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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Structure of Afar and the Northern Part of the Ethiopian Rift [and Discussion]

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The structure of Afar and the northern part of the Ethiopian Rift

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[Plate 20]

The major structural feature of the northern part of the Main Ethiopian Rift is an *en échelon* belt of Quaternary tensional faulting with the individual faults trending approximately N 20° E. Farther north, towards central Afar, this structural pattern gives way to a zone of complex faulting. Northern Afar is dominated by a linear, axial central rift region, marked by active fissure volcanism, normal faulting and open tensional faults, all trending generally NNW. However, this central rift zone dies out northwards as it is traced towards the Gulf of Zula.

Left-lateral shear along the length of the Main Ethiopian Rift is proposed as the cause of the *en échelon* tensional fault zone, which can be traced into Afar, but is apparently not continuous with the zone of faulting associated with the median trough of the Red Sea. The latter appears to be replaced in an *en échelon* fashion southwards by zones of crustal extension in central and northern Afar.

1. Introduction

The Afar or Danakil depression is a low-lying, roughly triangular-shaped area situated within Ethiopia at the southern end of the Red Sea. Physiographically it is very clearly defined, being bounded on all sides by upland regions: the Ethiopian Plateau to the west, the Somali Plateau to the south, and the Danakil and Aisha horsts to the northeast and east respectively.

Structurally the region is of considerable interest because of its position at the junction of the Red Sea, Gulf of Aden and Ethiopian Rifts. It is the only place in the world where three well-defined rift systems join. The gross structure of the region is also important in relation to pre-drift reconstructions of the Ethio-Arabian areas and in elucidating the possible relative directions and rates of movement of the different structural blocks.

In view of its undoubted importance, it is particularly unfortunate that, until recently, the geology and structure of Afar were poorly known, largely because of the inhospitable and inaccessible nature of the terrain. No systematic geological mapping in Afar had been undertaken before 1967, and our knowledge of the geology was derived from reconnaissance work by visiting travellers. This was summarized by Dainelli (1943). Later the geology of the whole Ethiopian region was summarized by Mohr (1962).

Air photographs of the whole of Afar became available in 1965 and these have allowed Mohr (in press) to draw detailed structural maps of Afar. However, this air photographic interpretation was not controlled by sufficient ground reconnaissance.

A structural and volcanological investigation of Afar was started in November 1967 and is continuing at present. At the time of writing, only preliminary results are available for parts of northern and central Afar (Tazieff, Barberi, Marinelli & Varet (in press); Barberi *et al.* this volume, p. 293).

At its southwestern end, Afar narrows to merge imperceptibly with the Main Ethiopian Rift.

Structurally this region is simpler than Afar and it is proposed in the following to deal first with the northern section of the Main Ethiopian Rift, and then to describe how the rift structures change as they are traced northwards into Afar. The Main Ethiopian Rift is much more accessible and better-known than Afar, and the comments below are based on the summary of the geology of the Ethiopian Rift by Mohr (1967*b*) and particularly on work on the Fantale region carried out between 1965 and 1968 (Gibson 1967).

2. Structural observations

(*a*) *The northern part of the Main Ethiopian Rift*

The rift valley in central Ethiopia is a very clearly defined topographic depression between the Ethiopian Plateau to the northwest and the Somali Plateau to the southeast. On the Ethiopian Plateau, thick flood basalt sequences overlie Mesozoic sediments. It is assumed that this downwarped and/or down-faulted succession continues underneath superficial Quaternary layers in the rift valley to reappear on the Somali plateau to the south. The gross structure of this section of the rift valley is poorly known. On the Somali side, step faulting appears to be the dominant feature, while to the northwest flexuring and downwarping of the flood basalt plateau succession is probably more important. Within the rift valley itself the structure is more readily apparent and the important feature is the ubiquitous tensional faulting along a north–northeasterly trend.

The tensional faulting clearly varies in age and is in general youngest along the medial line of the rift valley, becoming progressively older as one approaches the rift margins. The approximately axial line of Quaternary faulting has been termed the Wonji Fault Belt (Mohr 1960). One of its more striking features is that it is not a continuous line of faulting but in fact a whole series of fracture swarms arranged in an *en échelon* fashion. One of these fracture swarms, associated with the central volcano Fantale (latitude 8° 58′ N, longitude 39° 54′ E), has been studied in more detail (Gibson 1967). The faults which are found both to the northeast and southwest of the volcano frequently cut a hard compact welded-tuff unit. This makes the nature of the faulting particularly evident. In this region it is clear that many of the fractures are not normal faults with predominently vertical movement along a steeply dipping fault plane. Instead many are simple open fissures with little or no vertical movement. The hard, resistant nature of the country rock allows one to demonstrate unequivocably that these open fissures have been produced by a tensional separation which may exceed 2 m. Transitional types to 'normal' faults also occur in which there is a small amount of tensional separation and some vertical displacement.

To the southwest of Fantale are two further swarms of recent faults, each with its active or recently active silicic centre. The *en échelon* arrangement of the swarms emphasizes that here the most important direction of faulting is not parallel to the rift margin but inclined at an angle of about 20°.

Mohr (1967*b*) in his summary of the geology of the Ethiopian rift considered that the *en échelon* arrangement of the swarms was due to the line of the Wonji Fault Belt being off-set along approximately east–west transform faults. However, within the area mapped there are no surface indications of any transverse or transform faults.

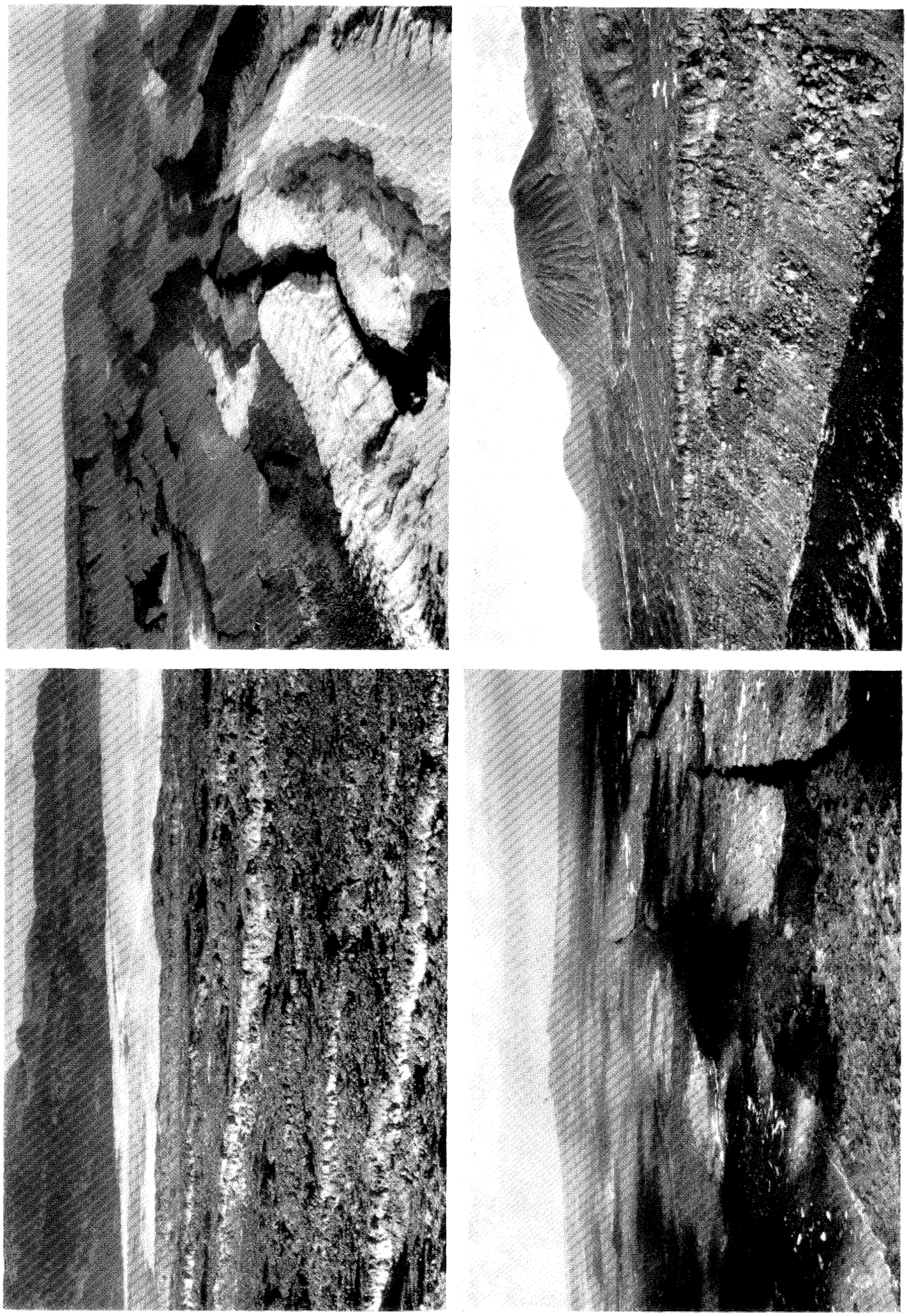

Figure 1. (*a*) Faulting on the east side of Lake Giulietti; (*b*) 'Horst' and 'graben' structure close to latitude 12° 45′ N, longitude 41° 15′ E; (*c*) view northwards along the axis of the Erta Ale range with the shield volcano Hayali Gub in the background; (*d*) normal faulting east of Lake Giulietti. Note the hyaloclastic cone in the background which is cut by a fault with a displacement of about 25 m.

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(b) *Southern Afar*

The line of Quaternary faulting has been traced northwards from Fantale both on the ground and on aerial photographs approximately as far as latitude 10° N, it being marked by tensional open faults and again by several further active or dormant silicic centres.

Between 10 and 12° N latitude, the present authors have made only a brief air reconnaissance. This suggests that north of 10° N, the zone of faulting appears less clearly defined. It would be subjective to delineate a single linear fault belt. The active silicic centres are no longer restricted to a narrow fault zone but occur widely over central Afar from the Lake Abbe region northwards; the faulting is also much more widespread.

A second important feature concerns the trend of the faulting. In southwestern Afar, and in the adjacent parts of the Ethiopian Rift, this trend is dominantly north-northeasterly. However, as the faulting is traced north into Afar, the trend veers northwards. In southeastern Afar the faulting is complex; but farther north around lake Abbe, northwesterly trending faults become dominant and the trend more regular.

(c) *Northern Afar*

The structure of Afar north of the twelth parallel is dominated by subvertical faulting and open tensional fissures with the development of conspicuous 'horst' and 'graben' structure (figure 1, plate 20). The open fissures are often several metres wide and are similar to the 'gjas' of central Iceland. The normal faults may show a vertical displacement of more than 150 m. Many of these features are clearly very young as they often cut Quaternary lavas and recent alluvial fans. North of latitude 13° N the fractures have a NNW trend, paralleling the major tectonic structure in the Red Sea. This trend characterises also the Depression south of latitude 13° N but for the eastern most part of it, where the faulting becomes almost N–S in trend.

North of Lake Giulietti, a single but complex 'graben' dominates the structure, although it is only morphologically apparent where it is not hidden beneath thick lava and evaporite sequences. Thus on the Salt Plain, the 'graben' is almost completely concealed, although geophysical work has recently established the presence of a major western boundary fault close to the present topographic escarpment. The axis of the 'graben' appears to be marked by a line of hot springs and isolated vents. This line extends directly southwards into the Erta'Ale volcanic chain, consisting of dominantly small basaltic shield volcanoes.

Volcanic activity in northern Afar is clearly related to the NNW fracture pattern and is particularly intense along the axis of the northern major 'graben'. Basaltic fissure volcanism largely predominates, although trachytes and rhyolites occur in the northern part of the Erta'Ale volcanic chain which appears to be older than the more southerly part which extends from Erta'Ale itself southwards as far as Lake Giulietti. The latter occupies a tectonic depression which apparently interrupts the Erta'Ale volcanic line. In the region to the south of Lake Giulietti, the volcanological pattern is more complex but probably dominated by the fissure volcanism of the Alaita range, a large elongate basalt shield volcano comparable to the Erta'Ale range. In contrast to the area to the north, individual rhyolite flows are larger: areas of silicic volcanism are also common.

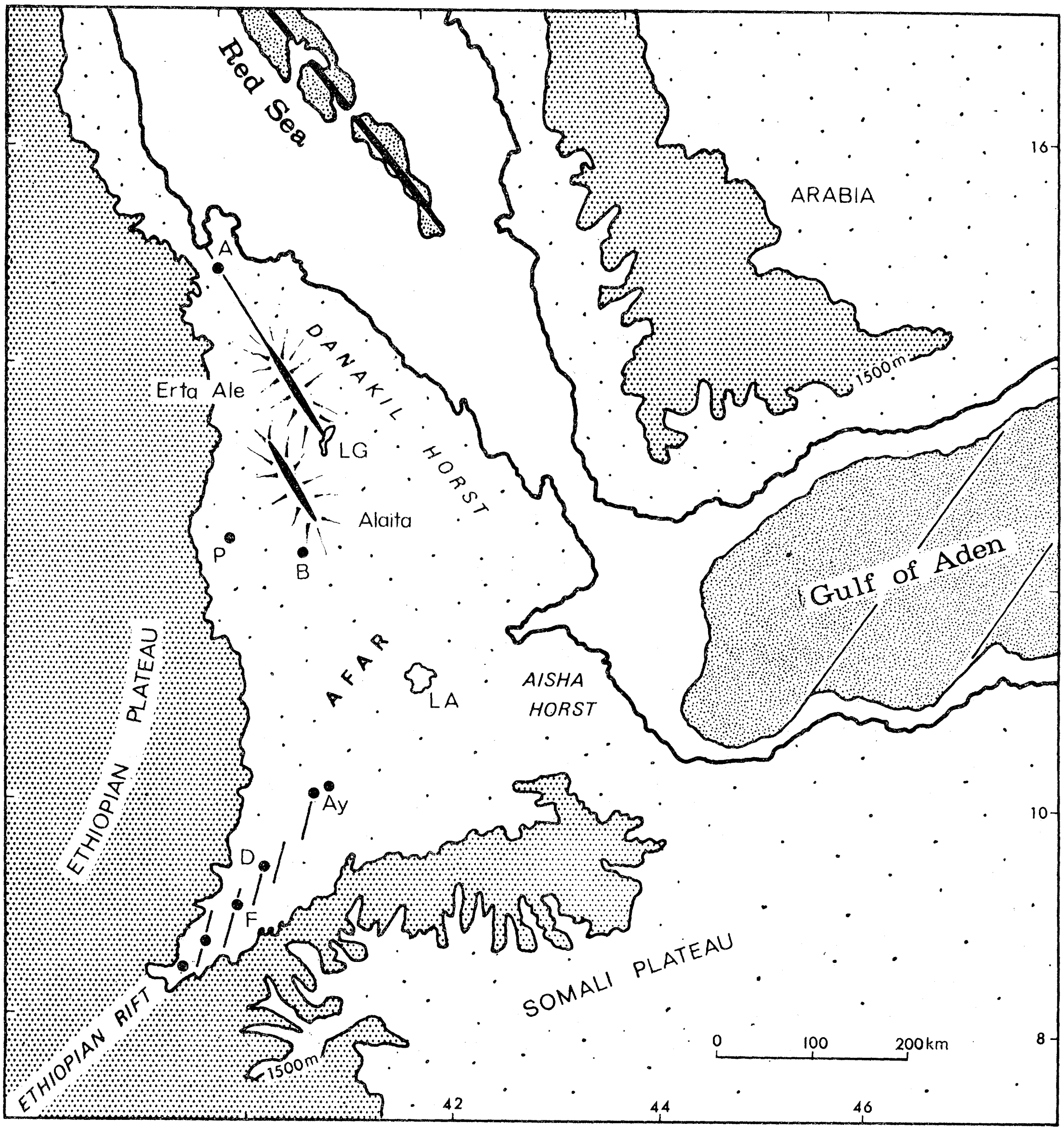

FIGURE 2. Afar and the surrounding region. In the north the *en échalon* arrangement of the Erta-Ale and Alaita chains and the Red Sea Central Trough is indicated, as is the line of Quaternary faulting in the Ethiopian Rift. Also shown are the silicic centres Fantale (F), Dofane (D), Ayelu (Ay), Boina (B), Pierre Provost (P) and Alid (A); Lake Abbe (LA) and Lake Giulietti (LG).

3. Transform and transverse faults

In three recent articles Mohr (1967*a*, *b*, 1968) has suggested that certain poorly defined but generally east-west linear structures within the Ethiopian region are transform faults. These are shown producing offsets in the linear zone of Quaternary tensional faulting in the Ethiopian rift, as well as breaks in the line of the rift scarps, particularly that bordering the western edge of Afar.

The concept of transform faulting in oceanic regions (Wilson 1965) is now generally accepted; however, one of the striking features of these faults is that they never continue from the areas of oceanic crust across into contiguous parts of the continent. Strictly 'continental' transform structures seem very rare. In the circumstances the Ethiopian examples warrant careful consideration.

Mohr (1967*a*) shows six transform faults cutting the northern part of the rift valley. In a later version of the same map (1968), some of these are omitted but three NW–SE offsets of the rift valley are indicated, one passing through Addis Ababa, and two others respectively north and south of the Galla Lakes. Detailed study in the field and examination of two different sets of aerial photographs reveal no ground evidence for any of these transverse structures. Offsets of the fault belt undoubtedly do occur and the line of the rift valley, where it can be clearly defined, is also broken and offset. However, east–west or northwest–southeast structurally controlled lineaments are almost completely absent, this portion of the Main Ethiopian Rift being dominated by north–northeasterly tensional faulting.

Detailed study of the nature of the offsets of the Wonji Fault Belt is also revealing. Normally the faulting associated with the zone of crustal spreading stops abruptly at the transform fault line, is off-set and restarts suddenly again on the other side of the fault. Examination of oceanic transform faults show that they closely follow this simple model. In contrast, studied offsets of the Wonji Fault Belt at the northern end of the Main Ethiopian Rift do not show this pattern. The generally northerly trending faults do not terminate suddenly. Instead they die out gradually and are replaced in an *en échelon* fashion by a second 'subswarm' offset in a right-lateral sense. Often the two subswarms run parallel to one another for some distance. This generally *en échelon* arrangement of the subswarms argues strongly against the presence of transform or transverse faults.

The writers are less familiar with the steep scarp facing the Afar depression. Study of large-scale topographic maps reveals obvious off-sets in the line of the scarp. However, air photographs suggest that tectonic east–west structures at the point of offset are rare or absent. In many places drainage in the tilted sediments or lavas has produced some east–west lineaments, but lateral offsets along these lines are invariably absent.

Finally, it is worth considering whether east–west transverse or transform faults are likely in view of our present knowledge of the regional structure of the Ethio–Arabian area. Careful oceanographic studies by Laughton (1966) have delineated several major and numerous minor transform structures cutting the truly oceanic floor of the Gulf of Aden. These faults trend very regularly NE–SW and are parallel or subparallel to a whole series of similar fractures cutting the northern part of the Carlsberg Ridge in the northwest Indian Ocean. This pattern of extensive areas of parallel transform faults is in fact typical of oceanic ridge regions surveyed to date. Two closely adjacent regional sets of transform structures at a sharp angle to one another are rare. Thus experience suggests that there is unlikely to be a set of east–west transform structures within Ethiopia so close to the well documented northeasterly trending examples from the Gulf of Aden.

In the circumstances, in view of the lack of surface evidence, the poor agreement with theoretical models and incompatibility with known regional structures, it is suggested that these east–west structures are rare and almost certainly not transform faults.

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4. Large-scale tectonic interpretation

In a recent article, Gass & Gibson (1969) have considered the problem of the origin of the Red Sea and Gulf of Aden Rifts and their relation to the Ethiopian region. They conclude that the origin of these rifts is due largely to the northeasterly drift of the Arabian block away from a more slowly moving African block. As repeatedly emphasized by Mohr, the major difficulty in this hypothesis involves the 'overlap' of the Arabian peninsula into Afar in any predrift reconstructions. Laughton (1966) overcame this problem by assuming that Afar was a region of crustal growth composed of post-drift volcanic rocks, clastic sediments and evaporites. We follow Laughton and wish to show in a little more detail how the structures in the Red Sea are related to those in Afar.

In seeking an explanation for the off-set nature of the fault belt within the Ethiopian Rift, one is forced to consider the gross structure of the region. In September 1967, at the U.M.C. Symposium on Rifts, Gibson (in press) suggested that the Main Ethiopian Rift is a zone of left lateral shear, produced by the slow northeasterly drift of the Somali block against the relatively more stable Nubian mass. As noted by Mohr (1968), this theory explains the *en échelon* nature of the tensional fault belt and it becomes completely unnecessary to propose east–west transform or transverse faults to account for the offset.

As the fault belt is followed northwards into southwestern Afar, its character changes and it becomes progressively less well defined. In the region of Lake Abbe, the pattern of faulting is more complex and the area affected more extensive. Presumably the change in the nature of the fault zone is due, in part at least, to the widening of the shear zone as the Ethiopian Rift broadens northwards to merge with the Afar depression. The structure of central and eastern Afar is very complex, as this region is not only affected by the relative shear between the Somali and Nubian blocks, but also by deformation associated with the northward drift of the Arabian block relative to the Nubian mass. This latter movement has led to the development of the Red Sea and the Jordan Shear. Within Ethiopia, this same relative movement of Arabia has produced the very extensive tensional faulting along a 'Red-Sea' (or 'Erythrean') trend in northern Afar. Northern Afar is in fact an area of very rapid crustal extension, characterized by NNW–SSE open tensional fissures, subvertical normal faults and active fissure basalt volcanism (Tazieff *et al.* in press). This major tensional zone dies out northwards, and where it crosses the coast of the Gulf of Zula, the amount of crustal extension is very small. Apparently this tensional zone is replaced, again in an *en échelon* fashion, by the medial Red Sea rift zone (figure 3). At latitude $13\frac{1}{2}°$ N, the NNW–SSE tensional zone in Afar is very pronounced, while the medial Red Sea Rift is only barely discernible. However, north of here tensional faulting in Afar diminishes in importance, while the Red Sea rift zone widens progressively to reach a maximum width at about 18° N.

We wish to stress that the tectonic and volcanic pattern in central and northern Afar, as observed in the field and described above, does not support the suggestion of Mohr (1967*a*) that the Wonji Fault Belt continues from Central Afar, northeastwards across the Danakil Horst to join with the Red Sea medial rift zone. It is suggested here that, if such a direct link does exist, it is completely subordinate in importance to the indirect, *en échelon* link through northern Afar described above.

We also feel that the approximately axial line of volcanism in northern Afar suggests that this region is not underlain by a single westerly tilted crustal block (Holwerda & Hutchinson

1968), although extensive normal faulting does form the western margin of the depression (Tazieff 1969).

Finally, the surface evidence does not bear directly on the problem of the presence or absence of sialic basement beneath Afar. Certainly, as Laughton (1966) indicated, the majority of the surface rocks within the Afar depression are very recent in age, and yet they are severely attenuated. This suggests that any pre-volcanic sialic basement (if present) must be even more

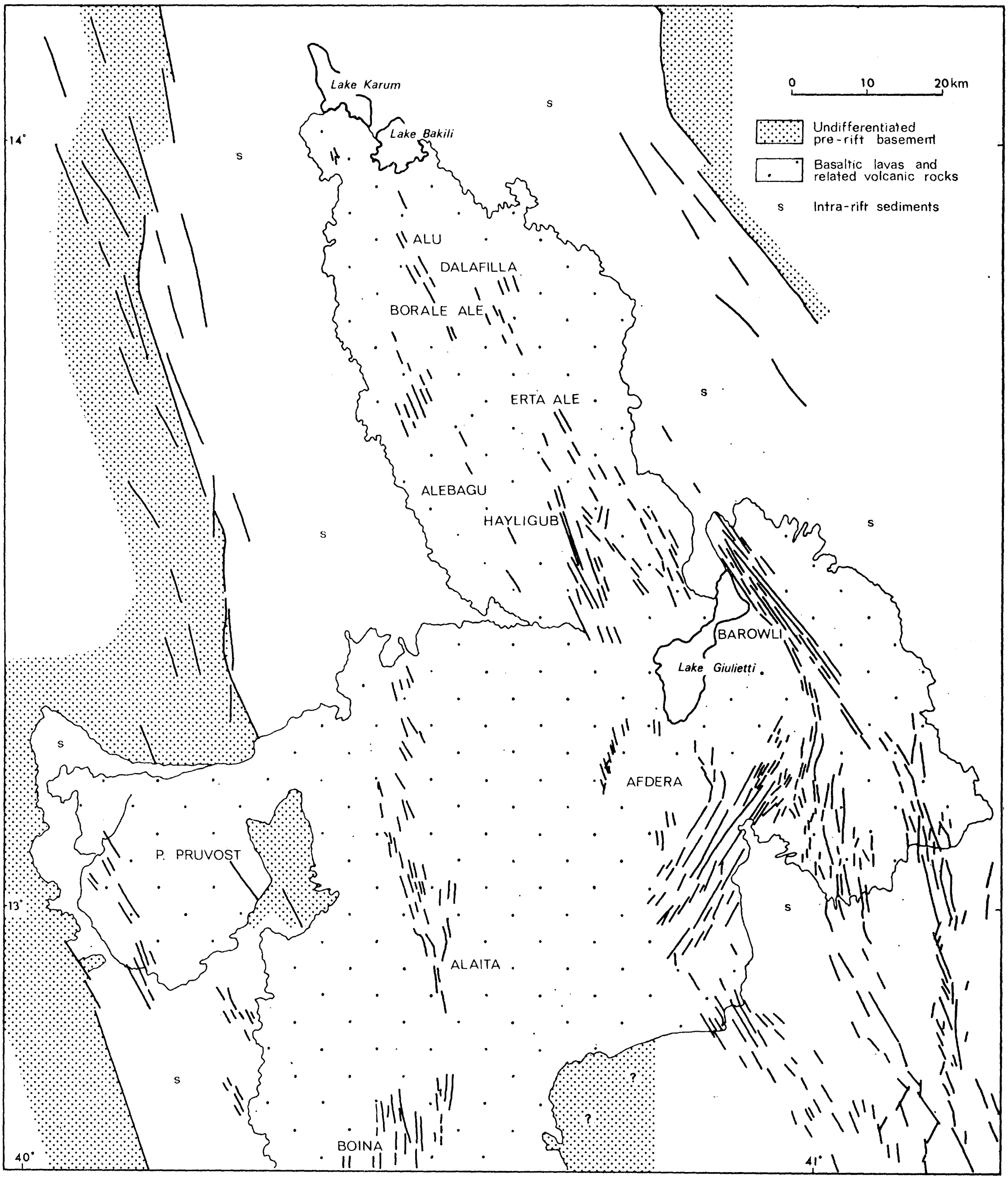

FIGURE 3. Faulting in Northern Afar from detailed ground survey by H. Tazieff, F. Barberi, G. Marinelli and J. Varet.

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fragmented and stretched, probably largely by the injection of basaltic material. Certainly, the petrological evidence of Barberi *et al.* (this volume, p. 293) suggests the proportion of sialic crust must be very small beneath the Erta'Ale volcanic chain.

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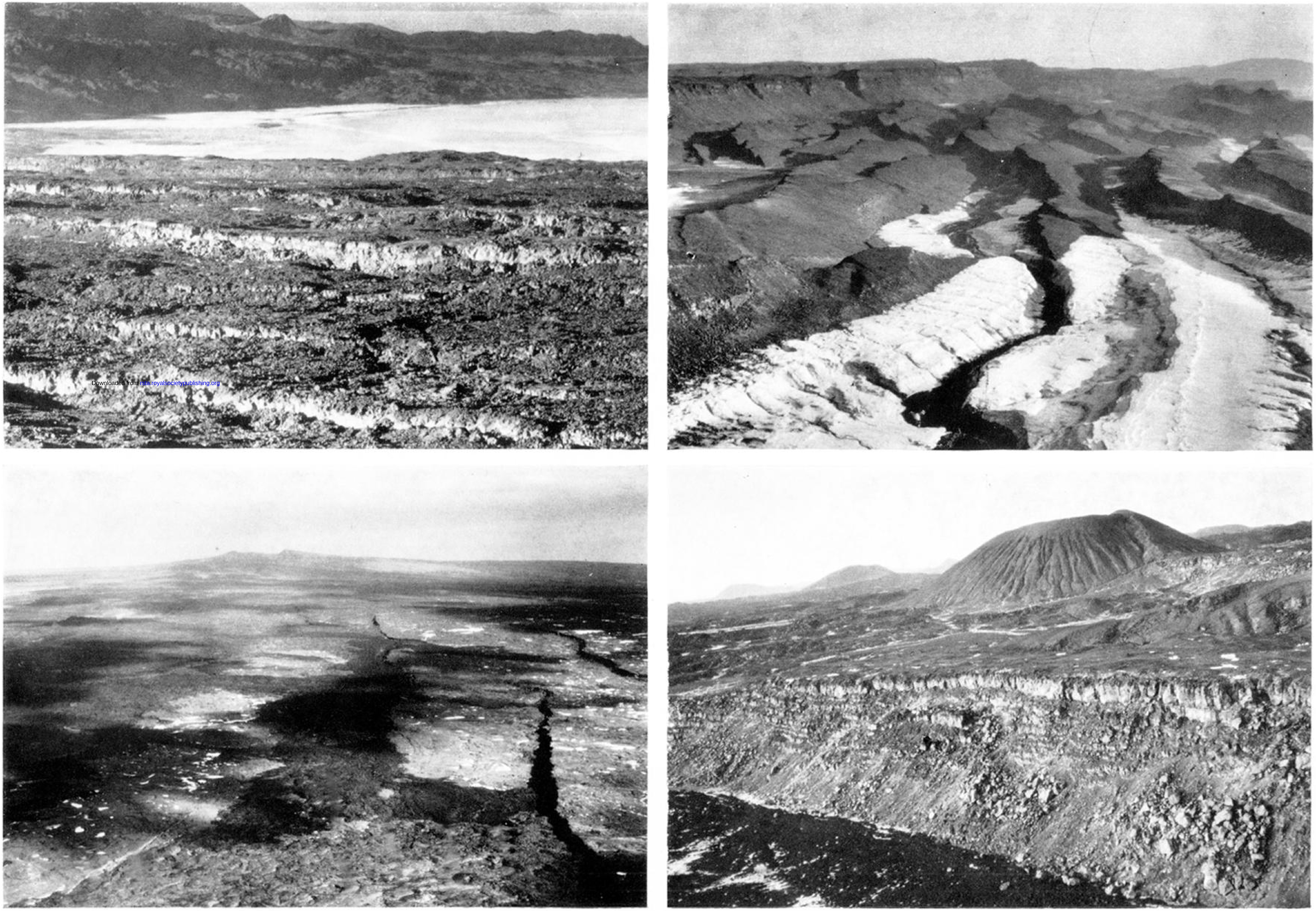
Discussion

J. V. Hepworth (*Institute of Geological Sciences*). It was interesting that Dr Gibson had emphasized the *en échelon* arrangement of the groups of faults in Afar and that this *en échelon*, or offset, arrangement could not be attributed to displacement by any transverse structure. It was also interesting that he had found no transcurrent or transform faults. (He (J. V. H.) suspected that in some people's minds the two words had become synonymous.) This was the same *en échelon* patterns of faults which occurred in the northern part of the western rift in Uganda. Typically one group of faults died out and was replaced by another group offset from the first, although the sense of direction was the opposite to that in Afar. This applied both to the early formed 'graben' and to the later faults which faulted the floor of the 'graben'. The floor of each segment of the Western rift, i.e. each separate 'graben' which collectively made up the 'Rift Valley', was approximately rhomb-shaped and was tilted down towards the northeast corner.

This *en échelon* arrangement was to be seen in other rift valleys and seemed to be a characteristic. If this arrangement were not understood, or if it were concealed beneath sea, it would be possible to attribute it to a series of transform faults. But in fact it was nothing like a transform fault system. It consisted essentially of a series of offset, tilted crustal blocks with no more dilation across the rift than was necessary for the blocks to founder. He asked Dr Gibson whether there was any sign of tilting of the blocks between the groups of faults he had described.

Dr Gibson *replied* that the blocks between the *en échelon* fault swarms in the Main Ethiopian Rift were not tilted.



(a) (b) (c) (d)

FIGURE 1. (a) Faulting on the east side of Lake Giulietti; (b) 'Horst' and 'graben' structure close to latitude 12° 45′ N, longitude 41° 15′ E; (c) view northwards along the axis of the Erta Ale range with the shield volcano Hayali Gub in the background; (d) normal faulting east of Lake Giulietti. Note the hyaloclastic cone in the background which is cut by a fault with a displacement of about 25 m.