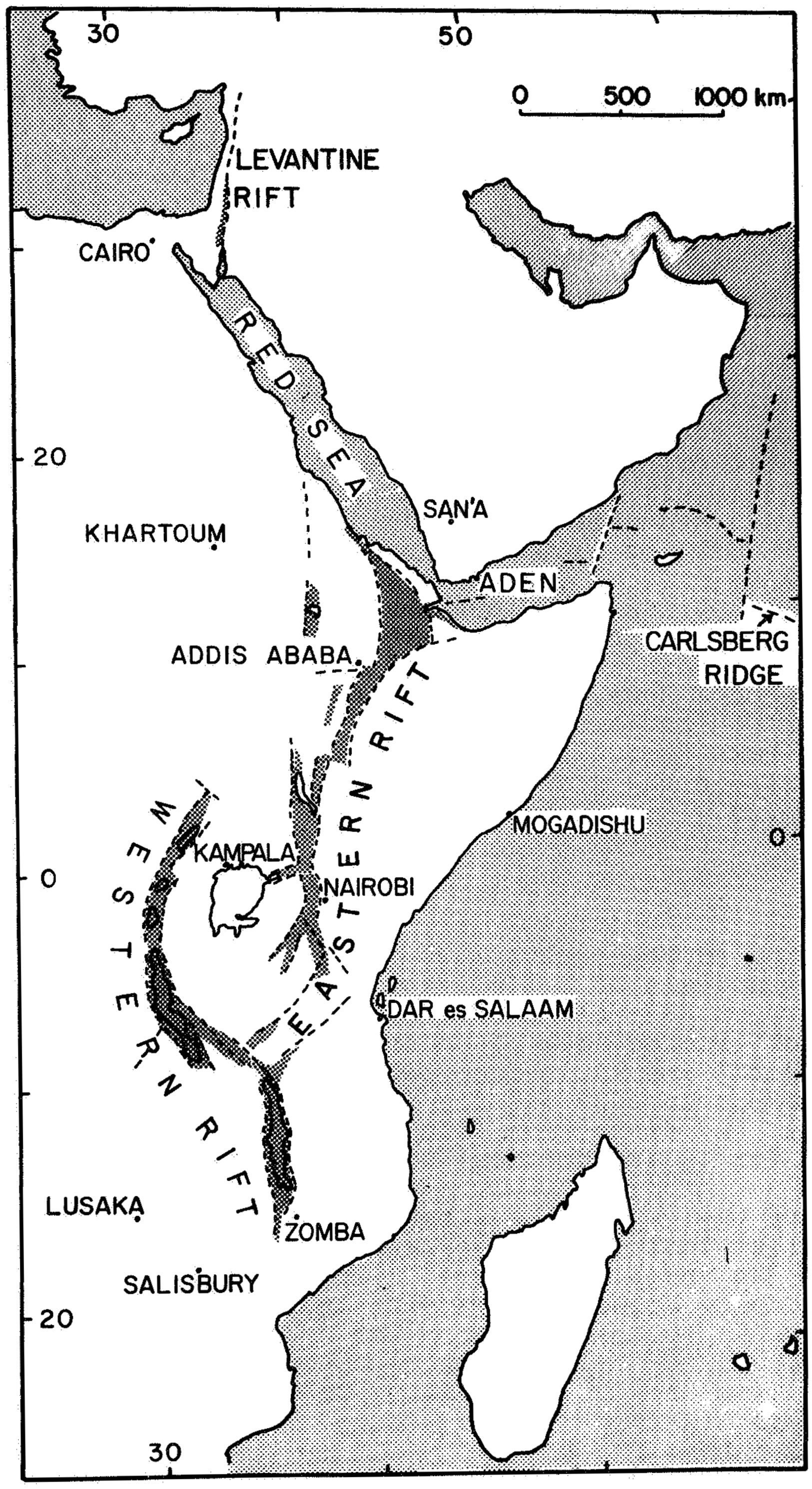

Figure 1. The East African rift system (rift valleys stippled).

This paper presents a summary of information interpreted from the mapped sheets. The sheets themselves will be published by Smithsonian Astrophysical Observatory in the final report on this work. In lieu of these sheets here, the reader should seek geographical assistance from the maps in Baker et al. (1972) and McConnell (1972).

## METHOD OF MAPPING AND GROUND CONTROL

Although detailed mapping and study of the Precambrian fold-belts of eastern Africa falls outside the scope of the present work, an important question concerning the African rift valleys is the degree of parallelism of rift faults to pre-existing structures. Therefore, trends of strike-lines in exposed Precambrian terrain have been mapped from the ERTS imagery where these lines are clearly expressed. The problem is complicated by the fact that strike-lines are best observed in regions of appreciable topographic relief where the degree of lateritic palaeosoil cover is minimised. Instances of an apparent transition from strongly to weakly expressed Precambrian strike features, for example in Katanga and northern Ethiopia, can be related to the degree of soil cover and not to any change in structural style.

Precambrian strike-lines identified on ERTS imagery usually denote lithological strike of tilted or folded strata, particularly for younger Precambrian rocks such as comprise the Bukoban System of northwestern Tanzania, the Karagwe-Ankolean of Burundi, the Lufilian and Irumide belts of northern Zambia, or the Precambrian sequence of northern Ethiopia. This type of strike-line is characteristically curvilinear and frequently reveals broad synclinoria/anticlinoria. Where deformation and metamorphism have been intense, lithological strike is obliterated or at least obscured to the extent that the identified strike-lines can be said to represent a new, refoliated grain. This is notably the case in zones of deep-seated cataclasis, known from ground surveys, as for example in the Rukwa rift and the central sector of the Lake Tanganyika rift, and in the Aswa Mylonite Zone of southern Sudan against which the Western Rift terminates. This type of strike-line is characteristically precisely linear over distances of the order of 100km, and when followed by Cainozoic rift faulting the two types of structure can become virtually indistinguishable on the ERTS imagery.

Boundaries between different, regional lithological types in Precambrian terrain, though in some places clearly expressed on the ERTS imagery, have not been mapped in the present work. Some circular structures, including ring-intrusions, have however been included as possibly marking otherwise masked lines of ancient crustal weakness.

The faulting which gives form to the present-day rift valleys of eastern Africa is generally recognised to be of Pliocene-Quaternary age (Baker et al., 1972). The topographical expression of the faults is therefore usually sharp, and because of this they are easily detected on the ERTS imagery. This is especially so for east-upthrown faults, which cast a sun-shadow at the time of imaging. Northwest-upthrown faults can sometimes be detected by illumination of their scarp, showing as a bright strip on the imagery, but where the scarp is somewhat denuded then the modest increase in brightness can be lost amongst background variations. It cannot be denied, therefore, that in regions where ground-truth is lacking there may be a bias favouring representation of the eastern boundary faults of graben (and western boundary faults of horst) on the author's maps.

The direction of throw on rift faults can be detected not only from sun-shadow or illumination, but frequently also from identification of the drainage pattern. The darker tones of afforestation are not a reliable guide: in some semi-desert areas, forest occurs along the foot of fault-scarps, presumably where there is near-surface groundwater. In some hilly terrain, forests are denser above the scarps because prevalent mountain mists foster a cold, rain forest. Complete afforestation makes the detection of faults very difficult, even where strong faults are seen to enter such an area.

Evidence for large-scale transcurrent faulting in the African rift system has not been found in this study, and it is probably best that this phenomenon be sought initially from ground and aerial photographic surveys. Likewise, no thrust-faulting has been identified in the rift system; the Precambrian Nandi fault of western Kenya (Sanders, 1965) is remarked on the ERTS imagery, but its nature, controverted even on the basis of ground studies, is not revealed thereon. ERTS imagery is a suitable tool for determining the nature of regional faults only insofar as the linearity of the fault trace can be related to topography and lithological strike. Even here some ambiguity can arise, as shown by the fact that regional rift faults with steep hade can show an almost perfectly linear trace whereas small, short faults of the graben floor, also with near-vertical hade, yet have a characteristically sinuous trace.

The third class of structural feature identified in this work is covered by the non-generic, descriptive term of lineament. Lineaments usually have the form of a linear arrangement of topographic features, either continuous or interrupted, without clear evidence of crustal displacement that defines a fault. Many of them trend at a large angle to the main rift faulting. Where Precambrian structures are largely masked by superficial cover, their vague and intermittent surface expression can form a type of lineament; but lineaments as mapped in this study can also cut across the strike of well-exposed Precambrian terrain, and could represent regional jointing or an overprinted or secondary structural trend. Lineaments are distinctly rare in the Mesozoic-Eocene sedimentary basins of the Horn of Africa, perhaps because of the weakly consolidated nature and low rigidity of the rocks concerned, but in the Cainozoic volcanic fields can be common. Where a volcanic field is only a thin pile of lavas, the structural trend from adjacent Precambrian terrain can, as in central-north Ethiopia, be traced as lineaments into the volcanic field; but other lineaments in such fields can be discordant both to the nearest exposed Precambrian structures and rift faults. Indeed, the latter form the most characteristic type of lineament, whose trace can extend, though discontinuous or offset, for several hundred kilometres.

A not-yet-understood property of the ERTS imagery is its differential emphasis of structural features according to the overall tone of an image. Some darker images emphasise linear faults and lineaments, whereas lighter, more contrasted images bring out faults with large topographic displacements. Differential emphasis also comes, of course, from the different spectral bands employed by the ERTS-1 satellite, and in the present work it has been consistently noted that band 5 (6000-7000Å) best brings out geological structures, except where the overall tone is dark when band 7 (8000-11000Å) yields a lighter and more contrasted image. Band 7 images are also preferred for regions of extensive vegetation cover, and for regions subject to partial cloud-cover.

Ground survey data have been referred to throughout the author's mapping as a check against doubtful features expressed on the ERTS imagery. Whilst a few structural lines were recognised on this imagery only subsequent to a search originating from knowledge of ground data, it must be emphatically pointed out that in all cases the mapping has proceeded first from the images and then been checked against ground data. In this process, for example, the direction of fault-throw, or the manner of bifurcation or intersection of faults, has occasionally required correction from closer re-scrutiny of the images. In no case whatsoever has the author indicated on his maps structures that cannot be discerned on the ERTS imagery, even though there be an important feature (according to ground surveys) which is actually present. Therefore it will be discovered that the new ERTS-based maps lack some structural data shown on geological maps, and add new data previously unsuspected. The ERTS-based maps add to, and do not supersede existing structural maps.

Owing to the present lack of cloud-free imagery, no mapping has yet been possible of the Western Rift between latitudes 1°N and 3°S, nor the southern end of the main Ethiopian rift, nor of the Kilimanjaro area.

## RESULTS

### Relation of rift faulting to Precambrian structures

This knotty and persistently controversial topic basically concerns two alternative interpretations: 1. the pattern of the

rift faults is a faithful reflection of major Precambrian structures, owing (to an extent which is disputed) to continuity of a single tectonic style from the Precambrian up till the present. The principal proponent of this viewpoint has been McConnell (1972, and numerous other papers referred to therein).
2. the rift faults have taken advantage of the pre-existing Precambrian tectonic 'grain', but the overall pattern of the rift system has not been determined by this grain but by a fortuitously superimposed, completely different structural event. This viewpoint has been advanced by, amongst others, King (1970) and Baker et al. (1972).

The ERTS imagery provides, for the first time, an overview of the entire problem, and indeed this is the sort of task to which satellite imagery is well-suited. Precambrian rocks are extensively exposed in proximity to the African rift system, the centres of the Ethiopian and Kenyan swells excepted, and along much of the Western Rift the rift faults themselves occur in exposed Precambrian terrain.

It immediately has to be admitted that, on a regional scale, the frequent coincidence of Precambrian structures and rift faults is uncanny. The Eastern Rift, from Tanzania to Ethiopia, essentially follows the meridional Mozambique Belt, whose final activity is dated at 550 ± 100m.y. (Clifford, 1970; Shackleton, 1967). The Western Rift commences in the south (L. Malawi rift) by following the Mozambique Belt, but then turns northwestwards along the Ubendian (1850 ± 250m.y.) deformation zone before bending round to the north-northeast along the Kibaran (1100 ± 200m.y.) deformation zone (Clifford, 1970). The Western Rift abruptly terminates in the north against a cross-cutting Precambrian structure, the NW-trending Aswa Mylonite Zone (Whiteman, 1971). The essentially upfaulted crustal blocks between the rift zones in eastern Africa are formed of cratonic nuclei, typically older than about 2500 m.y.

Some specific regions mapped from the ERTS imagery can now be discussed. In Yemen, major ENE-NE trending fracture zones in the Precambrian appear to have been reactiviated by tectonism accompanying the opening of the Red Sea and Gulf of Aden, and some were sites for Cainozoic basaltic volcanism (Mohr, 1972b). However, typical Precambrian terrain in eastern and northern Yemen takes the form of a curving mesh of strike-lines with interspersed granitic intrusive bodies: young faults in this terrain are rarely identifiable, but where they are they usually run markedly oblique to the Preambrian strike. In fact, non-parallelism of Precambrian and rift structures in Yemen is hardly surprising in view of the proximity of an RRR-triple junction at Afar, unless this coincides with a Precambrian nexus. South of the Gulf of Aden, in northern Somali, non-parallelism is general (Mohr, 1962; Beydoun, 1970).

In Ethiopia, Precambrian zones of possible cataclastic deformation

(Mohr, 1972b) trend NNE from western Tigray province into Eritrea, where they turn to a meridional trend with several bifurcations and reunions. It is difficult to allow these structures as being parallel to the adjacent Red Sea basin. Central Tigray province exposes broad synclinoria and anticlinoria trending NNE-NE (Beyth, 1972): this regional Precambrian trend is slightly but definitely oblique to the Cainozoic margin structures of western Afar further east (Mohr, 1972a, 1973), and to the Tana graben further south. In northern Ethiopia and eastern Sudan, strongly expressed E-ESE Precambrian lineaments are not related to any known rift structures.

In central Ethiopia the Precambrian is masked by thick volcanic cover, but east of the main Ethiopian rift, along meridian 39°E, persistent and rather linear Precambrian structures (Chater and Gilboy, 1970) trend N-S, oblique to the NNE strike of Ethiopian rift faulting (But N-S faulting determines the Amaro horst and Galana graben at the southern end of the rift - see Levitte et al. 1974). Strongly discordant angles separate the meridional Precambrian strike of the Kenya-Ethiopia border region from superimposed NW-SE Cainozoic faulting, though numerous small basaltic centres appear to be aligned at intersections along the Precambrian trend.

East of the Gregory rift, in north-central Kenya between latitudes 2°N and 0°, the detailed ground-mapping of Baker (1963) is fully confirmed. The Precambrian strike here trends N-NNW, whereas the rift faulting immediately to the west trends NNE. This might seem to be a clear case of non-parallelism, yet the Precambrian structures project northwards into the precise alignment of the Mt Kulal volcanic range and related rift structures, east of Lake Rudolf. To the south, the same ancient structures pass via the Pleistocene volcanic centre of Mt Kenya (Baker, 1967) to the Cainozoic volcanics and faulting of the Yatta plateau. If the Gregory rift itself is following a 'discordant' NNE Precambrian trend, this is of course hidden by young volcanics and sediments. However, this possibility is rendered less likely by the fact that, west of Lake Rudolf, the western margin structures of the rift are precisely parallel to again NNW Precambrian strike-lines, though the rift structures are notably more linear than are the Precambrian ones (Mohr, 1972b).

The Western Rift is often regarded as the example par excellence of a rift valley determined by pre-existing structures, and a description of the polyphase Precambrian tectonism of the region and its influence on the Cainozoic rift faulting has been given by McConnell (1972). The Western Rift meets important NE-SW faulting at a structural node at latitude 9°S, longitude 33½°E; here the Rift trends NW-SE and its unusually linear faulted margins are strongly developed in the southern L. Tanganyika-L. Rukwa -northern L. Malawi sector. This strong expression and linearity are matched in the precisely parallel Ubendide structures the cataclastic character of which emphasises a zone of intense crustal deformation separating two cratonic nuclei (Sutton and Watson, 1959; Brown, 1962; McConnell, 1972). By contrast, the NE-trending Cainozoic faulting, expressed both northeast of the node (Usangu and Fufu faults) and to the southwest (Luangwa valley faults), are seen on the ERTS imagery to be superimposed on mild, NE-trending Irumide structures that are obliterated by the ostensibly older Ubendide structures at the node itself. At any rate, the predominant Precambrian trend is also the predominant Cainozoic fault trend here. Directly to the west, NE-SW faulting of the Upemba and Mweru half-graben is generally close to parallelism with structures of the relatively mildly deformed Kibaride belt (Cahen, 1970); however, no important Cainozoic faults are revealed along the imposing structural arc of the end-Precambrian Katangides (Cahen, 1970).

The L. Tanganyika rift, roughly 70km wide, is at first glance strongly controlled by the NW-SE Ubendide structures. In fact this only holds for the central sector of the rift; at latitude 6°S the rift trough is offset dextrally and thus, proceeding northwards, the rift escapes from the influence of the Ubendide structures continuing west of the lake, and follows the meridional trend of the related Rusizian structures though with some influence also from the Kibaride belt. Again, this younger Precambrian belt is largely obliterated where it crosses the older Rusizides (see McConnell, 1972, for a discussion on this problem). Similarly, proceeding southwards from the central sector of the L. Tanganyika rift, the Ubendide structures run straight, southeast across mountainous terrain to the L. Rukwa rift. But the L. Tanganyika rift itself, maintaining its normal width, extends SSE-wards until terminating in a region of Cainozoic cross-faulting.

ERTS imagery of the L. Tanganyika region therefore suggests two key points for an understanding of the Precambrian-Cainozoic structural relations problem. First, where Precambrian crustal deformation has been most intense, rift faulting is also more strongly developed. It is as though the Precambrian cataclastic zones provided trans-crustal sutures which became planes of weakness when tensional strain accumulated during the Cainozoic. Second, the L. Tanganyika trough persists in its curving arc, even where forced to make a lateral offset, in defiance of the linear Ubendide structures: the rift here is not a straight NW-trending valley superimposed on the length of the Ubendide belt.

In conclusion of this section, Precambrian structures have a powerful local influence on the Cainozoic rift structures. On the regional scale revealed by the ERTS imagery, however, the rift valleys are seen to persist in trends that transgress the Precambrian structures, suggesting that a new stress-field has been imposed with the generation of the rift valleys. Whether, on the sub-continental scale, the near parallelism of the African rift system and the Mozambique Belt is of fundamental structural significance cannot be answered here, but the question is of importance to possible relations of thermal plumes and plate motions.

## The regional fault pattern

The fault pattern of the African rift system is known from ground and aerial surveys in varying degrees of detail for different sectors of the system. Ground surveys are fairly complete for the southern and central sectors of the Gregory rift, for the southern and western regions of the L. Malawi rift, and for Afar; they are only of reconnaissance type for much of the Western Rift and the Ethiopian rift, and are virtually non-existent for the graben occupied by lakes Tana, Stefanie and Mweru, and the Luangwa valley.

The great merit of the ERTS imagery is that, for the first time, it provides the means for a unified mapping of the major structures of the whole African rift system, formidable task though this is. As emphasised previously, this mapping is not a substitute for, but an adjunct to ground mapping. Nevertheless the satellite imagery enables a first interpretation to be made of unsurveyed regions in the light of what it reveals about well-surveyed regions. Furthermore, some significant additions and revisions are provided from ERTS imagery of even well-surveyed regions.

The fault pattern in Yemen is revealed by ERTS imagery to show a coastal zone of major warping and associated antithetic faults, both for the Red Sea and the Gulf of Aden (Gass et al., 1965). In the interior of the Yemen plateau, NE-ENE trending fracture zones have been identified. Other important faulting runs southeast across northern and eastern Yemen, parallel to the Red Sea structural trend north of its Yemeni, SSE-trend narrowing. These and other features have been discussed by Mohr (1972b).

The African rift system meets the Red Sea and Gulf of Aden at the Afar triple junction (Tazieff, 1970, 1972; Mohr, 1970, 1972a). Mapping of Afar margin structures from ERTS imagery has been described elsewhere (Mohr, 1973). Essentially, the western margin of Afar shows a gently sinuous plan which, in detail, reveals the powerful influence of NNW-trending 'Red Sea' structures. As the western margin runs close to meridian 40°E throughout its extent, this requires that the NNW-trending structures be offset dextrally. These offsets occur in sectors where the dominating structural trend in NNE; this trend parallels the Precambrian 'grain' west of northern Afar, and in the south occurs as a forceful extension of main Ethiopian rift faulting projecting right across southern Afar. Marginal warp-zones, and marginal graben associated with belts of antithetic faulting can be identified on the ERTS imagery.

The southern margin of Afar can be mapped accurately for the first time from the ERTS imagery. The western sector of the margin shows the influence of dextrally offset Ethiopian rift structures that turn off northwards into Afar (Mohr, 1973); this pattern changes abruptly near longitude 41°E where a Gulf of Aden trend is imposed, though this fades out south of the Aisha horst (Canuti et al., 1972; Mohr, 1967, 1972a). Further east, along the northern margin of the Somalian plateau, the dominant fault trend is WNW and is especially strongly developed in the Asseh graben and on the Cape Guardafui peninsula - the latter is revealed for the first time on the ERTS imagery. Inland, WNW faulting again determines the Nogal and Darror graben (Azzaroli and Merla, 1957).

The SSW-trending faulting of southern Afar continues directly as the main Ethiopian rift to almost latitude 5°N (Baker et al., 1972; DiPaola, 1973). The aerial photographic mapping of DiPaola is largely confirmed and amplified by the ERTS imagery, which shows however that the importance of dextral en-echelon offsets in the rift has been exaggerated (eg. Mohr, 1967). Only the axial Wonji fault belt of the rift floor shows such offsets (Mohr, 1962), and as in places this belt can show two parallel developments, and elsewhere can be absent, the term en-echelon is a misnomer on the regional scale. Immediately west of the main Ethiopian rift, the parallel structures of the Omo valley can be traced northwards via the Guder valley to possibly as far as the Tana graben. The asymmetrically developed Tana graben occurs within the Ethiopian plateau block, and its fault pattern has been accurately mapped for the first time, using the ERTS imagery.

The regional link between the Ethiopian and Gregory (Kenyan) rifts was poorly known until the advent of the ERTS imagery. This reveals that the faulting at the southern end of the Ethiopian rift, and the Kino Sogo fault belt east of L. Rudolf, lie on a common NNE-oriented alignment. An unfaulted 'gap' of about 100km length separates the terminal faults of the two rifts (note: to the west of this region the Omovalley faulting passes through a broad zone of horst-graben structures into the Lake Rudolf basin). The transition of the rift system across this gap was thought by Mohr (1967) to be effected through the L. Stefanie graben via a dextral offset; but the imagery shows that this graben lies west of the alignment, and is formed of NNW-trending faults crossed by secondary but important ENE-faulting.

The transverse faulting of the L. Stefanie graben projects as lineaments across the structural gap between the Ethiopian and Gregory rifts. In the opposite direction it projects across Turkana, where lineaments line up with WSW-SW faulting on the eastern side of the L. Albert rift. Here is tentative evidence that the Western Rift, though indubitably terminating against the Aswa Mylonite Zone north of L. Albert, may persist through a minor tectonic offshoot across to the Eastern Rift, though not, it must be emphasised, as a graben. The structural gap between the Ethiopian and Gregory rifts is likewise a gap to some NW-SE tectonism, superimposed on a prominent, parallel Precambrian structure, extending from Moyali to the Omo valley.

The regional structures of the northern half of the Gregory rift (Baker et al., 1972) are shown in their unity on the ERTS imagery as a magnificent, regular fanning-out northwards. The rift widens from 60km at latitude 0° (at the junction with the transverse

Kavirondo rift) to 130km at latitude 2°N, and to about 300km for less clearly defined structural margins at latitude 4°N. Within this structural widening, the weakly faulted L. Rudolf basin shows a northward fanning-out into the southern Ethiopian plateau. Two major points require emphasising here: firstly, that although the northward widening of the Gregory rift structures coincides with the topographic decline from the centre to the margin of the Kenyan swell, it also coincides with a widening of the Precambrian structures. This raises a fundamental question: would swell uplift in the Cainozoic have formed a continuous, quasi-midoceanic ridge from Ethiopia to Tanzania if dissipation had not been enforced by a pre-existing structural pattern? Second point: strongly expressed rift structures do cross from the Kenyan to the Ethiopian swell without apparent diminution in strength (N.B. the gap noted above lies upon the fringe of the Ethiopian swell, and not between the two swells), though there does seem to be a greater complexity and less regularity to the structural pattern in the boundary region.

At the conjunction of the ENE-trending Kavirondo rift with the main Gregory rift, the latter undergoes an abrupt change from a N-NNE structural trend in the north, to a NNW-NW trend in the south. The southern half of the Gregory rift comprises a majestic curve, concave to the west, from the equator to latitude 4°S where the structural trend has finally turned to NE-SW. Characteristic platforms, not found in the Ethiopian or Western rifts, occur along the eastern side of the Gregory rift (Baker et al., 1972), and from the western margin several turn-off structures are revealed on the ERTS imagery. West of the rift, within the L. Victoria block, several important structures trend ENE-NE: these include the Kavirondo rift, the Uitimbara-Siria faults, the Speke Bay graben, and the L. Eyasi faults at the southern end of the Gregory rift. If these tensional features are contemporaneous with the Gregory rift, what homogeneous stress-field could have given rise to the overall fault pattern? Has there been a slight anti-clockwise rotation of the L. Victoria block?

Although the Gregory rift terminates southwards in a fanning-out zone, this phenomenon is shown on the ERTS imagery to be much more abrupt and less symmetrical than at the northern end of the rift (Baker et al., 1972). The main faulting, as mentioned above, turns to a SW direction, and lineaments of this trend continue across the Dodoman nucleus to the Western Rift. Faults of S and SE trend are relatively minor in the fanning zone, and the ERTS imagery shows that there is no significant connexion of the Gregory rift with the Usangu-Fufu faults farther south (see also Hepworth, 1972). Therefore it seems misleading to speak of the Eastern Rift as meeting the Western Rift at Mbeya: the Eastern Rift has already terminated further to the north.

East of the Gregory rift, a NNW-trending belt of strongly deformed Precambrian rocks extends from southern L. Rudolf, passes close to Mt. Kenya and along the Yatta plateau, and reaches northeastern

Tanzania at the Pare-Usambara graben-horst structures (McConnell, 1972). Once again, the control of Precambrian 'grain' on in this case extra-rift tectonism is emphasised: the corollary of course is that there must be important structural sub-divisions to be made within the Mozambique Belt.

We now turn to the Western Rift. Near the northern end of the Western Rift, the powerful NE-trending faulting of the Lake Albert sector curves, proceeding northwards, to a NNE-trend and a weak graben is juxtaposed west from the northern end of the lake. The faults of this weak graben impinge upon, and are abruptly terminated by the Aswa Mylonite Zone, on the Uganda-Sudan border (Whiteman, 1971). No NE-trending faults are revealed by ERTS imagery to continue northeast of the Aswa Mylonite Zone, where rather the tectonic trend is NW-SE, related to the northward widening of the Gregory rift.

The Aswa Mylonite Zone is a strongly, almost violently expressed structure for which there is as yet little ground-survey information. It forms a narrow, linear zone of cataclasites, about 150km long, whose ends are splayed with a slight clockwise bias; the southern splay is closed, indicating the presence of a broad folded structure. Cainozoic faulting is almost certainly imposed upon the Mozambiquian Aswa structures (Almond, 1969), with upthrows to the southwest if interpretation from the ERTS imagery is correct; Almond (1969) also regards the zone as being one of sinistral shear, and this is compatible with the clockwise splay. Faults continue northwestwards for at least a further 200km from the Aswa zone. Lineaments are also observed to project southeastwards from the zone, and pass via the southern fringe of Mt Elgon to the Precambrian Nandi thrust fault (Sanders, 1965). However, this southeastward continuation of the Aswa zone across northern Uganda cannot be matched with the narrow, continuous belt of cataclasites indicated by Almond (1969), perhaps owing to the effect of variably masking soil cover on the ERTS imagery. It is interesting to note that the Aswa Mylonite Zone and its continuations form a major Precambrian structure that has not been utilised in the development of the African rift system: this gives further support to the view that the rift system is a new and distinct structural unit rather than an ongoing re-activation of ancient transcrustal sutures.

ERTS imagery of the Western Rift southwards from Lake Albert is largely cloud-covered, and no useful structural maps can be constructed for as far as the northern end of the L. Tanganyika rift. The important relationships between the faulting of this rift and the Precambrian structures have been discussed briefly in the preceding section. The northern part of the L. Tanganyika rift is a graben superimposed on the Rusizian trend (N-S), but with some intersecting or adjusting faults of NNE-NE, Karagwe-Ankolean trend immediately east of the rift. The central sector of the L. Tanganyika rift is faulted parallel to the NW-NNW Ubendide structures, though the rift trough itself jumps across these structures at latitude 6°S: thus the Kiyimbi horst west of the lake lies on the precise alignment of the Kungwe horst east of the lake, such that the rift is asymmetrically developed in one sense north of latitude 6°S, and in the opposite sense south of 6°S. At latitude 7½°S there is a further, 35km dextral offset of the graben faulting, which continues SSE as far as latitude 9°S. On the western side of the graben, however, at latitude 8½°S the marginal faulting is largely overuled by strong NE-SW faulting that extends southwest to the Mweru Wantipa graben-horst structures.

West of the L. Tanganyika rift, NE-ENE faulting, with predominant southeasterly upthrows, forms the Kabamba-Upemba and L. Mweru half-graben as well as more doubtful features north of the lower Lukuga river. It is of interest that the same NE-ENE trend is manifested in graben faulting west of the Eastern Rift (see above), as well as in numerous lineaments between the two Rifts. The termination of the L. Tanganyika rift in the south may be related to the presence of such cross-lineaments.

The L. Rukwa rift develops south of latitude 7°S, and runs about 130km east of the L. Tanganyika rift and with a SE trend that is significantly different from the SSE trend of the L. Tanganyika rift at the same latitudes. The intervening terrain is also strongly faulted, with a prominent high horst. The ERTS imagery reveals this faulting accurately for the first time. The faults of both margins of the L. Rukwa rift are exceptionally long and linear, and follow Precambrian cataclastic zones (Brown, 1962) of the Ubendides. The faulting of the L. Rukwa rift continues beyond the Mbeya node and into the L. Malawi (Nyasa) rift, and is particularly strongly developed on the northeastern side of the latter, in the Precambrian migmatites of the Livingston Mts. Mapping of the L. Malawi rift (Bloomfield, 1966) is not yet completed from ERTS imagery (Mohr, 1972b), and so discussion on the southern end and termination of the Western Rift is deferred.

In summary, the overall pattern of the African rift system as revealed from ERTS imagery suggests an incipient plate boundary struggling to express itself. The diffuse complexity of the pattern perhaps stems from both the slow rate of extensional movement in thick continental crust (McKenzie et al., 1970), and from the influence of the pre-existing Precambrian structures. It can be remarked that the Red Sea and Gulf of Aden cut straight enough and singly in their respective traverses across the Arabo-African continent, but their spreading rates are appreciably faster and there were no cratonic nuclei to deflect their initial paths. The Tanganyika block (Dodoman nucleus) has surely played an important role in the division of the Western from the Eastern Rift.

## Other features

The ERTS imagery reveals numerous other features of interest to the structural geologist, the volcanologist, the glaciologist, the sedimentologist and the economic geologist. Not all these features can be even briefly referred to here.

Noteworthy from the ERTS mapping is the persistent occurrence of ENE-trending lineaments. As mentioned in the previous section, there are important extra-rift normal faults of this trend, branching from or intersecting with the western margins of both the Western and Eastern Rifts. However, these faults tend to be curvilinear or even sinuous, whereas the lineaments, as their name implies, are linear. Well then, are these lineaments real structural elements, or are they 'hallucinosutures' (Shackleton, 1973; Tazieff, 1973)? Whilst the regular sun-angle obtaining during ERTS imaging might be expected to favour addiction to ENE-NE trending hallucinations, in fact there is sufficient variation of this angle with latitude and season that hallucinosutures might be expected to vary more in their trend than they actually do. In this work, given lineaments have been identified regardless of season, though their intensity of expression may vary. Also, although the writer once grossly exaggerated the importance of ENE-trending lineaments in Ethiopia (Mohr, 1967), yet there is sufficient ground-knowledge to relate some lineaments of this trend to linear faults, lines of warping, dykes, and possible fracture lines without significant displacement, such that their existence must be faced and not pre-diagnosed. The lineaments, now precisely located from ERTS imagery, require to be examined carefully on the ground, though their structural significance will probably only be realised from a synthetic study of the fracture pattern of the African continent as a whole.

Calderas, volcanic craters and associated young lava fields are usually prominent on the ERTS imagery of eastern Africa. Mapping from the imagery is revealing that at least some of the major volcanic centres are situated at tectonic nodes. That this is the case for the Rungwe volcanoes at the Mbeya node of the Western Rift was evident enough from ground surveys. But it is now seen, for example, that Alid caldera in northern Afar lies on the intersection of the Precambrian Atsbi horst (Kazmin and Garland, 1973) lineament of the Ethiopian plateau with the Quaternary fault-belt of the floor of northernmost Afar.

Glaciated valleys can generally be recognised without difficulty on the highest mountains of eastern Africa. In the Sagatu Mts, east of the main Ethiopian rift, such valleys cut across the margin dyke-swarm of the rift valley and have been mapped by the author and E.C. Potter (in preparation). The largest glaciated valleys in the whole of eastern Africa have been recognised from the ERTS imagery of the Simien Mts, northern Ethiopia (Mohr, 1963). There, glaciers as long as 40km flowed south and east from the southeastward tilted crest of the Miocene Simien shield volcano.

No certain meteorite craters have been identified from the ERTS imagery of eastern Africa. Worthy of possible attention, however, are the circular feature at 10°45'S, 27°45'E, and a better preserved but less symmetrical feature at 7°25'S, 28°15'E.

## REFERENCES

Almond, D.C., 1969, Structure and metamorphism of the Basement Complex of north-east Uganda. Overseas Geol. Min. Resources, 10, 146-163.

Azzaroli, A., and Merla, G., 1957, Carta geologica della Somalia e dell'Ogaden (1:500,000). Agip Mineraria-Consig. Naz. Ricerche, Firenze.

Baker, B.H., 1963, Geology of the Baragoi area. Geol. Surv. Kenya, Rep. 53, 74pp.

Baker, B.H., 1967, Geology of the Mount Kenya area. Geol. Surv. Kenya, Rep. 79, 78pp.

Baker, B.H., Mohr, P.A., and Williams, L.A.J., 1972, Geology of the Eastern rift system of Africa. Geol. Soc. Amer., Spec. Paper 136, 67pp.

Beydoun, Z.R., 1970, Southern Arabia and northern Somalia: comparative geology. Phil. Trans. R. Soc. London, A, 267, 267-292.

Beyth, M., 1972, To the geology of central-western Tigre. Rheinische Friedrich-Wilhelms Univ., Bonn. 159pp.

Bloomfield, K., 1966, Geological map of Malawi. Geol. Surv. Malawi.

Brown, P.E., 1962, The tectonic and metamorphic history of the Pre-Cambrian rocks of the Mbeya region, southwest Tanganyika. Quart. J. Geol. Soc. London, 118, 295-317.

Cahen, L., 1970, Igneous activity and mineralisation episodes in the evolution of the Kibaride and Katangide orogenic belts of central Africa. In: African Magmatism and Tectonics (eds, Clifford, T.N., and Gass, I.G.), Oliver & Boyd, Edinburgh, p. 97-117.

Canuti, P., Gregnanin, A., Piccirillo, E.M., Sagri, M., and Tacconi, P., 1972, Volcanic intercalation in the Mesozoic sediments of the Kulubi area (Harrar, Ethiopia). Boll. Geol. Soc. Ital., 91, 603-614.

Chater, A.M., and Gilboy, C.F., 1970, Stratigraphic and structural relations in the Shakisso-Arero region of southern Ethiopia. 14th Ann. Rep. Res. Inst. Afr. Geology, Univ. Leeds, 8-11.

Clifford, T.N., 1970, The structural framework of Africa. In: African Magmatism and Tectonics (eds. Clifford, T.N., and Gass, I.G.), Oliver & Boyd, Edinburgh, 1-26.

Di Paola, G.M., 1973, The Ethiopian rift valley (between 7°00' and 8°40' lat. North). Bull. Volc., 36, 517-560.

Gass, I.G., Cox, K.G., and Mallick, D.I.J., 1965, Royal Society volcanological expedition to the South Arabian Federation and the Red Sea. Nature, 205, 952-955.

Hepworth, J.V., 1972, The Mozambique orogenic belt and its foreland in northeast Tanzania: a photogeologically based study. J. Geol. Soc. London, 128, 461-500.

Kazmin, V., and Garland, C.R., 1973, Evidence of Precambrian block-faulting in the western margin of the Afar depression, Ethiopia. Geol. Mag., 110, 55-57.

King, B.C., 1970, Vulcanicity and rift tectonics in East Africa. In: African Magmatism and Tectonics (eds. Clifford, T.N. and Gass, I.G.), Oliver & Boyd, Edinburgh, p. 263-283.

Levitte, D., Columba, J., and Mohr, P.A., 1974, Reconnaissance geology of the Amaro horst, southern Ethiopian rift. Bull. Geol. Soc. Amer., (in press).

McConnell, R.B., 1972, Geological development of the rift system of eastern Africa. Bull. Geol. Soc. Amer., 83, 2549-2572.

McKenzie, D.P., Davies, D., and Molnar, P., 1970, Plate tectonics of the Red Sea and East Africa. Nature, 226, 243-248.

Mohr, P.A., 1962, The geology of Ethiopia. Univ. Coll. Addis Ababa Press, 268pp.

Mohr, P.A., 1963, Geological report on an expedition to the Simien Mountains. Bull. Geophys. Obs. Addis Ababa, 6, 155-167.

Mohr, P.A., 1967, The Ethiopian rift system. Bull. Geophys. Obs. Addis Ababa, 11, 1-65.

Mohr, P.A., 1970, The Afar triple junction and sea-floor spreading. J. Geophys. Res., 75, 7340-7352.

Mohr, P.A., 1972a, Surface structure and plate tectonics of Afar. Tectonophysics, 15, 3-18.

Mohr, P.A., 1972b, ERTS-1 imagery of eastern Africa: a first look at the geological structure of selected areas. Smithsonian Astro. Obs., Spec. Rep. 347, 57pp.

Mohr, P.A., 1973, Structural elements of the Afar margins: data from ERTS-1 imagery. Bull. Geophys. Obs. Addis Ababa, 15 (in Press)

Sanders, L.D., 1965, Geology of the contact between the Nyanza Shield and the Mozambique Belt in western Kenya. Geol. Surv. Kenya, Bull. 7, 45pp.

Shackleton, R.M., 1967, Complex history of the Mozambique Belt. 11th Ann. Rep. Res. Inst. Afr. Geology, Univ. Leeds, 12-13.

Shackleton, R.M., 1973, In: Implications of continental drift to the earth sciences (eds. Tarling, D.H., and Runcorn, S.K.). Academic Press, London (in press).

Sutton, J., and Watson, J., 1959, Metamorphism in deep-seated zones of transcurrent movement at Kungwe Bay, Tanganyika Territory. J. Geology, 67, 1-13.

Tazieff, H., 1970, The Afar Triangle. Scientific Amer., 222, 32-40.

Tazieff, H., 1973, About air and space photo interpretations of Afar. Trans. Amer. Geophys. Un., 54, 470 (abstract only).

Tazieff, H., Varet, J., Barberi, F., and Giglia, G., 1972, Tectonic significance of the Afar (or Danakil) depression. Nature, 235, 144-147.

Whiteman, A.J., 1971, The geology of the Sudan republic. Oxford Univ. Press, 290pp.