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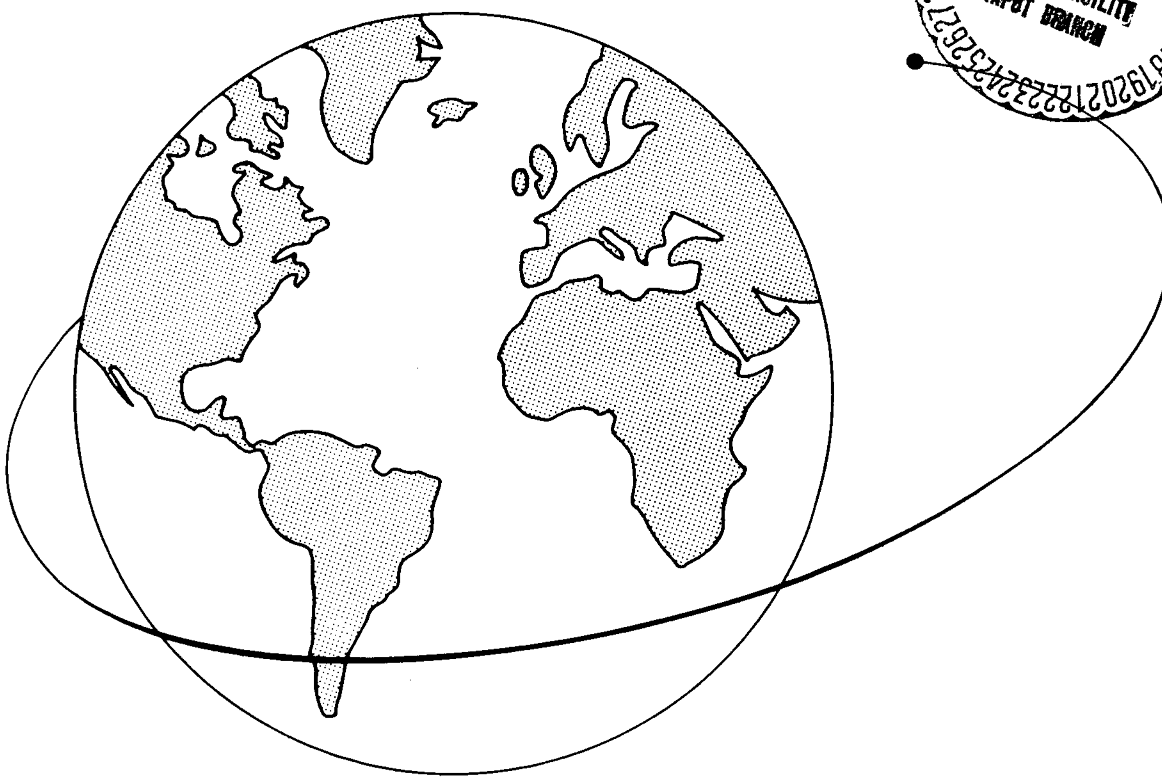
ETHIOPIAN TERTIARY DIKE SWARMS

P. A. MOHR



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ABSTRACT

Mapping of the Ethiopian rift and Afar margins has revealed the existence of Tertiary dike swarms. The structural relations of these swarms and the fed lava pile to monoclinal warping of the margins partly reflect a style of continental margin tectonics found in other parts of the world. In Ethiopia, however, conjugate dike trends appear to be unusually strongly developed. Relation of dikes to subsequent margin faulting is ambiguous, and there are instances where the two phenomena are spatially separate and of differing trends. There is no evidence for lateral migration with time of dike injection toward the rift zone, as has been postulated for the Icelandic rift.

No separate impingement of Red Sea, Gulf of Aden, and African rift system stress fields on the Ethiopian region can be demonstrated from the Tertiary dike swarms. Rather, a single, regional paleostress field existed, suggestive of a focus beneath the central Ethiopian plateau. This stress field was dominated by tension: There is no cogent evidence for shearing along the rift margins. A gentle compression along the rift floor is indicated. A peculiar sympathy of dike hade directions at given localities is evident but is not yet explained.

RÉSUMÉ

L'étude topographique du rift éthiopien et des marges des Afars a révélé la présence d'essaims de dykes tertiaires. Les relations structurales entre ces essaims et les accumulations de lave ainsi produites d'une part, et le plissement monoclinal des marges d'autre part, réflètent en partie un type de tectonique des marges continentales rencontré en d'autres parties du globe. Cependant, en Ethiopie, le développement des directions conjuguées des dykes semble être inhabituellement prononcé. La relation entre les dykes et les fractures subséquentes de la marge est ambigüe, et, en certaines occasions, les deux phénomènes sont géographiquement séparés et de directions différentes. Il n'y a pas de preuve d'une migration latérale fonction de l'époque d'injection des dykes vers le rift, comme cela avait été proposé pour le rift d'Islande.

Les essaims de dykes tertiaires ne permettent pas de démontrer que les champs de contraintes du système de rift de la Mer Rouge, du Golfe d'Aden et de l'Afrique ont eu une incidence séparée sur la zone éthiopienne. L'existence d'un champ unique et régional de paléocontraintes est préférée, suggérant un foyer sous le plateau d'Ethiopie centrale. Ce champ de contraintes était essentiellement caractérisé par des tensions. Il n'y a pas de preuve définitive en faveur de cisaillements le long des bords du rift. Une légère compression est suggérée au fond du rift. En certains endroits on observe une singulière concordance dans l'inclinaison des dykes, mais ce phénomène n'est pas encore expliqué.

КОНСПЕКТ

Составление карты Эфиопского рифта и Афарской полосы выявило существование Тертиарных дамбовых масс. Структурные связи таких масс и масс лавого происхождения с моноклиническими искажениями краев частично отражают вид краевых континентальных тектонических основ в других районах Земного шара. Однако в Эфиопии сопряженные дамбовые продвижения оказались необычайно сильно развиты. Связь дамбов с последующими краевыми сбросами неясна, и имеются примеры, когда два явления пространственно разделены и имеют различные направления. Нет доказательств миграций дамбы во времени в направлении рифтовой зоны, как было постулировано для Исландского рифта.

Разделенные столкновения стрессовых полей системы Красного моря, Аденского залива и Африканского рифта в Эфиопской области не могут быть продемонстрированы на примере Тертиарных дамбовых масс. При этом существуют отдельные региональные палеострессовые поля, что указывает на существование фокуса под Центральным Эфиопским плато. Эти стрессовые поля определяются, главным образом, напряженностью; нет убедительных доказательств существования сдвига вдоль рифтовых краев. Можно указать на небольшое сжатие вдоль рифтового дна. Спецефическая склонность угловых направлений дамбы в данной области очевидна, но пока не об'яснена.

ETHIOPIAN TERTIARY DIKE SWARMS

P. A. Mohr

1. INTRODUCTION

The tectonic evolution of the African rift system is still very imperfectly known. The relations between erosion surfaces and uplift of the East African plateau have been studied by Saggerson and Baker (1965) and Bishop and Trendall (1967), and among volcanism, uplift, and rift faulting by Baker, Mohr, and Williams (1971) and Baker and Wohlenberg (1971). These studies have revealed the importance of downwarping of the African rifts, especially during the early stages of their evolution. During the Tertiary period in Ethiopia, massive crustal warping down into Afar (Figure 1) was accompanied by flood-basalt eruptions from fissure swarms, but the nature of this warping, and the disposal of the dikes and their relations to the lavas, have hitherto been only sketchily known.

This paper attempts to show how field studies of dike swarms and their relationship to regional tectonism and volcanism, in particular their evidencing of the paleostress field, offer a new approach to African rift problems. Emphasis is placed on the dike swarms of the western margin of Afar with the Ethiopian plateau (Figure 1), but swarms from other sectors of the Ethiopian rift system are also discussed; and a regional paleostress field is constructed. Comparison is made with the Icelandic rift, where some very detailed mapping of dike and lava units in relation to regional crustal warping has led to theories of fundamental importance in rift geology (Walker, 1959; Bodvarsson and Walker, 1964; Gibson, 1967).

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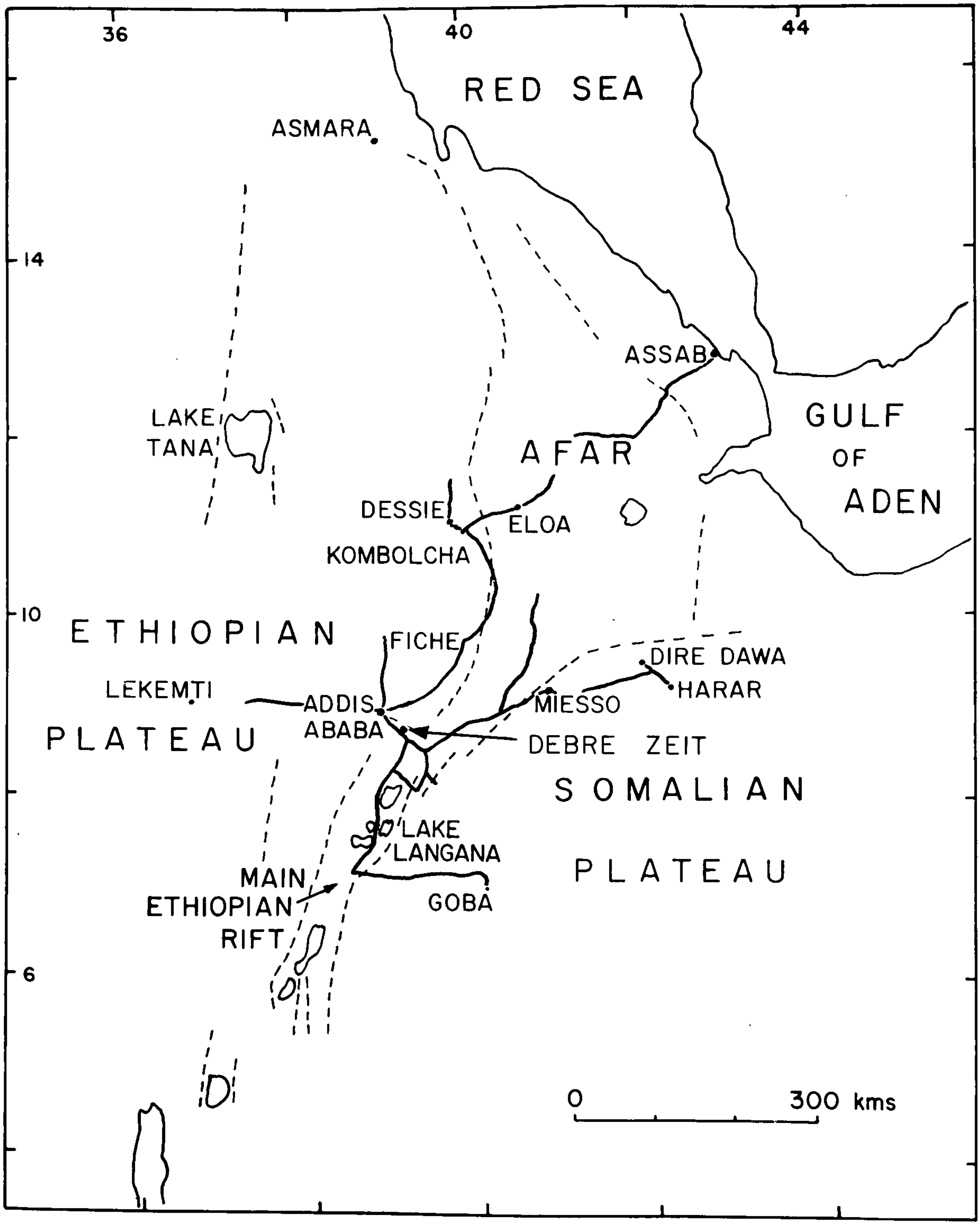

Figure 1. Location map of Afar and the Ethiopian rift. (Rift margin schematically dashed; thick lines show traverses made by the 1969 National Geographic expedition.)

The Afar triple junction lies at the conjunction of the Red Sea, Gulf of Aden, and African rift systems (Mohr, 1967a, 1970). A direct traverse of the western margin of the Afar depression is provided by the Dessie-Assab Road (Figures 1 and 2). The cuttings made during the building of this road in 1936 to 1937 have provided some excellent exposures of the lavas, faults, and dikes that manifest the structural evolution of the Ethiopian plateau-southern Afar margin. The present study, parallel with an independent one made by Abbate and Sagri (1969), examines the evidence for this evolution.

Figure 2. Structural map of the Ethiopian plateau-Afar margin zone between Dessie, Kombolcha, Batie, and Eloa and beyond to the Mille river. Solid lines indicate major Neogene-Quaternary faults, with direction of downthrow where known. Dashed lines indicate probable faults. Arrows show direction of dip of tilted stratoid lavas (see text for dip angles). Major rivers are shown and named, and the main Dessie-Assab road is also marked. Longitudes at the western and eastern terminations of the map are, respectively, 39°38' and 40°50' E.

2. TOPOGRAPHY

From Dessie (2525-m altitude, on the eastern rim of the Ethiopian plateau) the Assab Road descends abruptly to Kombolcha (1875 m). From Kombolcha the road continues eastward and declines gently to the Challeka valley (1520 m) before rising again to Batie (1670 m). From Batie it descends, rapidly at first, to Eloa (675 m) at the western edge of the Afar plains. East of Eloa the road traverses flat-lying lacustrine sediments and silicic volcanics, which obscure the older structures. The distances involved in the Dessie-Eloa traverse are the following:

	By road (km)	Direct (km)
Dessie-Kombolcha	22	12
Kombolcha-Batie	35	32
Batie-Eloa	50	37

The topography of this traverse is probably quite typical of the western margin of Afar south of latitude 13°N. The steep, east-facing escarpment of the Ethiopian plateau immediately south of Dessie overlooks the Borkenna graben (Mohr, 1962). Kombolcha is situated at the northern end and on the eastern boundary faulting of this narrow, "marginal" graben. Marginal graben development resumes farther north in the Menebay-Hayk sector (Mohr, 1967a) and continues intermittently along the plateau escarpment zone to the Red Sea coast in northern Eritrea.

Between Kombolcha and Eloa the eastward topographic decline is anomalously interrupted by the position of the Batie saddle. This saddle owes its existence partly to the influence of headwater erosion from the Challeka river system, west of Batie, but more fundamentally to major NNW-SSE faulting, which has caused block uplift on a scale not identified elsewhere in southwestern Afar. Immediately north of the Kombolcha-Batie line lies the strongly elevated (> 3000 m) highlands region within which lakes Hayk and Ardibbo are situated, a region whose intense and complex tectonics (Gouin and Mohr, 1964, p. 237ff) have not yet been studied, but to which the Battie saddle is almost certainly related.

The Dessie-Eloa Road traverses, from west to east, the drainage systems of the Borkenna, Challeka, Aya Kali, and Ledi rivers. All these enter the Awash river in Afar, though the Borkenna and, to a lesser extent, the Challeka are structurally diverted southward before resuming an eastward flow through the dissected Ethiopian plateau-Afar margin zone (Mohr, 1962, 1967a).

3. GEOLOGICAL SETTING

The Dessie-Eloa traverse exposes volcanic rocks confined to the Trap Series (Gortani and Bianchi, 1941; Abbate, Azzaroli, Zanettin, and Visentin, 1968). The age of this Series is considered to be Eocene-Miocene (Dainelli, 1943; Grasty, Miller, and Mohr, 1963). The precise nature and extent of the Trap Series in Ethiopia are not satisfactorily settled (Mohr, 1968a), and further work will very likely require a redefinition of this Series. Abbate et al. (1968) have subdivided the Trap Series of the western margin of Afar as follows:

3.	higher unit	characterized by abundant silicic volcanics.
2.	intermediate unit	predominantly composed of basaltic tuffs, with frequent sedimentary and paleo-soil intercalations, and occasional silicic volcanics.
1.	lower unit	olivine basalts alternating with basaltic tuffs, in flows rarely thicker than 10 m.

This classification is not easily reconcilable with that of Blanford (1870) or Mohr (1968a). Along the Dessie-Eloa traverse, Abbate et al. (1968) propose that between Dessie and the Challeka bridge (11 km east of Kombolcha) the intermediate unit of the Trap Series is exposed, with isolated patches of thin, overlying silicic lavas presumably representing the higher unit. On the basis of massive faulting at the Challeka bridge, the same authors identify the lower unit of the Trap Series from hereon eastward all the way to the foot of the escarpment at Eloa. Their classification and identifications will be examined critically in the discussion that follows.

Not exposed on this traverse, but outcropping farther north along the Afar margin, are marine sandstones and limestones of the Mesozoic and schists and granites of the Pre-Cambrian Basement, all underlying the Trap

Series. The Trap Series is estimated to be about 2500 m thick in the Kombolcha region (Mohr and Rogers, 1966). Thick Quaternary lacustrine sediments cover the floor of western Afar, but 40 km east of Eloa the first of numerous Pliocene-Quaternary silicic volcanic centers of the Aden Series is encountered.

The essential structure of the Dessie-Eloa traverse, as noted by Abbate and Sagri (1969), is formed by NNW-SSE antithetic faulting within a broadly downwarped zone affecting the margin of the Ethiopian plateau with Afar. The faults are antithetic to the main plateau escarpment at Dessie, are up-faulted east along west-dipping planes, and cut stratoid lavas now tilted down east toward Afar at angles between 10 and 30°. This faulting and stratoid tilting give a strong, meridional topographic lineation to the country, despite the degree of dendritic dissection by streams and despite a thick lateritic soil cover.

4. DETAILED STRUCTURE AND DIKES

4.1 Dessie-Kombolcha

West of Dessie, and well-exposed between Dessie and Magdala, the Trap Series stratoids lie subhorizontal with a tendency to a very gentle westerly dip. The exposed sequence is at least 1000 m thick, lying within the intermediate unit described by Abbate et al., though Rogers (Mohr and Rogers, 1966) has observed a major unconformity within the Bashillo valley squence. Persilicic lavas are interbedded in the uppermost basalts (Hieke Merlin, 1953).

Between Dessie and Kombolcha, the steep topographic decline exposes deeply eroded stratoids without evidence of preserved, major fault scarps. Farther south along the western margin of the Borkenna graben, some huge stepped scarps are preserved, from east-hading* faults of N10°W trend. This faulting diminishes rather abruptly near Dessie, coincident with the northern termination of the Borkenna graben, becoming smaller scale block faulting with hades both east and west. The faulting exposed along the Dessie-Kombolcha road cuts rarely has topographic expression, except for young N10° W faults of Borkenna graben trend: the main trends are the following (see Figure 2):

	Strike	Hade
1.	N10° W	W
2.	N60° E	NW
3.	N10° E	W

The second set of faults is less well developed than the first, and the direction of hade is correspondingly more variable, suggesting a N60° E block faulting.

*The old term "hade" is revived here because it provides a useful distinction from the term "dip." Dip is the vertical angle (down from the horizontal) of tilted lava units: hade is the vertical angle (up from the vertical) of fault planes and dikes. Thus in this paper, dip and hade have identical directional sense.

The dike pattern tends to coincide closely with that of the faults (Figures 2 and 3); a N10°E trend predominates over N60°E. The N60°E structural trend also coincides with the axes of numerous small, gentle folds. About 5 km south of Dessie some N70° W faulting is developed, which may be associated with the 1961 seismicity of this region (Gouin, 1971).

Detailed features of interest on this traverse are as follows: Dike AD 114 is an intrusion, 5.7 m wide, N10°E, composed of fine-grained aphyric basalt lacking chilled margins. It intrudes zeolitized scoriaceous olivine basalt flows that are affected by N60°E joints and fold axes. The folds are typically of 4- to 5-m amplitude and 15-m wavelength. Dike AD 114 has been displaced by a N65°E normal fault and hades 30° to the northwest, with a throw of 200 to 300 m. Slickensiding on the fault plane suggests a final motion of sinistral shear.

Almost all the dikes between Dessie and Kombolcha are dark, dense basalt, sometimes finely feldspar phyric. They are typically less altered than the lavas they intrude, except where used by postintrusion faulting. The volcanic stratigraphy of this region is difficult to elucidate, lacking good marker horizons within the complexly deformed stratoids. However, the lavas have an overall dip eastward or northeastward at 10 to 45° in the western (Dessie) portion of the traverse. In the eastern (Kombolcha) portion, they dip southeastward at 20 to 30°, tilted from ENE-trending faults.

Excellent but tantalizingly restricted exposures in the vicinity of dikes AD 113 and 117 reveal two sharply contrasted country-rock lithologies, both cut by the dikes. They are zeolitized basalt flows and severely lateritized and zeolitized basaltic agglomerates. The flows appear to have ponded on a gently undulating landscape of agglomerate hills, but this relationship is obscured by subsequent severe faulting and tilting of local blocks (Figure 2).

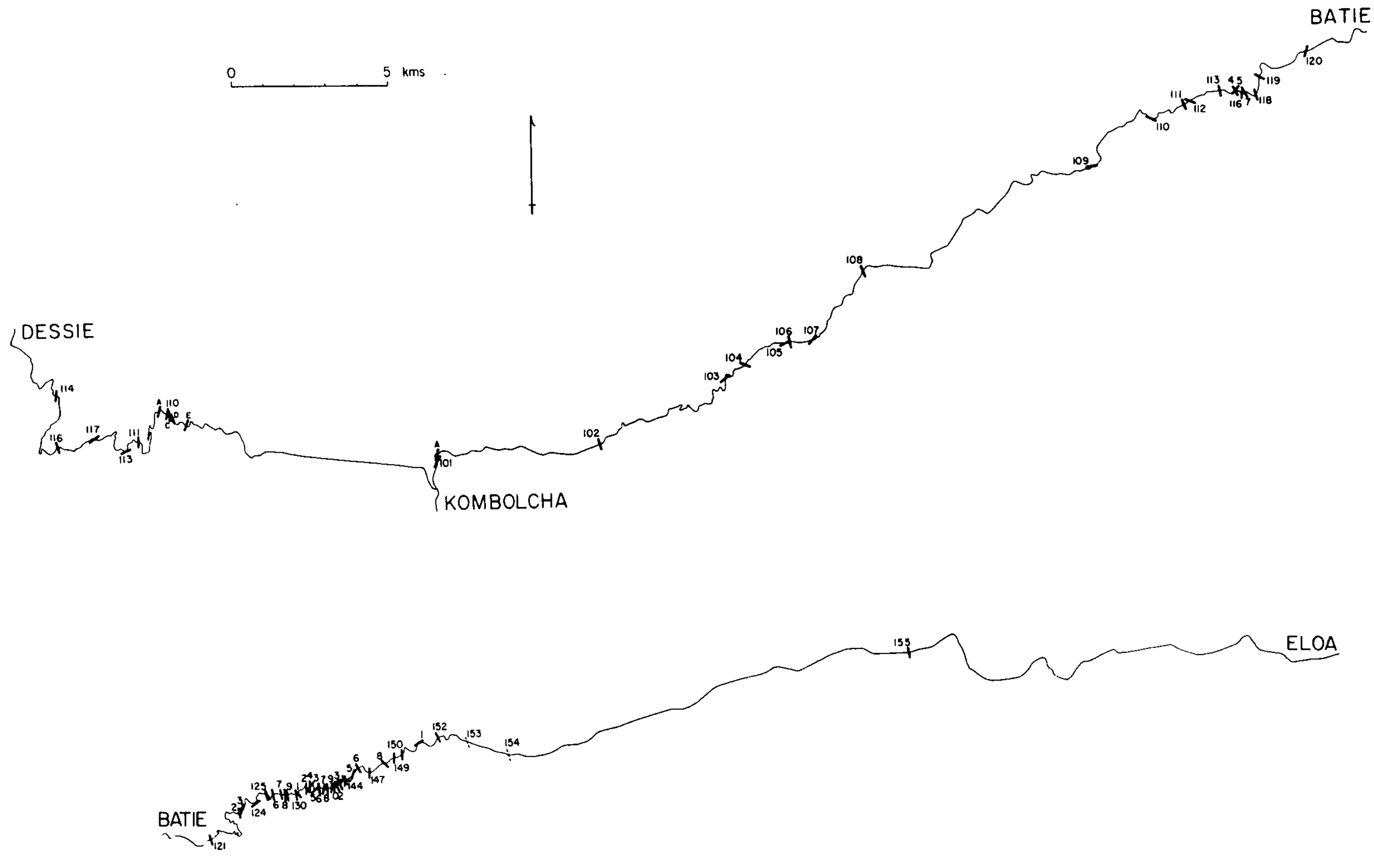

Figure 3. Reference map for sampled dikes between Dessie and Eloa. Dike numbers between Dessie and Kombolcha are prefixed by AD; between Kombolcha and Eloa, by KA. Where dikes are abundant, space allows only the last of the three digits to be shown.

The recognition of two distinct volcanic formations in the Dessie-Kombolcha region complicates the succession given by Abbate et al. (1968). They consider this region to be entirely composed of their intermediate unit, supposedly dominant basaltic tuffs. In fact, tuffs do not appear to be common here or east of Kombolcha to the Challeka fault zone. In this connection, the comment of Mohr (1967b) on the superficial resemblance of severely weathered and zeolitized porphyritic basalt flows to tuffs may be pertinent.

The prominent N70-80°E fault, downthrown north, passing through dikes AD 111 and 110E, is notable as having a trend strongly developed east and south of Batie (see later).

4.2 Kombolcha-Batie

The Kombolcha-Batie traverse lies within the upper basin of the Challeka river, on the southern flanks of the Ardibbo massif. It crosses ENE-dipping stratoids that are cut by some intense belts of NNW faulting, most notably 11 and 23 km (direct distance) east of Kombolcha. The faults are upthrown east.

The fault zone at 11 km is that identified by Abbate et al. (1968) as a conjunction between their lower and intermediate units of the Trap Series. These authors reckon that the intermediate unit, west of the fault zone, consists of subhorizontal basaltic lavas and tuffs, while the lower unit, east of the fault zone, consists of easterly dipping basalts. We have been unable to confirm this fundamental distinction, despite the evident importance of the faulting at 11 km. The country rocks throughout the whole of this traverse, and indeed throughout the entire Kombolcha-Eloa sequence, are to us a unified group of zeolitized porphyritic basalts characterized by large, platy plagioclase phenocrysts.

These purple-weathering basalts dip very predominantly eastward, inclusive of the Kombolcha-Challeka bridge sector, where Abbate et al. identify flat-lying stratoids. In fact, near Kombolcha the stratoids dip more steeply (20 to 30°) and have a southerly component added to their easterly dips, compared with the vicinity of the Challeka bridge. This modification is almost certainly related to the presence of the Borkenna graben, which has a well-developed eastern shoulder at Kombolcha. The argument of Abbate et al. (1968) that the Challeka-bridge faulting marks the conjunction of two separate, major volcanic units requires the removal of an enormous amount of rock from east of the fault at 11 km in order to expose the lower unit there (more than 1000 m in thickness, according to their own data).

It seems more realistic to envisage a greater degree of uplift and ensuing erosion closer to the plateau, in accordance with the section given by Abbate and Sagri (1969, Figure 4), and affecting a unified group of warped lavas.

The trends of the dikes between Kombolcha and Batie and to dike KA 130 on the eastern edge of the Batie saddle (Figures 2 and 3) are given below in order of importance:

	Strike	Hade
1.	N10°W	W
2.	N60°W	SW
3.	N50°E	variable
4.	N20°E	W

and for faults:

	Strike	Hade and downthrow
1.	N00-20°W	W
2.	N30°E	NW
3.	N50-60°E	W
4.	E-W	vertical

These data reveal a much more discrete grouping (see also Figures 5 and 6) than that given by Abbate and Sagri (1969, Figure 2). Some notable fold axes are parallel to N50°E, as found also in the Dessie-Kombolcha sector.

The dikes are mostly 0.5 to 3 m wide, averaging 1.5 to 2 m, and can be traced horizontally along the strike for a few hundred meters, occasionally more where exposures are better. They are dominantly composed of aphyric and feldspar-phyric basalts, rarely of augite-feldspar-phyric basalt. Dip angles, for both dikes and faults, vary between vertical and 55°, with an average value of 70°, but except for the main N10°W trend there is a lack of coincidence for the two types of structure.

The country-rock lavas are dominantly feldspar-phyric basalts, now more or less severely zeolitized, but olivine and olivine-augite-phyric varieties are locally common. Aphyric and scoriaceous olivine basalts are rather rare among the lavas. The flows average a thickness of only a few meters.

Some details of the Kombolcha-Batie traverse can be noted. There is patchy occurrence of thin (< 20 m) silicic volcanics upon the basalts. They show sympathetic dips with the basalts, but these may be depositional rather than due to subsequent warping. The silicic rock types are peralkaline and vary from orbicular comendites and pitchstones to strongly welded tuffs.

Dike KA 102, 5 km east of Kombolcha, is a gabbroic intrusion 35 m wide and trending N10°W and dipping 80 to 85° to the west. Its intrusion followed that of coarse augite-phyric agglomerates intensely baked by the dike. Meridional faulting in this vicinity is unusual in showing dips of 75° to the <u>east</u>.

Eastward from KA 102, the Challeka stream follows a linear valley determined by a N75°E fault. This fault, in its latest movement at least, is a reverse fault downthrown a few meters to the south and dipping 75° to the north. The country-rock stratoids are folded along N50°E axes, north of this fault, and compression has evidently acted along the Afar margin, the thrust coming from the north (cf. Mohr and Rogers, 1966, p. 20).

At the "Rex" building, 8 km east of Kombolcha, the Challeka valley turns to the northeast, though the N75°E fault and related fold axes can be observed to continue farther across dissected hills. Between dike KA 102 and the Challeka bridge (at 11 km) there is some intense N40-50°E faulting, downthrown northwest, with crush zones 1 m wide developed. This trend is followed by some very young (Holocene?) curvilinear faulting northeast of Kombolcha and can be traced farther into internal Afar. It may be identifiable with the cross-rift lineaments of Mohr (1967a).

Between 8 to 11 km east of Kombolcha, the N20°W regional faulting is abundantly developed, though throws tend to be small. More than 40 faults are exposed in a road section 1.5 km long in this region (Figure 2). Faults of the same trend but with very large throws are encountered at the Challeka bridge, and the easterly upthrow has produced a topographic escarpment that remains fairly well preserved. Abbate and Sagri (1969) emphasize the importance of this faulting, which is concentrated within a zone 2 km wide. The fault trend averages N25°W, and fault-plane dips are 65° to the west. However, immediately west of the Challeka bridge a massive N10°W fault dips 70 to 80° to the <u>east</u> and shows a crush zone 2 m wide; it cuts lateritized basalts that dip <u>south</u> at 20°. East-hading faults are also found east of the Challeka bridge, for example near dike KA 105 (Figures 2 and 3). Thus, the dominant antithetic fault pattern of the Afar margin is evidently mixed with some block faulting.

East of the Challeka bridge, the stratoid lavas show a strong regional dip to the ENE. Between dikes KA 105 and 108, a N55°E lineation affects these lavas, owing both to jointing and to faulting. This is also the trend of dikes KA 105 and 107 and of the fold axes farther west.

The Challeka plain is encountered east of dike KA 108 and extends for about 8 km before dike KA 109 is reached. Here an old, dissected topography is buried under a fill (> 100 m) of silts and underlying boulder beds. These plain sediments are now gently tilted down to the east, indicating recent tectonism associated with the Challeka bridge faults or perhaps the Borkenna graben, and are in turn being actively dissected. The silts of this sequence were presumably deposited in a lake formed by the ponding of the Challeka river against the antithetic fault zone at 23 km (see later). This fault zone controls the course of the Challeka river for a distance of 20 km downstream, forcing it to flow SSE-ward before it escapes eastward down the dip slope to the Awash valley of Afar. The topography buried by the Challeka plain sediments shows features of both N20° W and N45° E trend, but the rare exposures reveal no dikes.

At the eastern margin of the Challeka plain (23 km) a further antithetic fault zone is encountered (Figure 2). The N20-30° W faults cut ENE-dipping (20 to 30°) zeolitized basalts overlain by normal and welded silicic tuffs. Less intense faulting runs N45° E and N75° E, though the latter trend intensifies farther east (see below).

The dike orientations between the faults at 23 km and Batie (35 km) are frequently divergent from the regional fault trend, and some northwest-southeast dikes (KA 110, 112, 118, and 119) are not related to any evident faulting. Nevertheless, the dominant dike trend remains N10-30° W, and many of these dikes have been used by later faulting, especially in the KA 113–119 zone. Near dike KA 118, some bedded silicic tuffs lie <u>within</u> porphyritic basalt flows, and the whole sequence is tilted at 40° down to N80° E and is cut by N10° W faults dipping 70° to the west. Dike KA 119 is observed to be displaced by a N30° E fault dipping 75° to the southeast. In the region immediately west of Batie, dikes are sparsely exposed and trend anomalously northeast-southwest (e.g., KA 120 and 120A and unsampled dikes exposed 1 km south of the road).

4.3 Batie-Eloa

Batie lies on a marked topographic saddle of meridional trend. The steep (~30°) stratoid dips ENE indicate that the origin of the saddle must be related to antithetic faulting hading west and passing near Batie itself. But the steepness of the east-facing escarpment at Batie is difficult to account for on this basis alone, even allowing for the effects of headward denudation by the Ledi, Aya Kali, and Gawis drainage systems. There has certainly been influence from abundant NNE-NE faulting, hading west at rather shallow angles (35 to 45°), and from east-west faults, both exposed immediately east of Batie. But the interactions of these fault systems with the steeply dipping regional N20° W faults have not yet been elucidated. No lateral displacements have been proved along any of the faults of this region.

The dikes between Batie and Eloa have the following trends, in order of importance (it should be noted that the orientation of the road being ENE, encounter with dikes of similar trend, e.g., N50°E, is prejudiced):

	Strike	Hade
1.	N05°E	W
2.	N20° W	SW
3.	N50°E	variable

Correspondingly the faults show the following trends:

	Strike	Hade
1.	N20° W	SW
2.	N10°E	W
3.	N60-75°E	N
4.	N50°E	variable

Throughout the whole of this traverse, the stratoid basalt lavas maintain a regional dip (10 to 40°) to the ENE. Some broad folds occur with axes sub-parallel to this direction of dip.

In the region between KA 130 and 150, the dike and fault trends are strongly influenced by a NNE-SSW structural element (Figures 2 and 3) oblique to the main NNW trend of the Afar margin. The dikes and also the lavas of this region commonly include olivine-augite-phyric basalts. The N60-75°E faults, approximately perpendicular to the N20°W regional trend, are particularly abundant in a zone passing through Batie itself. They extend east to the margin of the Afar plains and west to the block controlling the SSE flow of the Challeka river (the fault zone at 23 km described previously). This "Challeka block" is strongly affected by these "cross-rift" faults, upthrown south, and especially between 10 and 20 km south of Batie.

A major physiographic change occurs just east of dike KA 154, about 10 km directly east of Batie. Between Batie and this point, the tilted stratoids are dissected by a dendritic drainage pattern, but farther east the country suddenly becomes much smoother and less dissected, and the rivers take on a more meandering path. However, in the boundary zone between these two physiographies and immediately to the west, tectonic lineations give a zigzag pattern to the courses of the Aya Kali and Dirma rivers (Figure 2). The lineation trends are N15°E, N80°W, and N20-30°W.

The physiographic boundary can be traced both north and south of the road and generally has a NNW trend, though with local sectors of NNE trend. It has no visible influence on the rather steep dips of the stratoid lavas of this region, and the implication is that it represents the margin of an old, uplifted base level. Its sharpness further suggests it may mark a paleoshoreline similar to the well-preserved one at Eloa. Yet it may be significant that no dikes have been identified from east of the boundary until the antithetic fault zone at KA 155 is reached, some 12 km farther east (Figures 2 and 3). The lack of dissection inhibits exposure of any such dikes, however. The N25°W regional lineation is very strongly expressed in this smoother country, and local virgations can be clearly traced.

Near dike KA 155 another zone of strong antithetic faulting of N20°W trend is encountered. The Ledi river is diverted southward by this faulting before escaping eastward to the Afar plains. The fault zone is 2 to 3 km wide and shows left en-echolon offset to the north of the road. This offset occurs where there are numerous N60-70°E faults on a continuation of the zone passing through Batie (see above). The stratoid dips appear to be steepened east of the antithetic fault zone, though irregular deformation has produced small blocks with variable direction and degree of tilt. From this antithetic fault zone to Eloa, such irregular block faulting is typically superimposed on the regional structure.

Interestingly anomalous structures occur north of the road in the KA 155 region, as identified from aerial photographs. The affected country extends from 3 to 4 km north of the road, to the Waranzo river a farther 10 km to the NNW (Figure 2). It forms a belt 5 to 6 km wide, limited west by the intense KA 155 antithetic fault zone and east by other, less strong antithetic faults. The country has a very smooth physiography and is composed of rocks with a very finely stratified nature. Within these strata occur dark massive lenses concordant with the strike (NNW-SSE). Either these lenses are late-Trappean intrusions within a sequence of thin basalt flows or else a completely different rock series is exposed here — perhaps Pre-Cambrian schists and intrusives.

From the KA 155 antithetic fault zone to Eloa, the topographic decline is matched by decreasing dip of the stratoid basalts. These basalts are still the same feldspar-phyric types encountered between Kombolcha and Batie, with characteristic purple weathering and strong zeolitization. This region west of Eloa is intensely though not deeply dissected, reflecting its elevation close to base level. The faulting remains dominantly N20-30°W, but close to the edge of the Afar plains the direction of upthrow is more commonly southwest than northeast.

The ultimate escarpment separating the Afar plains from the gently dipping stratoids (where last seen) is determined partly by N30° W faults but is fundamentally an erosional one. Its abruptness, combined with a sinuous form, indicates it to be an old lacustrine shoreline. This is confirmed by the occurrence of thick pumiceous silts on the adjacent Afar plains, lying subhorizontally and cut only by some local N20-30°E and N65-75°W faults.

The Afar plain sediments extend monotonously eastward for 35 km from Eloa before reaching, immediately west of the Mille river, several young silicic volcanic cones and craters with end-phase pumice deposits. These centers are situated on well-developed N30° W graben and horst faulting, cut by subordinate N70°E faults upthrown north. This may conveniently be taken to be the limit of the present traverse, before the major northwest-southeast fault belts of Afar at Tendaho are encountered.

5. DISCUSSION

5.1 Introduction

The salient conclusions of the previous descriptive section of this paper can first be summarized. The stratigraphy of the Dessie-Eloa traverse is confined to the Trap Series sensu lato, inclusive of occasional silicic lavas near or at the top of the succession. The distinction of Abbate et al. (1968) between lower and intermediate units of the Trap Series, exposed respectively east and west of the Challeka bridge antithetic fault zone, is improbable both on lithological and on structural evidence.

The regional structural trend is NNW-SSE. Presumed major escarpment faulting at Dessie, upthrown west, is faced by antithetic faulting in the Kombolcha-Eloa sector. Antithetic faulting is especially concentrated within five narrow zones: at Kombolcha and at 11, 23, 36, and 54 km ENE of Kombolcha. The distance intervals increase eastward: 11, 12, 13, and 18 km. Each fault zone is associated with a renewed steepening of the ENE-dipping stratoid basalts in the block immediately east of the zone, indicating upwarping of the upthrown block. However, between Kombolcha and the fault at 11 km there is an added southerly component to the general eastward dip.

The densest dike swarms follow the regional NNW trend, but other trends are significant and include NNE, ENE, and ESE (Figures 3 and 5). Dikes generally dip to the west, and the average angle between dikes and lavas is 100 ± 12°. This close perpendicularity may suggest intrusion before warping and tilting: Du Toit (1929) considers that postintrusive tilting has given the present dips to the dikes of the Lebombo monocline in eastern Transvaal. Along the Afar margin, this priority is confirmed by the frequent utilization of dikes by subsequent faulting. Syntectonic and posttectonic dikes appear to be rather rare. Furthermore, manifestly young dikes are always vertically inclined.

Abbate and Sagri (1969) discuss three possible models of warping of the plateau-Afar margin and find the antithetically faulted model to be the most suitable (their Figure 4C). The stratigraphic and gravity evidence (Gouin and Mohr, 1964) suggests important east-downthrown boundary faulting near Eloa, in accordance with Abbate and Sagri's Figure 4B model. Although a combination of antithetic faulting and inner boundary faulting is an acceptable model for the Dessie-Eloa region, it should be noted that 150 km farther north, in southern Tigray, the warping of the plateau-Afar margin commences west of the plateau escarpment (Mohr and Rogers, 1966). Cox, Johnson, Monkman, Stillman, Vail, and Wood (1965, p. 130) accept that a master fault is not always present with antithetic-type faulting, where possibly there have been lateral movements of the upper mantle relative to the crust.

A simple antithetically faulted model for the Ethiopian plateau-Afar margin is inadequate in several respects, and it is probable that more than one tectonic episode has occurred. On the basis of denudational features, at least two phases of regional upwarping along NNW antithetic fault zones can be recognized. This faulting and warping of the western margin of Afar has been considered to be of Miocene age (Mohr, 1962). The dike swarms of this margin, with particular reference to preferred orientations and hade directions, provide a further means of investigating the tectonic evolution of the rift in terms of crustal stress patterns. Before such an analysis is attempted, comparison is made with the much better studied Icelandic plateau and rift.

5.2 Comparison of the Afar Margin with Eastern Iceland

Instructive comparison between Iceland and Ethiopia is possible because of the common tectonic situation on warped volcanic rift zones. Walker (1959, 1960, 1963) has mapped in detail the structure of the flood basalts in eastern Iceland and the relationships of dike swarms to this sequence of Tertiary lavas. He finds that the flood basalts have a regional dip of 4 to 8° westward toward the active rift zone of central Iceland. This dip is considered to be due mainly to posteruptive tilting; it steepens at elevations closer to sea level, though Gibson (1967) suggests that the dips flatten out again at depth, with the lava piles having a resultant lenticular shape in cross section.

Walker shows that the dike swarms that fed this lava pile tend to run parallel to the strike of this dipping sequence, though occasional nonparallelism is related to local irregularities in the subsequent tilting process or to the influence of central volcanos, which are notably situated on such swarms. However, in addition to the major proportion of dikes following the NNE Icelandic rift trend, there occur subordinate northwest-southeast dikes whose age relationship with the NNE dikes remains unknown.

The eastern Iceland dikes are concentrated at points or along lines of crustal weakness. Thus, dike swarms increase in intensity in the vicinity of central volcanos, and silicic dikes become added to the regional basaltic ones. Dikes are also concentrated along flexure lines where the dip of lavas is steeper (25 to 30°) than usual. A notable feature of the Icelandic dikes is their diminution in number with increasing elevation above sea level. This is an obvious consequence of the dikes being feeders to the lava pile and points to the necessity of care in making comparisons of dike intensities between different regions of Afar.

The Icelandic dikes are "characteristically disposed approximately at right angles to the lava stratification. This may be because they are preferentially injected along the jointing of the lavas, but more probably it implies original vertical attitude and subsequent tilting of the dikes with the lavas" (Walker, 1959, p. 383). This argument may well explain the observed perpendicularity of the Afar lavas and dikes. However, perpendicularity does not necessarily imply an original vertical attitude to the dikes: the stress field within a developing monocline would seem to favor perpendicularity regardless of the degree of tilting of lavas and dikes, unless the dikes were derived from subcrustal depths subject to a different stress field.

The Afar margin dikes have a median (most frequent) thickness of 1.5 m (Figure 4). The arithmetic mean thickness is 3.5 m, precisely the same as for the Icelandic dikes (Walker, 1959). While dike swarms are almost

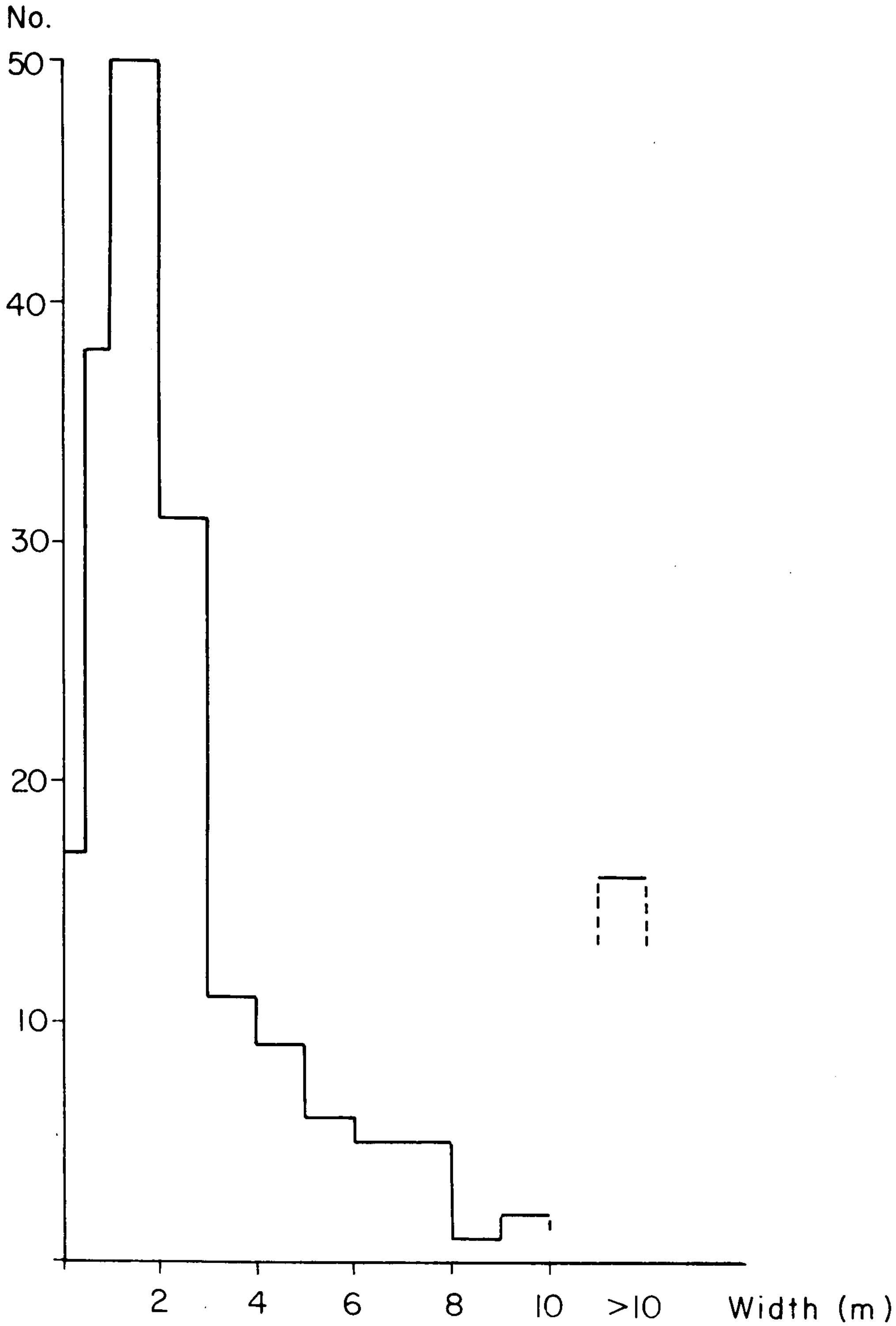

Figure 4. Histogram of dike widths in central Ethiopia.

certainly present along the Afar margins (e. g., KA 130–150), exposures are too irregular in quality to compare the intensity of dike injection with that of Iceland. Furthermore, the number of dikes depends critically on the level within the lava pile (Walker, 1960), and this level is not known for the Afar margin traverse. Walker (1959) calculates an average total width of 40 m of dikes per kilometer (perpendicular to the dike trend) at sea level in Iceland. Within swarms, this figure can rise to 120 m/km. The maximum observed intensity on the Dessie-Eloa traverse occurs 4 km east of Batie, where a 1-km strip of country is injected with a total of 60 m of dikes. It is significant that such dike concentrations do not usually coincide with the subsequent zones of intense antithetic faulting.

Estimating the thickness, number, and horizontal extent of the dike-fed lavas of the Afar margin involves several problems. Not only is the thickness of individual flows variable (e. g., east of Kombolcha, flows tend to thicken eastward), but the intensity of weathering and zeolitization can make delineation of flows difficult. A rough average for lava thickness is 3 to 4 m, closely comparable to Icelandic lavas near their dike feeders (Walker, 1963). Flood lavas tend to thicken away from their extrusion site (Gibson, 1969), which suggests that the lavas of the Kombolcha region originally flowed eastward from feeders farther west. Gibson also considers that in both Iceland and the Columbia plateau of western U. S. A., two contemporaneous basalt types were injected: olivine-poor tholeiites near the swarm axes, and olivine basalts at the swarm fringes. In the Afar region, there is no clear evidence for such a petrographic distinction.

The number of individual lava flows exposed in the Afar margin must run into several hundred, but the complications resulting from the regional antithetic faulting make a strict evaluation impossible at present. Gibson (1967) considers the total thickness of lavas in eastern Iceland to be 2 to 4 km, and a similar order is feasible for the Afar margin (Jepsen and Athearn, 1962; Mohr and Rogers, 1966), where, however, the lava pile rests on continental crustal rocks.

The horizontal extent of individual lava flows in Afar is again poorly known, but the regularity of thickness of some units along the strike, as evidenced on aerial photographs, suggests a minimum of 10 or more kilometers. This is appreciably more than in Iceland, according to the data of Walker (1959) and Bodvarsson and Walker (1964). No contemporaneous central volcanos (with end-phase silicic lavas) are known from the exposed dike swarms of the Afar margin, though nearer to the Ethiopian plateau escarpment occur the centers of Woti, Membret, and Abuya Mieda. The sources of the silicic lavas between Kombolcha and Batie have not yet been identified, and no silicic dikes nor pipes occur along the road traverse.

No examples of lava ponding, with any accompanying columnar jointing, have been observed from the Afar margin, though several examples are known from localities within the Ethiopian and Somalian plateaus. Lineations in the Afar margin lavas suggest that flowage continued during the early stages of crystallization in many or most cases.

In summary, there are clear resemblances in the volcano tectonism of the Afar margin and eastern Iceland. Differences include the more severe tilting and antithetic faulting of the Afar margin lavas, the presence of cross-rift faults and dikes in the Afar margin, and the more alkaline nature of the Trap Series volcanics.

5.3 The Crustal Stress Pattern of the Afar Margin

The angular relationships of individual dike (and fault) trends in the Afar margin can be compared with various crustal stress models. Besides the regional NNW trend, the Afar margin displays subordinate fault-dike trends of NNE, ENE, and ESE and fold axes trending northeast (Figures 5 and 6). It is superficially tempting to relate the NNE and ENE trends to extensions of fundamental structures from the Ethiopian rift and Gulf of Aden, respectively. But unless one particular trend can be demonstrated to be of widely differing age from the others, it is preferable to relate the subordinate and regional trends in a single crustal stress system (see Vail, 1970; May, 1971).

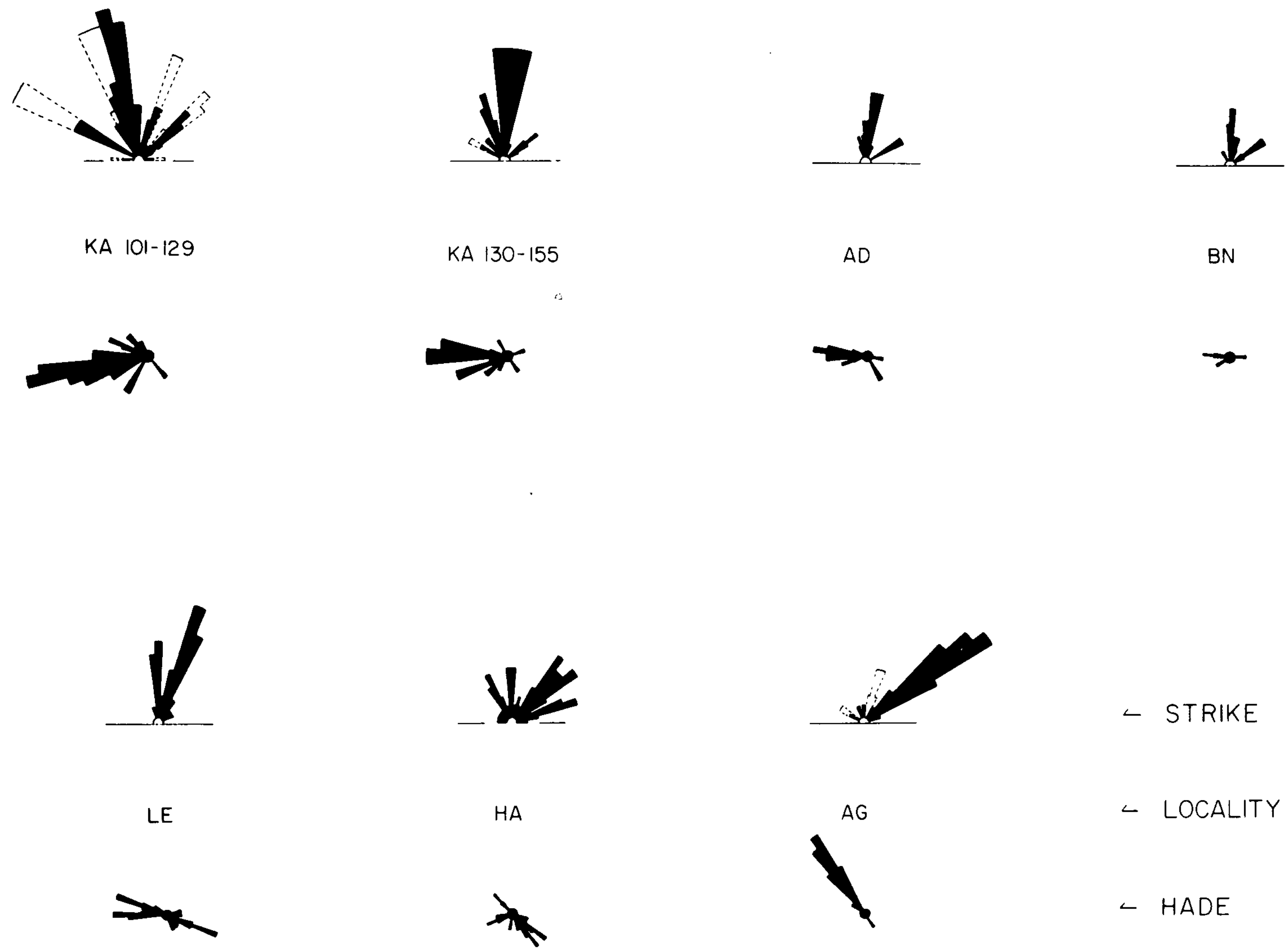

Figure 5. Rose diagram of dike trends for various Ethiopian localities. (KA: Kombolcha to Eloa; AD: Addis Ababa to Dessie; BN: Addis Ababa to Fiche; LE: Addis Ababa to Ghedo (and Lekemti); HA: Miesso to Dire Dawa and Harar; and AG: Adaba (and Langana) to Goba.)

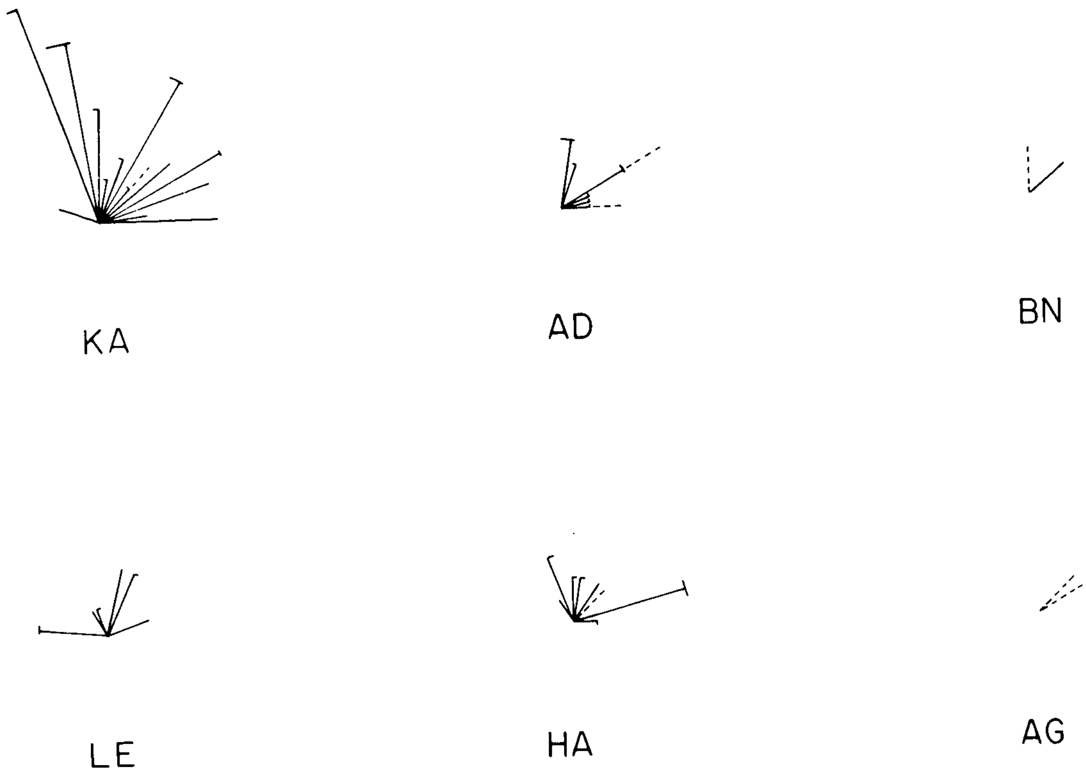

Figure 6. Fault trends and hade directions in association with dikes.

Figure 7 shows (a) the main structural trends observed in the Afar margin and (b) the fracture pattern resulting from tension acting in an isotropic crust. Taking 30° as a typical value for θ (Friedman, 1964) and then applying this pattern to the Afar margin would give extension fractures along the regional NNW trend, with associated NNE and NW shear fractures and ENE relaxation fractures. Crustal anisotropy could modify this picture somewhat by changing the values of θ. It is conceivable that a strong basement grain in the Afar margin crust would effect such an anisotropy, and the typical meridional trend of this grain in central Ethiopia might yield an asymmetric positioning of the regional (NNW) extension fractures between NNE and ESE shear fractures, forming in response to northeast-southwest (Red Sea?) crustal dilatation. The N50°E fold axes and N70-80°E lineations fit quite well with relaxation fractures in this stress pattern. In the flood basalt province of the Columbia plateau, the fold axes are approximately perpendicular to the main extension fractures and dikes (Gibson, 1969).

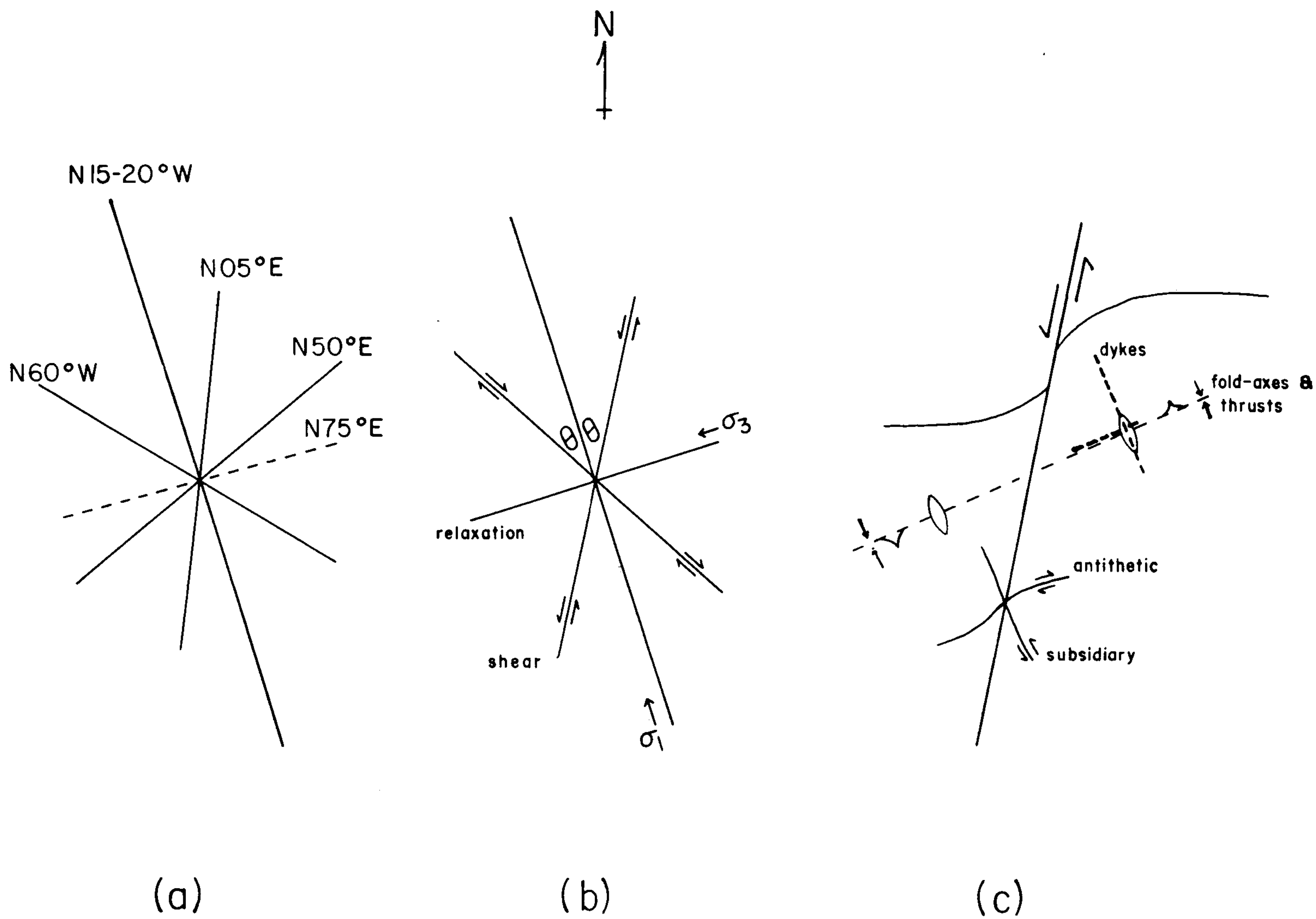

Figure 7. Theoretical crustal stress models for western Afar, considered in text.

The possible role of transcurrent faulting along the western margin of Afar, and its effect on the crustal stress pattern, can be reexamined; the sense of any such shearing is likely to be sinistral (Gouin and Mohr, 1964; Mohr, 1967a). Figure 7c shows the idealized pattern of frictional deformation in an isotropic medium resulting from sinistral shear (Freund, 1965; Bishop, 1968). Besides the primary graben shear lines, two sets of secondary shear can develop: one in the same sense as the main fault and at an acute angle to it, the other in an opposite sense at an obtuse angle (Freund, 1965, p. 198). Also, there may be normal faults striking at a high angle to the main fault, and reverse faults approximately perpendicular to the normal faults and with fault planes dipping away from the main fault. Dike injection on this model is primarily controlled along the normal faulting orientation.

Gibson (1969) and Mohr (1968b) have related the en-echelon pattern of NNE faulting in the main Ethiopian rift to crustal shearing along the rift in a northeast-southwest direction. This direction has to be changed slightly if the Afar margin faults and dikes are to be interpreted in terms of primary shear (Figure 7c). If the NNE trend is chosen as a line of sinistral slippage, then the N50°E fold axes and ENE thrust faulting conform with this scheme, though the thrusting should come from the south rather than the north (see above). The regional NNW dike faults become the main tensional features, approximately at right angles to the reverse faults and fold axes. The N60°W faults become subsidiary shear fractures of sinistral sense, and the N50°E faults become antithetic shear fractures of dextral sense.

It must be emphasized that no such horizontal displacements have yet been observed from the Afar margin or identified on aerial photographs. Indeed, unless the component of longitudinal shear is minor, the solution of the Afar margin fault-dike pattern in terms of primary shear is too forced to be convincing and can hardly be reconciled with the warping and antithetic normal faulting of the margin lava sequence down into Afar. Despite the evidence for sinistral shear in central and eastern Afar (Mohr, 1968b; 1971a; Dakin, Gouin, and Searle, 1971), it is considered best to assume the simpler crustal-tension model discussed previously and to see how this fits with observations elsewhere in the Ethiopian rift system.

5.4 Dike Swarms from Other Parts of Ethiopia

5.4.1 The Ethiopian plateau near Addis Ababa

The dikes described here lie within the plateau or on the outer fringe of the deformed margin with Afar. Their equivalent position on the Dessie-Eloa traverse would be west of Dessie.

Sparse concentrations of dikes between Debra Berhan and Debra Sina trend N05-10°E with steep westerly hades. One N15°W trachytic dike, below Debra Sina, hades southwest. These dikes conform precisely with the much more strongly developed fracture-injection pattern of the Dessie-Batie region.

About 80 km north of Addis Ababa, between the Chancho and Deber streams on the Debra Markos Road, there are mediocre exposures of a dike swarm 10 km wide. The main trend is N00-15°E, hading mostly west, and coincides with the western topographic margin of the Gorfu Mountain range. A subsidiary trend is N20-30°W with southwest hade. The dikes of this region are aphyric basalts that cut lateritized and zeolitized feldspar-phyric basalt flows. Some north-south fold axes are developed in these flows in the dike-swarm region.

At Entotto, immediately north of Addis Ababa, the prominent ENE ridge of silicic lavas and tuffs is cut by vertical N50-60°E feeder dikes. This trend is developed in the form of jointing in the basalt lavas and dikes of the Trap Series exposed north of Entotto.

From Addis Ababa due westward to the Guder valley, occasional good exposures of the Trap basalts reveal no dikes, except 67 km from Addis Ababa (just east of Wolenkomi) where some N30°E dikes, 5 m thick, are very badly exposed. They are aphyric basalt and cut coarsely porphyritic trachybasalt flows. They occur in a region marked by a strong gravity anomaly (Gouin and Mohr, 1964) and also by young basaltic volcanism. From

Wolenkomi to Ambo, a variety of aphyric, feldspar-phyric and olivine-phyric basalt lavas and agglomerates are exposed. The lavas show an overall tendency to dip 15° to the southeast (i. e., toward the rift) and are cut by N30° W jointing but lack any dikes.

Immediately west of the Guder valley, a notable dike swarm cuts a thick sequence of zeolitized, coarsely augite-phyric basalt lavas. The dikes are similar in composition to the lavas and in one case (LE 112) can be observed to feed into a flow. The average thickness of these dikes is only about 50 cm, much less than the Dessie-Eloa dikes. The dominant trend is N25°E and hades to the west in the eastern half of the swarm but to the east in the western half of the swarm. If all the dikes are contemporaneous, this would seem to indicate a shallow focus of activity. A strong subsidiary dike trend is north-south with hades to the west.

The lava sequence west of the Guder is intensely faulted along several trends and is sometimes steeply tilted down to the east. The main fault trends are N15-25°E with steep hades to the east and N80-90° W with shallow hades to either the north or the south. The latter faults and some rare N60°E faults show crush zones 1 to 5 m wide and are evidently planes of major movement. Jepsen and Athearn (1962) and Mohr (1962) have noted the existence of faults of this trend between Addis Ababa and Ambo that form a sharp boundary between the central and southern parts of the Ethiopian plateau (Baker, Mohr, and Williams, 1971). Near dike LE 111 a small N20° W reversed fault thrusts from the southwest.

No dikes are exposed in the Trap Series farther west from the Guder region, until east of Ghedo, where the products of young rhyolite cones and domes cover the basalts.

5.4.2 The northern Ethiopian plateau

The Miocene Simien volcanic center of northeastern Beghemder is cut by irregularly developed dike swarms of two main trends (LeBas and Mohr, 1970):

	Trend	Hade
1.	NNE	W
2.	ESE	N

These two trends are also well developed as joints and dikes in the upwarped zone immediately west of Lake Tana and are strongly developed in other parts of the northern Ethiopian plateau, suggesting an overall tectonic unity.

Abbate et al. (1968) have mapped dense ESE dike swarms cutting the eastern edge of the Ethiopian plateau in southern Tigray, exposed on the watershed between Kobbo and Lalibela. The dikes are thin (~30 cm wide) and composed of aphyric basalt. Hades are about 80°, more frequently to the north than the south, similar to Simien. Farther north through Tigray, dikes are rare, despite some excellent exposures of the Trap Series, which is strongly deformed in the Amba Alaji region (Mohr and Rogers, 1966). In the vicinity of Makalle, some very thick northwest-southeast basaltic dikes are related to flexure folds in the Antalo Limestone (Abbate et al., 1968). South of Makalle, near Debub Wogherat, a swarm of N40°W silicic dikes occurs with vertical hades; these may represent a younger phase of tectonism than do the basalt dikes.

North of Makalle, in the vicinity of Adigrat, the watershed region of the plateau is cut by a sparse swarm of ENE basaltic dikes cutting thick, coarsely olivine-phyric basalt lavas. In the Asmara-Decamere-Adi Ugri region of southern Eritrea some swarms of NNE basaltic dikes have hades to the west (Abbate et al., 1968), similar to the Simien dikes.

5.4.3 The Danakil horst

The geological maps of Brinckmann and Kürsten (1969) show basaltic and silicic dikes of northwest trend in the northern part of the Danakil horst; hade is not indicated. Fissures that have supplied Quaternary basalts in the southern Danakil horst have the same northwest trend, which is evidently fundamental to this horst.

5.4.4 The northern Somalian plateau

The Dire Dawa-Harar Road section reveals many dikes cutting the northern escarpment of the plateau, but none is found on the plateau itself between Alemaya and Harar. It is not known whether this represents a tectonic concentration or whether it is merely an elevation effect of the type recognized by Walker (1960) in Iceland.

The Dire Dawa dikes, as they may conveniently be termed, tend to be several meters thick and some might better be termed elongated plugs. They are predominantly composed of aphyric basalt. The main trends are the following:

	Trend	Hade
1.	N50°E	vertical (occasionally NW)
2.	N70°E	S
3.	N-S	vertical (occasionally W?)

It is noteworthy that the N70°E dikes, whose trend is that of the Gulf of Aden, hade into the plateau just as do the dikes of the western Afar margin. However, the faulting of the plateau escarpment in the Dire Dawa region is normal, stepped, and not antithetic, suggesting that the cause for the plateau-ward hade of the dikes is more deep seated than the surficial fracturing of the crust.

The Pre-Cambrian gneisses and Mesozoic marine sedimentary rocks are well exposed in the Dire Dawa region and frequently reveal the relationships of dikes and faults to older structures. In several cases, a parallelism or subparallelism with the Basement foliation is developed (e.g., HA 122 and 125). This may account for the unusual variety of dike trends, as well as for the sinuous trend of individual dikes-cum-plugs. The regional faulting of the Somalian plateau-Afar margin at Dire Dawa is ENE, downthrown north. It is stepped block faulting, which has imparted steep southerly dips to the Mesozoic and Trappean strata. The fact that the ENE dikes hade south in spite of this southerly tilting of the lavas they fed indicates that dike hades cannot always be attributed solely to postinjection tilting. South of Harar, the basalts of the Marda range have been fed from a northwest-southeast line of plug-like bodies.

The Chercher Mountain traverse between Harar and Asba Tafari follows the northern rim of the Somalian plateau. The region traversed is strongly deformed by rather complex faulting, and strata dips are very variable locally. Between Chellenko and Kollubi, some extraordinary interpositionings of the Trap Series and Upper Sandstone (Cretaceous marine? sands) are seen, and 12 km east of Chellenko, sandstone "dikes" cut massive basalts.

The Chercher traverse crosses two dike provinces: (a) between Kollubi and Harar, the dominant trend is NNW-NW with steep southwest hades; and (b) between Kollubi and Miesso the dominant trend is NE-ENE with steep hades to the southeast. The boundary between these two trends at Kollubi is sharp, with only a single northeast dike (HA 115) occurring east of that town. The dikes are mostly aphyric basalts, with augite-phyric basalts much less common. Silicic dikes occur at the two extreme ends of the traverse (HA 101, 102, and 121). The Chercher dikes tend to be less than 1 m thick and, where exposed, are not notably concentrated in swarms. Among the complex fault pattern of Chercher, the two dominant fault trends are N70-80°E and N00-35°E, with variable directions of hade.

5.4.5 The southern Somalian plateau

The road from Shashamanne to Goba runs eastward from the rift valley (elevation 1920 m) in a direct ascent of the plateau escarpment to Kofole (2645 m), thence 70 km down a gentle planar dip slope to Adaba (2395 m). Eastward from Adaba, the road crosses the Batu Mountains (3500 m at col) before descending to Gurie and Goba (2700 m). From Shashamanne to Adaba, thin silicic tuffs overlie zeolitized basalts (Mohr and Gouin, 1968), but no dikes are exposed. Good exposures of the Batu Mountain basalts (post-Trappean in age?) east of Adaba reveal no dikes until a swarm is encountered between 18 and 25 km east of Adaba (direct distances). Further sporadic dikes are exposed as far as the road col (32 km), but despite some good exposures, no further dikes are found between the col and Goba.

The swarm dikes trend N50-60°E and hade steeply northwest. Only a single dike (AG 115) has a different trend (N00-20° W). The dikes are very predominantly aphyric basalts and cut lateritized, zeolitized olivine-augite-phyric basalt lavas. The lavas are subhorizontal or dip very gently westward, and they are sometimes very gently folded along N45-60°E axes. Between the swarm and the col, sporadic dikes keep the same regional trend, and some silicic dikes are a feature of the col region. The col and much of the Batu Mountain plateau is pierced by grotesquely eroded plugs of coarse basaltic agglomerate and by natural walls of weathered-out dikes.

The singular strike of the Adaba dike swarm, with a virtual absence of other trends such as is not the case anywhere else in Ethiopia, has prompted a careful examination of aerial photographs of the region. These reveal a strong and extensive faulting or jointing of N20° W trend in the western fringe of the Batu plateau. Both north and south of the road in this fringe region, small swarms of N15-30°E dikes are clearly visible, despite their absence from the road col. A few silicic dikes form walls with a N50-65° W trend. It is therefore evident that a single traverse of a region that, unlike the Afar margins, has been subjected to considerable central-type volcanism can give a distorted picture of dike trends and thus the crustal stress pattern. In this respect, a full-scale survey of the Batu Mountains is very desirable. Their summit regions reveal denuded flows, lacking visible dikes except for radial swarms around some parasitic centers. Subsidence features, 200 to 500 m across, are preserved on some summits. From the aerial photographs, a possible sequence of dike injection can be suggested:

1. N60°E basalts,
2. N20°E basalts,
3. N65° W silicics.

Faulting does not appear to have strongly affected the Batu plateau. The largest observed faults trend N70°E, in particular a fault that extends eastward from the road col and south of Gurie. This fault is upthrown south, and the upthrow is associated with strong upwarping from the south. This upwarped region is cut by N20°E dikes. The youngest silicic lavas appear to postdate this relatively late faulting episode.

5.4.6 The Ethiopian rift and Afar

The lack of denudation on the relatively low-lying floor of the rift system is inimical to exposure of dikes. Furthermore, the rift system is the site of young and continuing volcanism, where numerous fissure flows undoubtedly cover dikes at depth.

East of Addis Ababa, some isolated dikes are exposed. For example, at Gara Bushu, between Dukam and Akaki, a 2- to 2.5-m wide basalt dike of N20°E trend is older than the summit cinder deposits. The eastern ridge of Mount Yerer, a Pliocene biotite-anorthoclase trachyte center, has a northwest-southeast topographic trend, which is that of some contained basalt and trachyte dikes, as well as of faulting upthrown northeast. This cross-rift structural trend has been discussed elsewhere (Mohr, 1967a).

On the rift floor itself, basalt fissures or gaping gjá occur at various places along the main Ethiopian rift, the trend being dominantly NNE. In Afar, where the tectonics are more complex (Mohr, 1967a), various fissure trends are observed: NNE in the Wonji fault belt of southern Afar, northwest in eastern and northern Afar, and north-south in west-central Afar. These features belong to a much younger phase of tectonism than the dikes discussed in this paper and will not be considered further here.

5.5 The Regional Stress Pattern

The great majority of the dikes examined in this study were feeders to the Trap Series flood basalts. Although the dikes may not all have been closely contemporaneous, the controlling stress field is perhaps unlikely to have altered much during this single, extended volcanic episode. Therefore, it seems not unreasonable to approach the Ethiopian dike patterns as the result of an instantaneous stress field, until evidence to the contrary emerges. This approach is also confirmed by the work of May (1971).

Figure 8 summarizes the structural orientations of dike swarms from known Ethiopian localities, as well as giving relative abundances of differing dike orientations at each locality. Certain features of the regional pattern are immediately evident.

The major dike orientations do not everywhere parallel the later, faulted rift margins (Mohr, 1962, 1967a). Along the Dessie-Eloa traverse, where the dikes are intimately related to the marginal warping of Afar, the narrow belts of Pliocene-Quaternary antithetic faulting have followed the strike of the warping. But farther north, where the Afar margin faulting continues northward through Tigray, the main dike trend turns to northwest.

On the Somalian plateau, there are some gross anomalies between the dike and subsequent fault orientations. In the Adaba-Goba region, the dike swarms have an ENE main trend, contrasting with the NNE faulting of the rift valley immediately to the west. The northern rim of the Somalian plateau is injected with a northeast-trending swarm of dikes, which in the Dire Dawa-Harar region is oblique to the ENE marginal faulting of southern Afar.

Dike hade directions are relevant to the problem of nonparallelism between dikes and subsequent faults. On the Dessie-Eloa traverse, the direction of dike hade is westward (the same as for the later, antithetic faults), fitting with the classic concept of perpendicularity of feeder dikes and warped flood lava flows (Du Toit, 1929; Wager and Deer, 1938; Challis, 1961; Cox et al., 1965; Gibson, 1966). But if this relationship were to continue farther northward, the marginal warping of Afar should turn northwest into the Ethiopian plateau and away from the meridionally faulted topographic margin of Afar. While the geology of central northern Wallo

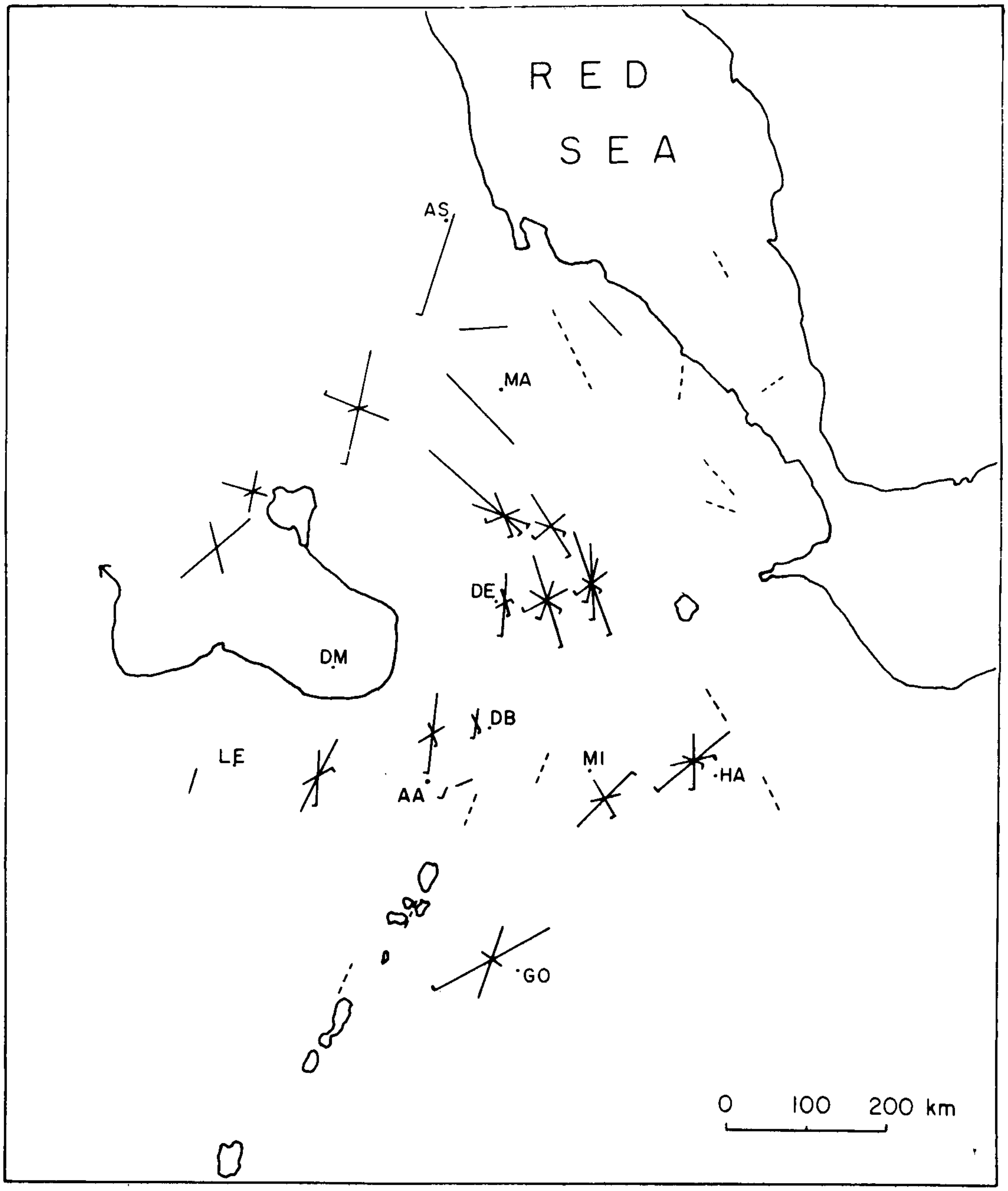

Figure 8. Schematic representation of regional dike trends and hade directions in Ethiopia (where known). Length of lines indicates relative abundances of intersecting trends for the particular locality. Dotted lines indicate Quaternary fissure basalt lines. (AA: Addis Ababa; AS: Asmara; DB: Debra Berhan; DE: Dessie; DM: Debra Markos; GO: Goba; HA: Harar; LE: Lekemti; MA: Makalle; Mi: Miesso.)

and southern Tigray is not well known, it is certain that the degree of warping along the present, faulted margin of Afar diminishes considerably north of latitude 13°N. The Simien Mountains, at latitude 13°N but in the central part of the Ethiopian plateau, contain a possible northward downwarp (Mohr, 1967b). Several east-west tight monoclines occur at the eastern rim of the Ethiopian plateau but are warped down southward (Mohr and Rogers, 1966; Abbate et al., 1968). The evidence remains inconclusive, but there is a hint that in northern Afar there was a divergence in the pattern of Paleogene crustal warping and fissure basalt activity, from the present faulted topographic margin of Afar.

On the Somalian plateau, the warping of the northern margin down into Afar is reflected by the southerly dike hades in the Miesso region. Farther east near Dire Dawa, the dikes parallel to the margin retain this southerly hade, despite the subsequent southerly block tilting and faulting (Gouin and Mohr, 1964). But the main dike trend in the Dire Dawa region is northeast, and the hades are northwest. These dikes may have affinity with the Adaba-Goba dikes, which also hade northwest and are unassociated with any lava pile warping. Apparently not all dike swarms in Ethiopia are related to crustal warping.

In the interior of the central Ethiopian plateau, the main dike trend is NNE parallel to the main Ethiopian rift tectonism. In eastern Wollega, near-vertical or west-hading dikes cut steeply eastward-dipping lavas in an intraplateau zone of Trappean deformation. This style of deformation, with the same structural orientations, occurs in the Lake Tana basin (Mohr and Rogers, 1966) and may continue to the Asmara region of Eritrea, where it intersects the northwest-trending Red Sea margin.

An impressive feature of the main dike-swarm trends in Ethiopia is the arcuate regional strike, particularly for the Ethiopian plateau. This strike forms the eastern half of a circle in which dike hades are directed toward the focus of the circle (only the Miesso dikes fail to conform to this pattern).

It can be speculated that a major Trappean magmatic source lay within the semicircle, under the central Ethiopian plateau. Alternatively, the main dike orientations may reflect a warped protomargin of the Nubian crustal plate (McKenzie, Davies, and Molnar, 1970) against Arabia and the Indian Ocean during the Paleogene. In this case, the Pliocene-Quaternary faulting of the main Ethiopian rift traversed at an acute angle the southeastern edge of the Nubian plate, thus isolating the once contiguous Somalian and Ethiopian plateau blocks. If this argument is correct, then dike orientations in unmapped parts of Ethiopia may be predicted: for example, northeast in Gamu Gofa,* and north-northeast in the Aisha horst (but north-northwest if this horst was once part of the rotated Danakil horst (Mohr, 1970)).

In Ethiopia, there is a frequent, if not ubiquitous, symmetry of complementary dike trends about the main trend. The θ values (Friedman, 1964) are 30 to 45°. Cases of asymmetry (e.g., Batie-Eloa, Adaba-Goba, and Miesso) may be related to anisotropy of the Pre-Cambrian continental crust or possibly to complication from dike injection of a subsequent episode. Otherwise, the symmetry and the θ values together confirm that the principal stress has been acting along the strike and that the dikes have formed in response to tension at right angles to the strike.

The complementary dikes participate in a remarkable feature found at all known Ethiopian dike localities. At any given locality, the hade directions are "sympathetic". That is, there is no opposition of hades between adjacent dike trends, excepting the necessary instance at a line that can conveniently be termed the bisector. This phenomenon is clearly seen for the Dessie-Eloa dikes (Figure 8), where the bisector orientation is approximately east-west. The same orientation applies in northern Wallo and southern Tigray and also possibly in the Addis Ababa region. However, in the Wollega and especially the Harar regions, the bisector orientation is closer to northeast-southwest.

*A young dike swarm in the Amaro horst, at the southern end of the main Ethiopian rift and partially mapped in the summer of 1971, trends north northeast parallel to the rift-valley faulting.

Whatever the significance of the bisectors, their orientations coincide with perpendicularity to the structural trend of the Red Sea and western Afar, that is, with the direction of Neogene sea-floor spreading (Mohr, 1970). The sympathetic hades of dike trends at a given locality is a feature not yet explained, though J. De Boer (personal communication, 1970) has suggested the possibility of different stress fields operating at different levels in the crust.

The complexity of the dike-swarm patterns in Ethiopia compared with other parts of the world (e.g., see Gibson, 1969) may be related to the proximity to a plate-tectonics triple junction. Certainly, the abundance of complementary dike trends appears to be unparalleled in Iceland, western U.S.A., or southern Africa, for example. This complexity is also reflected in the fault patterns of the Ethiopian rift margins, where two intersecting fracture trends are not infrequently developed. The perpendicular "cross-rift lineaments" (Mohr, 1967a) may be secondary shears related in a single stress pattern to the main tensional fractures. Additionally, there is a regional N50°E trend of gentle folding affecting much of the Ethiopian rift and Afar margins, indicating a northwest-southeast compression that is known to have begun at the end of the Mesozoic and continued throughout the formation of the Trap Series (Mohr and Rogers, 1966). This compression coincides closely with the direction of principal stress as indicated by the dikes of the Dessie-Eloa traverse.

It is evident that investigation of paleostress fields in Ethiopia is in its infancy. Further detailed field surveys are required on the Ethiopian and Somalian plateaus, and in Yemen, now detached by the spreading zones of the Red Sea and Gulf of Aden. The Quaternary fissure basalt lines of the rift floor also require detailed mapping. Petrographic studies and radiometric dating of dikes and intruded lavas will further help to elucidate some of the problems raised here.

6. CONCLUSIONS AND THE EVOLUTION OF THE ETHIOPIAN RIFT

The western margin of Afar with the Ethiopian plateau has been a broad zone of major crustal downwarping since its initiation in the Jurassic (Mohr, 1962; Hutchinson and Engels, 1970). Severe marginal flexuring during the Paleogene in central and southern Afar was accompanied by extrusion of flood basalts from dike-swarm feeders. At a subsequent date, probably in the Miocene, the flexured zone of continuing volcanism was cut by massive upfaulting of the Ethiopian plateau: this tectonism was accompanied and followed by strongly developed antithetic faulting east of the main synthetic fault. During the Pliocene, tectonic and volcanic activity migrated into internal Afar, except that in the late Pliocene-Quaternary there has been important upfaulting and graben formation along the line of the Ethiopian plateau escarpment (Mohr, 1967a).

The flood-basalt lavas of the margin zone are ascribed to the Trap Series (Mohr, 1968a), but no lithological divisions of regional significance can be demonstrated within the Series (cf. Abbate et al., 1968, whose claims are disputed earlier in this paper). The basalt petrography shows a rather monotonous uniformity of zeolitized, coarsely porphyritic labradorite basalt types, frequently with olivine and occasionally with augite phenocrysts. The petrography of the feeder dikes is rather similar, except that the wider dikes have coarse-grained interiors that tend to be richer in pyroxene relative to olivine. Undersaturated olivine-augite basalt lavas and dikes are notably more common in the plateau interiors than at the margins.

The lavas show a consistent easterly regional dip toward Afar, at angles varying between 10 and 30°, the average figure being closer to the latter. The dikes of the swarms that run parallel to the margin zone hade west at an average angle of 20° from the vertical. There is thus near perpendicularity between the lavas and feeder dikes. In detail, the dike orientations show a statistically discrete grouping whose symmetry is highly suggestive of a single stress field, with complementary trends manifested at 30 to 50° to the major axis.

The antithetic faulting of the Afar western margin, postdating the dikes (and crushing many of them), shows a concentration within narrow zones whose spacing increases eastward away from the main plateau escarpment. Again, these faults show multiple orientations suggestive of a single stress field (not always precisely coincident with that of the dikes), with complementary fracturing at 30 to 45° to the main axis. This stress field includes an observed mild folding along northeast-southwest axes. The occurrence of at least two erosion surfaces within the margin zone points to two phases of antithetic faulting, the later one of which is of probable Villafranchian age (Taieb, 1971).

One of the most interesting tectonic features of the Ethiopian region as a whole is the nonparallelism in places of dikes and subsequent rift faulting. This is largely due to the peculiar, arcuate regional strike of the main dike trends, with hades toward a hypothetical arc focus situated in the west-central Ethiopian plateau. While the cause of this arcuate regional dike injection remains speculative, it does imply that the Paleogene margin of northern Afar was not coincident with the subsequent, Neogene-faulted one. The remarkable "sympathy," about a bisecting line, between dike hade directions for any particular locality has been demonstrated, but no evident explanation is yet forthcoming. It is probably significant that the bisectors trend parallel to the direction of crustal spreading in Afar.

The main Ethiopian rift, as distinct from Afar, shows some ambiguous relations between dike swarms and the Pliocene-Pleistocene faulting. This may in part be due to the lack of suitably deep exposure along the margins of this young rift but also reflects the lessening degree of crustal warping southward. Indeed, the dikes of the west-central Somalian plateau are not associated with any marked warping or subsequent faulting: their northwest hades imply that any downwarping would have been to the southeast, away from the later rift!

The evolution of the Ethiopian rift system cannot yet be detailed, but mapping of dike swarms has revealed many new facts, some as yet inexplicable in relation to the present-day pattern of rift faulting. Complexities undoubtedly derive from the proximity of the Afar triple junction, yet it is clear that detailed study of Ethiopian dikes is yielding new and somewhat unexpected insights into continental-rift evolution.

7. ACKNOWLEDGMENTS

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APPENDIX A

RADIOMETRIC AGES

APPENDIX A

The author's attention has been drawn to the recent publication (and oral presentation) of Megrue, Norton, and Strangway (1971) on K/A ages on some of the dike specimens listed in Appendix B. These whole-rock ages show several apparent features: (a) the oldest ages extend back to the Paleocene and are found both on the Kombolcha-Eloa traverse and in the Harar-Dire Dawa region, (b) there is no evidence that the dike ages become progressively younger riftward, as has been postulated for the Icelandic rift (Gibson, 1967), and (c) the dike swarms of the central Ethiopian plateau (Guder region) and central Somalian plateau (Batu Mountain region) are of Miocene age, tending to Upper Miocene.

The reliability of whole-rock K/A ages on basalts has been disputed, especially where as in the Ethiopian flood basalts there is almost always some degree of zeolitization present. The samples analyzed by Megrue et al. were oriented ones collected for paleomagnetic work (G.H. Megrue, personal communication), where freshness was considered secondary. This age reliability problem has been emphasized by further study of the K/A ages obtained by Grasty, Miller, and Mohr (1963) on the Abbay (Blue Nile) basalts, where the obtained ages do not match the stratigraphic sequence. Both argon loss and the possible presence of inherited argon can be significant (Miller, 1967). Rex, Gibson, and Dakin (1971) have used feldspars from two ignimbrite units interbedded in the flood-basalt sequence east of Addis Ababa (Kassam gorge section) for dating purposes, but such interbedded units are too rare to provide a complete alternative to whole-rock basalt analysis. Furthermore, argon leakage is usually more serious from feldspar than from most ferromagnesian minerals, so that the Neogene age-range obtained by Rex et al. for the Kassam flood-basalt sequence must be treated as minima.

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If the radiometric data currently available on the Ethiopian flood basalts are accepted at their face value, they confirm a Paleocene-Lower Eocene initiation for the Trap Series volcanism, the younger age of the Trap Series in southern Ethiopia compared with the type area to the north, and a measure of constancy in the stress field of the Afar margins during the Tertiary. What is now required is detailed structural mapping of the flood basalts and rift margins of Ethiopia, and the careful selection of specimens suitable for radiometric dating.

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APPENDIX B

LIST OF SAMPLED DIKES, GIVING THEIR ORIENTATION, DIP, AND THICKNESS; DISPOSITION OF INTRUDED LAVAS; GENERAL REMARKS

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Kombolcha					
AD 102					Plug intruding flood basalts (AD 101) 92 km from Addis Ababa, along Kombolcha Road.
AD 103	N05° W	90°	1.5	0-10° W	Olivine-augite basalt dike, sampled 1 km NW of AD 102.
AD 104	N05° E	90°	3		Porphyritic basalt dike intruding tuff-lava sequence, 26 km from Debra Berhan, along Ankober Road.
					Note: many good exposures from Debra Berhan to Mussolini tunnel, but no dikes.
AD 106	N10° E	70-80° W	1		Amygdaloidal vesicular trachybasalt dike at Dux Road hairpin, intruding scoriaceous platy-feldspar basalt lavas with laterite horizons and some zeolitized aphyric basalts (AD 108 – "Statuette flow").
AD 107	N10° E	70-80° W	2		Occurs 4 m E of AD 106.
AD 109	N15-20° W	80-85° W	1		Trachybasalt dike in a 400-m lateral exposure of severely decomposed lavas, about 3 km N, down road from Debra Sina.
					Note: no dikes found along Borkenna graben, from Robi to Kombolcha, but exposures poor except near Karakore and down Borkenna river canyon.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Dessie (see Figure 3 for locations)					
AD 110	N05°E	75-90°W	0-1	30-45°SE	Zeolitized aphyric basalt dike of irregular form, cut by later faulting.
AD 110A	N10°E		2	10°E	200 m up road from AD 110, with intervening NNE fault dipping 80°W, thrown 4 m up E. Dike intrudes lateritized basalt flows 4 to 5 m thick.
AD 110B	N-S	80°W	0.5		Occurs 50 m below AD 110.
AD 110C	N20°W	60-80°W	0.1-0.6		Finely porphyritic basalt dike.
AD 110D		variable	0.5		Intimately associated with AD 110C as a dike sill, but much fresher rock.
AD 110E	N10°E	85-90°W	0.6	20-30°S	Intrudes strongly zeolitized basalt flows.
AD 111	N-S	90°	1.5-3	30°W	Dense aphyric basalt dike with 10-cm chilled margins; inside these, 15- to 20-cm bands of flow shearing. Horizontal columnar joints.
AD 111A	N-S	75-90°W	0.5		Porphyritic hyalobasalt dike with intensely zeolitized core. Intimately associated with AD 111, which it probably predates. Intrudes zeolitized porphyritic basalt lavas (AD 112). 100 m farther NW, a very linear E-W fault dips 45°N, thrown 1 m up S.
AD 113	N60°E	10-90°E	1	~30°E (NW of fault)	S-shaped form, intensely shattered by strong faulting of this region. Intrudes broad syncline of thin basalt flows on folded massive lateritic formation.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Dessie					
AD 113A	N60°E	90°	7	~20°S (SE of fault)	Dike immediately S of large fault and gully. Bakes and distorts intruded laterite, and has zeolitized core. Flow slickensiding indicates S60°W component to vertical intrusion.
AD 114	N10°E	85-90°E	5.7		Dense aphyric basalt dike, lacking chilled margins. Possibly repeated by N70°E normal fault, dip 60°NW, throw 200 to 300 m with sinistral shear component. Dike intrudes zeolitized scoriaceous olivine basalt (AD 114A), which has N60°E jointing and axes of gentle folding N-S. 200 m to SE, fold axes NW-SE.
AD 115	N20°E	80°W	0.7-0.8		Weathered dike in basalt flows (AD 115A) with N60°E fold axes, fold amplitude 5 m, and wavelength 15 m.
AD 116	N00-10°W	70°W	1	25°NE	Sinuous dike in strongly faulted lavas (faults strike N60°E, vertical, with small throws up W).
AD 117		20°W	0.5-1	45°NE	Deformed dike in strongly faulted and mildly folded agglomerate, with thick flows of lateritized, zeolitized basalt.
Dessie-Hayk					
DE 101	N60°E	80°SW	1	subhoriz.	Finely porphyritic basalt dike intruding lateritized lavas. Occurs at N end linear offshoot of Borkenna graben.
					Note: despite many excellent exposures between Dessie and Hayk, no other dikes found.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Eloa (see Figure 3 for locations)					
KA 101	N20°E	80-85°W	2	20-30°E	Intrudes lateritized basalt flows cut by N60°W joints and an E-W fault with horizontal slickensiding. Flows thicken to E.
KA 101A	N10°E	55°W	1	20-30°E	Occurs 40 m W of KA 101. Both dikes may have fed a fresh flow lying at surface on the lateritized basalts.
KA 102	N10°W	80-85°W	35		Coarse-grained, leucocratic basalt dike intruding intensely baked, recrystallized (with large pyroxenes) coarse basaltic agglomerate (KA 102A), which may have preceded dike up injection plane. KA 102B is parallel, smaller dike immediately to E, cut by massive N-S faults dipping 75°E.
					Note: between KA 102 and 103 runs a linear N75°E reversed fault, dipping 75°N, thrown a few meters. Lavas N of fault are folded. Regional faulting is N40-50°E, dipping 75-90°W, normal throw, with 1-m crush zones.
KA 103	N50°E	SE?	2	subhoriz.	Deformed dike intruding fissile zeolitized basalt lavas.
KA 103A	N50°E	80°SE	1.0	subhoriz.	Occurs 50 m NW of KA 103; completely rotted and used by faulting.
KA 104	N60°W	90°	2.5	~10°SE	Used by later faulting, but horizontal columnar jointing partly preserved.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Aloa (cont.)					
KA 105	N60°E	85°NW	2		Used by later faulting. Rift faults (N10° W) strongly developed and dip steeply E. Intruded lavas are zeolitized, platy-porphyritic basalts (KA 105A).
KA 106	N10° W	90°	0.55		Not used by faults that cut KA 105A-type lavas.
KA 107	N45°E	80°NW	1.5		Weathered dike in KA 105A-type lavas. Dike parallels margin of sediment-filled graben 20 m to W.
KA 108	N15° W	70-90° W	0.5		Very weathered (?)dike in region largely covered by Challeka valley sediment fill.
KA 109	N90°E	90°	1	~10°E	Weathered, contorted dike, cutting strongly zeolitized basalt lavas (and fresh (?)sills).
KA 110	N60° W	90°	2.5	20-30°E	Intruded by a second-stage dike, 0.5 m wide, and of sinuous form within the linear main dike. Intrudes zeolitized basalt lavas.
KA 111	N20° W	70° W	2.5		Intrudes rotted zeolitized basalts.
KA 112	N60° W	65°SW	3	15-20°E	Intrudes rotted zeolitized basalts.
KA 112A	N60° W	65°SW	0.2		Occurs 15 m W of KA 112. 50 m W of KA 112 occurs fresh augite-olivine-phyric basalt (KA 112B), either flow or sill(?). Numerous N10° W faults, dipping shallower than 70°W.
KA 113	N10° W	60° W	1	20-30°E	Dike mashed by later faulting. Intrudes severely zeolitized platy-porphyritic lavas.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Eloa (cont.)					
KA 114	N20° W	70° W	6	E	Cuts dike KA 115, in usual zeolitized basalts.
KA 114A	N20° W	50° W	2.5	E	Occurs 25 m W of KA 114.
KA 115	N50° E	90°	0.6-0.7	E	Cut by KA 114.
KA 116	N20° E	65° W	4		Porphyritic augite basalt dike, possible feeder to KA 112B rock. Intrudes usual zeolitized porphyritic basalt lavas.
KA 117	N20° W	55° W	2.5	15-20° E	E margin and middle of dike faulted. Cuts zeolitized platy-porphyritic basalts.
KA 117A	N20° W	55° W	1	15-20° E	Occurs 60 m E of KA 117. Parallel, numerous faults with wide crush zones.
KA 118	N30° W	85-90° W	5-15	E	Irregular dike in zeolitized basalts.
KA 118A	N10° W	50° W	4	40° ENE	Porphyritic basaltic dike(?) in strongly faulted region. Separates contorted basalt lavas to W from silicic tuffs (KA 118 B) overlain by porphyritic basalts, to E.
KA 119	N60° W	85-90° SW	6	20° E	Chilled margins against zeolitized platy-porphyritic basalts (KA 119A). Dike is cut by N30° E fault, dipping 75° SE, but without any apparent displacement.
KA 120	N20° E	60° W	1.2	E	Aphyric basalt dike with horizontal columnar jointing. Cuts rotted zeolitized lavas.
KA 120A	N40° E	80° NW	1		Completely rotted.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Eloa (cont.)					
KA 121	N10° W	45-70° W	1-1.5	30° ENE	Platy-porphyritic basalt dike of variable dip. Strong N30° E faulting, dipping 65°NW, and E-W faulting.
KA 122	N20° E	30-60°NW	0-1	30° ENE	Dike pinches out at base, in well-bedded basaltic tuffs and porphyritic lavas (KA 122A). Numerous shallow-angle (35-45° W) N00-20° E faults.
KA 123	N-S	30° W	0.5-0.55		Cut by N70° W fault, dipping 50°S, whose drag on dike indicates normal displacement.
KA 124	N50° E	65°NW	1.8		Augite-plagioclase-phyric basalt dike cutting zeolitized aphyric basalt lavas. Numerous faults: N10° W (vertical) and N30° E (dip 35°NW).
KA 125	N10° W	60° W	0.8	~10° E	Aphyric basalt dike cutting rather fresh scoriaceous aphyric basalt lavas (KA 125A).
KA 126	N10° W	65° W	0.2	20-30° E	Persistent dike in intensely zeolitized lavas.
KA 126A	N-S	45° W	1		Used by fault.
KA 127	N10° W	75° W	0.5 total		Trio of thin dikes, each separated by 0.3 to 0.5 m. Intrude strongly faulted, weathered lavas.
KA 128	N-S	65° W	2.5-3	20° E	Cuts severely zeolitized basalt lavas.
KA 129	N10° W	70° W	0.6	30° ESE	At W end of road cutting; cuts zeolitized lavas and fresh aphyric basalt(?) sills.
KA 129A	N-S	75° W	0.6		Middle of cutting. Used by fault.
KA 129B	N25-35° W	85° W	1-1.5		Aphyric basalt dike pinching out at top. Joins KA 129C through sill.
KA 129C	N25-35° W	70° W	~0.5		

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Eloa (cont.)					
KA 130	N15° W	W	~4	30°E	Upper surface used by big fault. Also N20°E fault dips 70°NW, cutting zeolitized basalts.
KA 131	N40° W	60°SW	7	40°NE	Very weathered.
KA 131A	N-S	65° W	2.5-3	25°SE	Cuts zeolitized basalts, immediately W of KA 132.
KA 132	N10°E	70° W	1		
KA 132A	N-S	70° W	2.5		Occurs 20 m E of KA 132. Could be continuation of KA 133.
KA 133	N50°E	90°	2.5-3	10-15°E	Aphyric basalt dike cuts platy-porphyritic basalt lavas (KA 133A).
KA 134	N10°E	80° W	0.7	15-20°E	Cuts porphyritic augite-platy feldspar basalt.
KA 135	N50°E	~90°	3-4		
KA 136	N-S	80° W	1	30°E	Coarsely feldspar-phyric basalt dike cuts platy-porphyritic basalt and coarse olivine-augite-phyric basalt (KA 136A).
KA 137	N10°E	85° W	1.2	E	Cuts same country rock as KA 136. Aphyric basalt dike.
KA 138	N-S	80° W	6		Lower margin used by fault. Intrudes platy-porphyritic basalt lavas. Aphyric basalt composes dike.
KA 139	N10°E	90°	5		Porphyritic basalt dike.
KA 139A	N10°E	90°	7		Porphyritic basalt dike, immediately E of KA 139.
KA 140	N10°E	65° W	4		
KA 140A	N10°E	70° W	3		Adjacent to KA 140, in strongly zeolitized lavas.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Eloa (cont.)					
KA 140B	N30° W	80° W	0.1		Occurs between KA 140 and 140A in road cutting, but no intersections exposed.
KA 141	N55°E	75°SE	0.5		Porphyritic basalt dike, near post at 425 km.
KA 142	N20° W	65° W	10	20°ENE	Medium-grained aphyric basalt dike, S of KA 141. 60 m farther down road, E-W fault.
KA 143	N10° W	90°	12		Aphyric basalt dike with faulted margins. Intrudes zeolitized porphyritic basalts.
KA 144	N20° W	80°E	2		
KA 144A	N60° W	90°	2-2.5		Contorted dike, 15 m E of KA 144.
KA 144B	N60° W	60-90°W	1.5		Variable dip, 12 m E of KA 144A.
KA 144C	N-S	90°	4		Occurs 70 m E of KA 144B.
KA 145	N20°E	80° W	1.5		Cuts platy-porphyritic basalt lavas.
KA 146	N20° W	80° W	25		
KA 146A	N20° W	80° W	13		Separated by a few meters of mashed, faulted rock from KA 146 to W. Chilled margins indicate separate dikes at this level. Several possible but very poorly exposed dikes between KA 146 and 147.
KA 147	N-S	~ 40° W	15		Plug or dike?
KA 148	N40° W	40°SW	0.5		Platy-porphyritic basalt dike cutting complexly faulted plug: faults N-S, dip 70° W.
KA 149	N-S	60° W	0.5		Used by faulting. Intrudes massive, scoriaceous porphyritic basalt lavas.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Kombolcha-Eloa (cont.)					
KA 150	N-S	70° W	4		Very weathered dike. Other possible dikes nearby in faulted, massive, platy-porphyritic basalt flows.
KA 151	N60°E	80° W	3	15°SSE	Cuts platy-porphyritic basalts. Other possible dikes before KA 152, but poor exposures.
KA 152	N00-45°W	35° W	~20		Dike or plug?
KA 153					Plug.
KA 154					Plug.
KA 155	N10°W	90°	3-4		Aphyric basalt dike cutting subhorizontal zeolitized lavas (block-tilted nearby to dip 15°E). Paralleled by faults and stringers. Horizontal columnar jointing.
					Note: no further dikes exposed in the zeolitized porphyritic flows between KA 155 and Eloa.

Eloa-Assab

Some good exposures between Mille river and Tendaho, but no dikes. No dikes exposed on the S-upthrown E-W fault scarps S of the Awash river. In the Dobi graben region, excellent exposures of the Afar Series flood basalts, but not a single feeder found (see Mohr, 1971). Quaternary fissure basalt lines occur on the W side of the Danakil horst, 40 to 50 km SW of Assab.

Addis Ababa-Fiche

No.	Strike	Dip	Width (m)	Lava dip	Remarks
BN 101	N20°E	90°	2.5		Silicic dike, 2 road-km E of Entotto Col, cutting weathered porphyritic trachyte.
BN 102	N55°E	90°	4	15°SW	Occurs 50 m up road from BN 101. Vesicular porphyritic obsidian dike in finely brecciated tuffs.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Fiche (cont.)					
BN 103	N50°E				1 km SE of col, fine-grained trachytic dike chopped up by faulting.
BN 104	N60°E	90°	2.5		Occurs 50 m NW of BN 103. Weathered and rotten.
BN 104A	N55°E	90°	1		Occurs 15 m NW of BN 104. Fine-grained (?)trachyte.
					Note: at Entotto Col the volcanics strike N50°E and dip 15-20°SE.
BN 105	N05-20°W	~90	2-5		At knoll quarry, ~1 km SW of Lencha and 10 road-km NE of col. Vesicular porphyritic basalt, forming an upward widening pipe dike. Cuts dark, dense aphyric basalt (BN 105A) with N-S and N50°E jointing.
BN 105B	N-S	80°E	0.5		Porphyritic basalt dike, cutting S face of BN 105 quarry.
BN 106	N15°E	90°	1		33 road-km from col, 200 m NE of Chancho bridge. Intrudes subhorizontal, lateritized basalts.
BN 107	~N-S	~80°W	3.5		2 road-km NE of BN 106, near Kardaleti. Fresh, dark porphyritic basalt dike cutting coarsely vesicular, zeolitized flows (BN 107C).
BN 107A	~N-S	~80°W	0.5		Occurs 10 m W of BN 107.
BN 107B	~N-S	~80°W	0.5		Occurs 4 m W of BN 107A.
BN 108	N10°E	80°W	1		2 km NE of BN 107, road section near Legatama. Finely vesiculated basalt dike intrudes lateritized, subhorizontal augite-phyric basalt lavas (BN 108A). Lavas gently folded, axes N-S, wavelength 20 m, amplitude 1 m.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Fiche (cont.)					
BN 109	N30° W	75° SW	1		Occurs 50 m NE of BN 108. Zeolitized aphyric basalt dike with poor horizontal columnar jointing.
BN 110	N05° E	80° W	1		Occurs 2 km NE of BN 108 in Gorfa valley. Dark aphyric basalt dike intrudes gently folded, lateritized and zeolitized coarse agglomerate.
BN 110A	N-S	90°	2		Occurs 100 m NE of BN 110 near crest of hill. Weathered aphyric basalt dike with several offshoots and stringers (similar to BN 110).
BN 111	N-S	~90°	~1.5		Occurs ~50 m NE of BN 110A. Variable dip and thickness, with sill stringers. Intrudes gently folded, intensely zeolitized and lateritized basalt flows.
					Note: for the following 1.5 km from BN 111, good exposures but no dikes. No dikes in any further exposures to Debra Libanos, nor in the Zega Wodem gorge there.
Addis Ababa-Lekemti					
LE 101	N30° E		5		Occurs 67 road-km from Addis Ababa, ascending to Wolenkomi. Badly exposed aphyric basalt dikes in coarsely porphyritic trachybasalt lavas. Two other dikes occur immediately E of LE 101 (one is 2 m wide), and a 0.5-m dike 20 m W of LE 101.
					Notes: no dikes observed along the Gafarsa cuttings and fault scarps, between Entotto and Wachacha.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Lekemti (cont.)					
LE 101 (cont.)					No dikes in the thick flows exposed in the Jam-Jam river at Wolenkomi.
					At 91 road-km from Addis Ababa, quarry exposes 200 m length of thin, aphyric basalt flows with agglomerates (plug?), dipping 15°SE. No dikes. Joints and small faults N30° W.
					At 98 km, quarry exposes massive olivine-feldspar-phyric basalts. No dikes. Joints trend N30° W.
LE 102					16 km along road W of Ambo, on climb from Guder gorge, dike associated with inclined sill.
LE 103	N20°E	70° W	0.4		17 km from Ambo, at culvert parallel to ruined bridge. Coarse olivine-phyric basalt dike in zeolitized, massive, coarsely augite-phyric basalt lavas (LE 103B).
LE 103A	N20°E	50° W	0.5		Occurs 5 m W of LE 103.
LE 104	N25°E	80° W	0.5	10-15° W	Aphyric basalt dike, on outer road bend above LE 103.
LE 105	N-S	90°	0.5	10-15° W	Occurs 35 m W of LE 104. Coarsely porphyritic olivine-augite basalt dike.
LE 105A	N10°E	80° W	0.5	10-15° W	Occurs 10 m up road from LE 105. Weathered dike in intensely zeolitized augite-phyric lavas.
LE 106	N25°E	~90°	0.4		Occurs 100 m up road from LE 105A. Sinuous augite-phyric basalt dike. 15 m E of dike, a N25°E major fault, dipping 80-85°E, has 10- to 15-cm crush zone.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Lekemti (cont.)					
LE 107	N05°E	W	0.2-0.3		Contorted, zeolitized aphyric dike with overall westerly dip, intruding intensely zeolitized, very coarsely augite-phyric basalt lavas.
LE 108	N25°E	45°W	0.8		18 km from Ambo, and 100 m up road from LE 107.
LE 109	N25°E	60°E	1		Augite-phyric basalt dike, 100 m farther up road from LE 108.
LE 110	N25°E	70-90°E	0.6		Occurs 10 m NW of LE 109. Weathered zeolitized augite-phyric basalt dike cutting intensely zeolitized, massive, augite-poor lavas.
					Note: ~100 m up road from LE 110 occurs a small plug of aphyric basalt.
LE 111	N20°E	45°E	1		Occurs ~200 m up road from plug. Dike is cut by N20°W reversed fault, dipping 65°SW, throw 1 m.
LE 111A	N20°E?	80°E	~1		Impersistent dike, 15 m NW of LE 111. Cuts (?)E-dipping zeolitized vesicular augite-basalt lavas.
LE 111B	N30°E	50°E			Occurs 60 m up road from LE 111. Zeolitized pale basalt.
					Note: LE 111, 111A, and 111B could possibly be intensely deformed flows.
LE 112	N50°E	70°E	0.4		Occurs 250 m up road from LE 111. Zeolitized augite-phyric basalt dike, feeder to at least three sills (perpendicular to dike, and thus dipping gently to W). Intrudes zeolitized

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Lekemti (cont.)					
LE 112 (cont.)					agglomerates. 50 m SE of LE 112, large N70°E fault, vertical, with 1-m crush zone. 50 m NW of LE 112, very large N60°E fault, vertical, with 5-m crush zone.
LE 113	N35°E	75° W	0.5		Occurs ~100 m up road from LE 112. Intrudes very steeply E-dipping augite-basalt lavas that are strongly faulted.
LE 113A,B	~N-S	70° W			Two dikes at S end of same cutting in which LE 113 occurs. 20 m above (NW) LE 113, narrow apparent dike dipping 65°E is probably a flow or sill. At NW end of LE 113 cutting, a big N20°E fault, vertical dip.
LE 114	N-S	80° W	0.6		Occurs 100 m up road from LE 113. Zeolitized aphyric basalt dike, cut by very large N80° W fault, dip 45°N, 1-m crush zone. 20 m NW of LE 114, another E-W fault, dip 80°N, 15-cm crush zone. 50 m NW of LE 114, N15°E fault, vertical, 50-cm crush zone.
LE 115	N40°E	75°SE	0.7	35°SE?	Occurs 100 m up road from LE 114. Zeolitized, finely porphyritic augite-basalt dike with chilled margins. Intense, complex faulting in this region.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Lekemti (cont.)					
LE 116	N65°E	55°E	~1		Occurs ~100 m up road from LE 115. Rotted augite-phyric basalt dike, deformed by NE fault, dip ~30°NW. Further, near crest of road (19 km from Ambo), severe faulting cuts 15-35°E dipping lavas. One E-W fault dips less than 30°S.
LE 117	N-S	70°E	0.3		No good exposures from LE 116 for further 4 km before LE 117 in road-cutting N of bridge at bend. Coarsely porphyritic augite basalt.
LE 117A			0.2		Augite-phyric basalt dike possibly identifiable with LE 117B.
LE 117B	variable		0.2		On W side of cutting. Orientation twists from N70°E to N30°W going up the intrusion.
LE 117C	N15°W	75°E	1.5		Occurs 15 m N of LE 117B. Medium-grained augite-phyric basalt dike with pyroxene aggregates (xenocrysts?). Intrudes augite-phyric basalt agglomerate forming local knoll. To either side of agglomerate, well-bedded zeolitized flows.
					Notes: 13 km W of LE 117, possible N90°E vertical dike, 0.7 m wide, intrudes agglomerate and zeolitized augite-phyric basalt lavas dipping 20-25°E. Otherwise no dikes from LE 117 to here are exposed.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Addis Ababa-Lekemti (cont.)					
LE 117C (cont.)					No dikes exposed farther on to Ghedo, despite massive cliffs of at least a dozen flows in the Ghedo region. W of Ghedo, on the Jimmi-Tibbi plain, the Trap Series is covered by the erupta of N-S aligned rhyolite cones and domes.
Adaba-Goba					
AG 101	N60°E	90°	9		Occurs ~15 km E of Adaba. Gray-green trachyte dike in subhorizontal, severely zeolitized basalt flows with one fresh olivine-augite-phyric flow (AG 101A). Note: between Adaba and AG 101, some fair exposures of the zeolitized flood-basalt sequence, but no dikes. Sequence is subhorizontal or dips gently W.
AG 102	N60°E	90°	5		Intrudes subhorizontal, very gently folded lavas. The surface flow is 2 m thick and columnar jointed; it lies upon a massive, 10-m-thick, surface-lateritized olivine-augite-phyric basalt (AG 102A).
AG 103	N50-70°E	70-80°NW	1-1.5		Strongly zeolitized basalt?
AG 103A	N50-70°E	70-80°NW	1-1.5		Occurs 5 m E of AG 103, in olivine-augite-phyric flow.
AG 104	N50°E	variable	1.5		Sinuous dike with dip both NW and SE. Zeolitized aphyric basalt in olivine-augite-phyric lavas, zeolitized in their upper portions.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Adaba-Goba (cont.)					
AG 105	N55-60°E	80°NW	4		Severalzeolitized basalt dike in zeolitized flows.
AG 105A	N55-60°E	80°NW	1.5		Occurs E of AG 105.
AG 106	N50°E	85-90°NW	2		Zeolitized aphyric basalt dike in severely zeolitized basalt flows. Is exposed three, possibly four, times in road bends.
AG 107	N60°E	75°NW	6		Zeolitized aphyric basalt dike in subhorizontal zeolitized olivine-augite-phyric flows.
AG 108	N70°E	90°	1		Badly zeolitized and weathered dike.
AG 109	N50°E	90°	1		Sinuous dike: fresh aphyric basalt intruding dense olivine-augite-phyric basalt flows (AG 109A). 30 to 40 such flows are exposed on the south side of the valley (N slopes of Gara Arawa).
AG 110	N45-50°E	~85°NW	7		Aphyric basalt dike intruding lateritized olivine-augite-phyric flows that are subhorizontal and gently undulating.
AG 110A	N45-50°E	~85°NW	2		Occurs E of AG 110.
AG 111	N45°E	~90°	1-2		Weathered, fissile aphyric basalt dike of sinuous form. Cuts lateritized, zeolitized olivine-augite-phyric basalt flows. Other possible dikes, extremely weathered, about 5 m thick or more, occur in the proximity of AG 111.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
<u>Adaba Goba</u> (cont.)					
AG 112	N35°E	?NW	1.5		Rotted dike in severely lateritized, zeolitized flows.
AG 113	N50-60°E	~90°	0.5-1		At least three narrow dikes of rotted basalt in lateritized, zeolitized basalt lavas.
AG 114	N60°E	90°			Rotted dike in weathered, zeolitized basalt lavas.
AG 114A	N55°E	75°SE			Olivine-augite-phyric dike occurring E of AG 114.
AG 115	N20°W	?90°	2		Aphyric basalt dike.
AG 115A	N-S	?sill	0.5		Occurs 20 m E of AG 115. Aphyric basalt.
AG 116	N50°E	75°NW	0.5-1		Variably rotted aphyric basalt dike, occurring between AG 115 and 115A.
AG 117	N55°E	90°	1-1.5		Pale trachytic dike in zeolitized, scoriaceous aphyric basalt flows.
AG 118	N55°E	~85°NW	1-1.5		Dark aphyric basalt intruding zeolitized, lateritized flows.
AG 118A	N55°E	~85°NW	1-1.5		Occurs 0.5 m E of AG 118 and is more weathered/altered.
					Note: between AG 118 and 119 the road follows the N50°E trend of the dikes; also exposures are mediocre. ~500 m N of road (above AG 118) a huge dike is weathered out as an extensive, linear N50°E wall.
AG 119	N55-65°W				Feldspar-phyric trachyte dike or plug, with crude horizontal columnar jointing (resampled around road bend as AG 120). Some closely associated narrower dikes trend N50°E.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Adaba Goba (cont.)					
AG 119 (cont.)					Note: no further dikes are exposed from AG 119 (near the road col) to Goba.
Miesso-Harar					
HA 101	N40°E	55°SE	0.2-0.3	15-20°N	Zeolitized porphyritic trachyte dike, with variable dip. Intrudes scoriaceous basalt (HA 101A) flows with undulating dip toward Afar.
HA 102	N50°E	80°SE	~2		Zeolitized porphyritic trachyte dike cutting coarsely porphyritic trachyte flows. Dikes HA 101 and 102 occur N of Miesso on the line of a large NE-SW antithetic fault scarp, thrown up N.
HA 103	N50-55°E	45°SE			Aphyric basalt dike(?) in porphyritic trachytes.
HA 104	N45°E	~90°	5		Fissile aphyric basalt dike in coarsely porphyritic (?)trachybasalt.
					Notes: dikes HA 101–104 occur between Miesso and Asba Tafari. The further ascent of the Somalian plateau escarpment from Asba Tafari 10 km to the Ghelemso Road fork has good exposures of aphyric basalt flows, but no dikes.
					Possible N-S dike at 3 km E of fork.
					Possible N25° W dike, dip 70°E, at 7 km E of fork. For further 20 km along Harar Road, some good exposures of lateritized basalt flows but no dikes. Numerous faults cut plateau rim: N-S (dip E) and N35° W.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Miesso-Harar (cont.)					
HA 104 (cont.)					27 km E of fork, Antalo Limestone exposed below Trap Series at 2000 m. No dikes. E of Hirna, some basalt plugs but no dikes; strong N30-40°E faults, vertical dip.
HA 105	N90°E	90°	~2		Columnar aphyric basalt dike plug in nodular and zeolitized basalt flows of irregular thickness.
					Notes: Upper Sandstone exposed at 58 km from road fork, with Trap Series base at 2325 m. Near Karamili (at 89 km) the Upper Sandstone is faulted against the Trap Series: fault is N10°E with 25° W dip. Thin overlying trachyte is surface formation.
					92 km from road fork, columnar basalt plugs in Antalo Limestone (top of Limestone at 2050 m). Huge N80°E faults throw Limestone on N side against basalts to S. Faulting produces narrow N80°E graben along plateau rim here.
HA 106	N40°E	70°SE	0.5		Occurs at 5 km E of Deder Road fork (108 km E of Ghelemso Road fork). Aphyric basalt dike with porphyritic basalt margins. Intrudes rotted porphyritic basalt lavas, dipping 10°E.
HA 107	N70°E	~90°	0.1		Occurs 150 m E of HA 106. Thin aphyric basalt stringers.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
<u>Miesso-Harar</u> (cont.)					
HA 108	N50°E	90°	1		Occurs 6 km E of Deder Road fork on crest. Aphyric basalt dike cuts subhorizontal, coarsely porphyritic olivine-augite-phyric basalt lavas (HA 108A).
HA 108B	N55°E	~90°	~1		Occurs 50 m E of HA 108. Sinuous aphyric basalt dike in rotted basalt lavas.
HA 109	N55°E	80°SE	1		Occurs 1 km E of HA 108, in weathered aphyric lavas.
					Notes: E of Chellenko (11 km E of Deder Road fork, at km-post 445 from Addis Ababa) large N80°E faults throw 150 m up S. Upper Sandstone is 50 m thick here at 2110 to 2160 m, but has steep S and SW local dips. Excellent exposures for 10 km E of Chellenko, but no dikes.
					At 12 km E of Chellenko, 4 km W of Kollubi, basalt (?)sill or flow (HA 110) is overlain by sandstone.
HA 111	N75°E	~90°	0.5		Occurs 200 m E of HA 110. Augite-phyric basalt in very weathered basalt lavas.
HA 112	N35°E	90°	0.3		Occurs 150 m E of HA 110. Rotted augite-phyric basalt dike, which could be identical with HA 111 round road bend.
					Note: between HA 111 and Kollubi, peculiar sandstone "dikes" occur in the basalt lavas.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Miesso-Harar (cont.)					
HA 113	N-S	90°	1		Occurs 0.5 km W of Kollubi. (?) dike. Is a vertically fissile lateritized rock (apparently porphyritic) cutting conglomeratic sandstones.
HA 114	N25° W	80° SW	2		Occurs 17 km E of Kollubi, 13 km W of Dire Dawa Road fork. Altered aphyric basalt dike in Basement granitoid rocks. Microcline-quartz pegmatites (HA 114A) trend N35° E.
HA 115	N35° E	70° SE	~0.5		Occurs ~350 m E of HA 114. Cuts Adigrat Sandstone, which is vertically fissile within 20 cm of dike margins. Possible 0.5-m dike 20 m W of HA 115.
HA 116	N40° W	~90°	2		Occurs 100 m E of HA 115. Weathered aphyric basalt in cross-bedded Adigrat Sandstone.
HA 117	N50° W		13		Occurs 12 km W of Dire Dawa Road fork, at S apex of large bend. Rotted aphyric basalt dike of complex form, with several episodes of internal injection. Cuts subhorizontal sandstones.
HA 117A	N20° W	75° SW	0.15-0.2		Occurs 20 m W of HA 117. Zeolitized (?)basalt dike.
HA 118	N30° W	~90°	10		Occurs ~75 m E of HA 117. Fresh, gray aphyric basalt dike cutting subhorizontal sandstones and variegated silts. Sandstone is baked within 30 cm of dike. Thin stringer of basalt ~20 m E of HA 118 (HA 118A).

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Miesso Harar (cont.)					
HA 119	N30° W	90°	0. 3		Occurs 8 km W of Dire Dawa Road fork, on eastward descent to Karsa. Rotted aphyric basalt dike in Basement granitoids.
HA 120	~N-S	~90°	3		Occurs 3 km W of Dire Dawa Road fork. Rotted (?)basalt dike in sub-horizontal, coarse, cross-bedded Adigrat Sandstone.
HA 121	N60° W	90°	1		Occurs 1 km W of Dire Dawa Road fork. Purple porphyritic trachyte dike in Basement granitoids.
HA 122	N80° W	85-90° S	2-3		100 m W of Dire Dawa Road fork. Aphyric basalt dike paralleling metamorphic grain of Basement pegmatoids. Possible continuation of HA 136.
Dire Dawa-Harar					
HA 123	N40-50°E	70°NW	15		Occurs ~1 km S of Dire Dawa. Aphyric basalt dike in biotite-granitoids and pegmatoids.
HA 124	N15°E	90°	2		~2 km S of Dire Dawa. Weathered basalt.
HA 124A	N10° W-55°E		0. 8		Occurs 15 m SE of HA 124. Very sinuous form. Weathered basalt.
HA 124B	N50°E	75°NW	8 × 0. 5		Occurs 20 m SE of HA 124A. Eight dikes in 6-m-wide zone. Weathered feldspar or augite-phyric basalt cutting Basement granitoids.
HA 125	N35°E	90°	1		Nearly 3 km S of Dire Dawa. Rotted basalt dike in granitoids and biotite-schists (foliation dip 30°NE).

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Dire Dawa-Harar (cont.)					
HA 126	N-S		25		Occurs 4 km S of Dire Dawa (100 m S of small road col). Elongated basalt plug in biotite-schists and granitoids.
HA 127	N40°E	~90°	2-4		5 km S of Dire Dawa in lower of two sharp bends. Variable dip dike that thickens upward in a 10-m vertical section.
HA 128	N00-10°W	90°	25		6 km S of Dire Dawa, 100 m above upper sharp bend. Elongated plug of limited lateral extent. 2-m-wide offshoot occurs 3 m E of E margin of plug, and same trend. Dike HA 128 encountered 300 m farther up road on outside of sharp bend, trending N10° W.
HA 129	N70°E	85°S			Intrudes HA 128 at upper road exposure of latter. Aphyric basalt, more massive than fissile basalt of HA 128.
HA 130	N20°E	70°E	3		Occurs 70 m S of HA 129. Aphyric basalt in Basement biotite-schists with vertical pegmatites. Could be a possible extension of HA 127?
HA 131	N10° W	85-90° W	9		Occurs 100 m S of HA 130 on topographic spur. Rotted aphyric basalt with 0.4- to 5-m chilled margins. Cuts Basement schists and granitoids.
HA 132	N70°E		~20		About 7 km S of Dire Dawa, inside sharp bend. Vesicular, medium-grained aphyric basalt. Local gorge follows same trend.

No.	Strike	Dip	Width (m)	Lava dip	Remarks
Dire Dawa-Harar (cont.)					
HA 133	N70-90°E		~10		About 8 km S of Dire Dawa, at village. Aphyric basalt dike.
HA 134	~N70°E		7		About 0. 5 km S of HA 133, near pylon line. Variable trend, variable-width dike. Aphyric zeolitized basalt dike in Basement, exposed 50 m farther up road. Turns to N15°E for one short length.
HA 135	N70-80° W	90°	5-8		Occurs 200 m below Karsa Road fork. Purple aphyric trachyte dike that cuts HA 136 E of road. Possible continuation of HA 122?
HA 136	N30° W	~90°	20-25		At road fork. Rotted aphyric basalt dike. Cut by HA 135 where HA 136 turns abruptly to N75° W, 12 m wide. Dike HA 135 lies against southern side of the 12-m-wide sector.
					Note: from the road fork to Harar via Alemaya, several good exposures on the plateau but no dikes. Near Dire Dawa the Antalo Limestone dips S at up to 60°, but the road section itself does not traverse this formation.

BIOGRAPHICAL NOTE

PAUL A. MOHR received his B.Sc. in 1952 and Ph.D. in 1955 in geochemistry from Manchester University, under Professor W. A. Deer.

Before joining Smithsonian Astrophysical Observatory, he spent 10 years (1957-1967) at Haile Selassie I University (formerly University College, Addis Ababa), with intervening 1-year research fellowships at Sheffield University and Cambridge University.

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NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions come from the Staff of the Observatory.

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