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REGIONAL SIGNIFICANCE OF VOLCANIC GEOCHEMISTRY IN THE AFAR TRIPLE JUNCTION, ETHIOPIA

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Regional Significance of Volcanic Geochemistry in the Afar Triple Junction, Ethiopia*

Abstract: Progressive changes in volcanic chemistry along a traverse across the Arabo-Ethiopian swell suggest a shallowing of the zone of melting with concomitant crustal thinning from plateau to rift. The gradational nature of this thinning seems to exclude a predrift fitting of the Red Sea coastal escarpments and accords with geological evidence for extension of continental crust beyond the escarpments into the rift zone.

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INTRODUCTION

It is now well established that the Red Sea and Gulf of Aden are neo-oceanic basins, within which sea-floor spreading has been operating since the Miocene (Phillips _et al._, 1969; Laughton _et al._, 1970). This spreading has accounted for a northeastward migration of Arabia away from Africa. However, reconstruction of Arabia's original proximity with Africa involves superposing southwestern Arabia (Yemen) upon the Ethiopian Afar (Fig. 1), a land area situated at the Red Sea, Gulf of Aden, and African rift-system triple junction (Girdler, 1966; Mohr, 1967).

Among several outstanding tectonic problems concerning the existence and nature of Afar is the question of whether or not any sialic crust underlies this region. If such crust is significantly present, then severe constraints are imposed on conventional plate-tectonics analysis of the triple junction (McKenzie _et al._, 1970; Mohr, 1970a). In fact, Pre-Cambrian and Mesozoic strata of the Ethiopian and Somalian plateaus (Fig. 1) extend visibly into Afar for as much as 60 km beyond the main plateau escarpment, and isolated exposures of such rocks occur in central Afar and in the Danakil and Aisha horsts. Seismic surface-wave analysis led Jones (1968) to conclude that an attentuated sialic crust may be present under Afar, although Prof. P. Gouin (personal communication) considers that previous interpretations of gravity in Afar in terms of continental crust (Gouin and Mohr, 1964; Gouin, 1970) can be revised in light of the abundance of silicic magmatic activity during the late Tertiary in Afar.

This paper attempts a fresh, though indirect, approach to crustal analysis of Ethiopian plateaus and rift. A broad profile of volcanic chemistry is examined across the northern sector of the Arabo-Ethiopian swell (Mohr, 1962), where the Red Sea basin now separates the Yemen and Ethiopian plateaus. Specifically, the traverse begins in the Lake Tana basin of northwest Ethiopia and extends eastward across the northern Ethiopian plateau, across the downwarped-downfaulted marginal zone between plateau and rift, and into northern Afar (Fig. 1). The further eastward extension of the traverse crosses a complex tectonic regime: the problematic Danakil horst (Bannert et al., 1970; Mohr, 1970b), the Red Sea (considerably narrowed from its normal development north of latitude 16°N), and the Yemen plateau.

Average compositions for basalts and intermediate and silicic volcanics are examined along the traverse, and possible significance is sought in terms of crustal thickness and composition across the Arabo-Ethiopian swell.

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THE CHEMICAL EVIDENCE

The data of Tables 1-3 are based on the compendium of published rock analyses pertaining to the Ethio-Yemen region (Mohr, 1970c). In averaging the data, no account has been taken of any varying ages in the volcanic formations sampled. The generalized sequence of extrusion sites from oldest (Paleogene) to youngest (Quaternary) is as follows: Ethiopian and Yemeni plateaus, plateau-Afar margin, Lake Tana basin and Danakil horst, and Afar and the Red Sea (Mohr, 1968). The evidence suggests that at any given regional site, there has been no significant long-term chemical evolution of volcanics (Mohr, 1971), which in turn indicates that despite any horizontal spreading movements of the crust, factors that influence volcanic chemistry (e.g., depth of melting for basalts) have not changed during such migrations of the site.

The interpretations that follow are made in spite of some apparent limitations decreed by the standard-deviation values. These deviations are undoubtedly worsened by the SiO_2 variations in each grouping of rocks, but it is difficult to correct for the effect of these variations on the other oxides owing to the uncertainties in the petrogenetic scheme for the Ethio-Yemen alkaline volcanics. Yet the consistency of some trends across the Arabo-Ethiopian swell seems more than statistically fortuitous (Tables 1-3 and Figs. 2-4) and indeed is compatible with mineralogical trends (LeBas and Mohr, 1968; Mohr, 1970c). While a lot more data are obviously desirable, a preliminary discussion in which standard deviations are noted, but for given reasons are not always fully accepted, seems justifiable.

Basalts

The Ethio-Yemen basalt data (Table 1) show several consistent trends, which indicate a gradational change in petrogenetic environment from plateau to rift. This is better shown for the tectonically simpler western half of the traverse, where Si, Fe, and Ca increase from plateau to rift and Al decreases (Fig. 2). For these four elements, the Afar (rift) basalts compare closely with tholeiites dredged from the Red Sea central trough (Chase, 1969).

The chemical gradients show up clearly in the norms. Using the terminology of Green (1970), there is passage from Tana basanites (Ne > 5%), through the alkali olivine basalts of the Ethiopian plateau (4% Ne) and the Afar margin (3% Ne), to the olivine basalts of Afar and the olivine tholeiites of the Red Sea. Concomitantly, the Niggli parameter QZ increases regularly from -34 to -16. The differentiation index increases less regularly from 57 at Tana to 65 in Afar, perhaps because the variable presence of olivine phenocrysts in the basalts affects MgO content (Table 1 shows large standard deviations for average MgO values).

Sodium content is equable along the Tana-Red Sea traverse, but K decreases more and more rapidly toward the Red Sea, as shown in the ratio Na/K. Titanium increases by nearly 50% from plateau to rift, again in a progressive manner, but the Red Sea trough tholeiites are distinct from the Afar basalts in having low Ti (Table 1).

The eastern half of the traverse is less easy to interpret. The Danakil horst basalts show affinities with the Afar basalts in being normative olivine basalts and in having a high differentiation index of 72, but they also resemble the Ethiopian plateau basalts in having high Al and K and low Ti. This dual character may reflect a genesis beneath a continental block isolated in the middle of the Red Sea basin (Mohr, 1967, 1970b).

A single available analysis for Jebel Zukur island, a dormant volcanic center in the Red Sea at latitude 14°N, has a normative composition on the borderline olivine basalt-basanite. The island is notably situated where crustal spreading is slower than it is in the typical Red Sea central trough farther north (Mohr, 1970b). Unlike the Tana basanites, however, the Zukur analysis has high Ti and high differentiation index (69), while its Na/K ratio compares with the Afar margin basalts.

The Yemen Tertiary plateau basalts closely resemble those of the Ethiopian plateau in their chemistry, although they are less strongly alkaline (Harris, 1969) and are high in Ti. However, four Quaternary basalts from the Yemen plateau are normative olivine basalts with an average TiO_2 content of only 1.1%.

In summary, basalt chemistry along the traverse, particularly the western half from Tana to Afar, shows progressive changes over its entire length from plateau interior to rift floor. The rift margin is not a zone of steep geochemical gradients, even for sensitive parameters such as K and Ti. It is therefore considered unlikely that the rift margins mark an abrupt cutoff to continental crust at a supposed juncture with neo-oceanic crust. Rather, the gradational changes in chemistry indicate a gentle shallowing of magma genesis toward the rift. Relatively abundant shallow melting beneath the Red Sea yields olivine tholeiite magma, but melting becomes progressively deeper and more restricted away from the rift zone, and magmatic composition, more alkaline and undersaturated. Secondary fractionation processes during magmatic ascent are not considered to have significantly modified Ethiopian basalt compositions (Mohr, 1971).

Intermediates

The progressive changes found in the basalts of the traverse are absent from the intermediate volcanics (Table 2 and Fig. 3), except for a strong decrease in Al from plateau to rift. The Tana and Ethiopian plateau intermediates are strongly undersaturated, with 7% normative Ne reflecting the phonolitic mineralogy of many of these rocks. By contrast, the Afar margin and the Afar intermediates are oversaturated, 8% normative Q reflecting the occasional presence of free quartz in a trachytic mineralogy. However, the Afar margin trachytes are distinguished from the Afar trachytes by a strong Fe enrichment in the latter (Barberi et al., 1970), together with high Ti and P and low alkalis.

The sharp distinction between plateau and rift/rift-margin intermediate volcanism cannot be simply explained by parallel processes of fractionation or partial melting from the corresponding basalts of these sectors (discussed above). If shallow-level fractionation of intermediate magma from a basaltic parent is to be invoked, field evidence suggests that this has occurred under Afar where trachytes and basalts are closely associated both in their occurrence and in their mineralogy. On the Ethiopian plateau and in the Tana basin, phonolites and phonolitic trachytes form isolated stocks and plugs dissociated from any signs of contemporaneous basaltic volcanism.

An anatectic origin for the plateau intermediates is superficially attractive and immediately suggests a relationship to the presence of thick continental crust. King (1965), Sutherland (1965), Wright (1965), and Denaeyer (1968) have discussed the possible role of sialic crust in influencing magmatic composition in the African rift system. The question remains open and is indeed exacerbated in the case of the silicic volcanics discussed below. Nevertheless, the virtual absence of sialic xenoliths in the plateau phonolites suggests that these lavas attained their character before their ascent through the crust and that the sharp distinction between plateau and rift/rift-margin intermediates does not signify an abrupt boundary to continental crust. Rather, it seems that there are lateral inhomogeneities in the mantle processes giving rise to the more silicic magmas, with boundary conditions related to the major tectonic zones and not to the compositional nature of the overlying crust.

The Yemen plateau intermediates have a more saturated character (1% normative Q) than do their Ethiopian plateau counterparts, although there is currently no reason to suspect that the thickness of underlying sialic crust is significantly disparate (Niazi, 1968; Gouin and Searle, 1971). The Danakil horst intermediates are weakly Ne normative; they also have abnormally high Na/K values compared with Afar and Yemen intermediates, suggestive of an absolute soda enrichment (Mohr, 1971).

Silicics

The silicic volcanics (Table 3 and Fig. 4) show fewer, less distinct differences along the traverse than do the other rock groups. The most notable feature is a progressive riftward enrichment in Na from Tana to Afar, with concomitant replacement of normative C by Ns. There is also a less regular increase in chemical Ca. A somewhat erratic pattern for K fails to obscure a progressive riftward increase in Na/K, which is manifested in both the western and the eastern halves of the traverse. Titanium is equable along the traverse and does not reach the high values found at some centers in the main Ethiopian rift (Lacroix, 1930).

Considering that the plateau and rift intermediate volcanics are so distinctive, it is perhaps surprising that the silicic volcanics are so similar. But the field evidence indicates that the great bulk of the ignimbritic silicics are unrelated in their occurrence to the intermediates, especially on the plateaus. In this connection, the discussion by Williams and McBirney (1969) on the genetic problems of the Central American late-Tertiary ignimbrites is relevant: "Any postulated origin of the ignimbrites must account for several remarkable features, namely their huge volume and rapid eruption, their characteristic chemical and mineralogic composition, and their place in the geologic history of the region" (p. 53).

These are precisely the problems of the Ethiopian late-Tertiary ignimbrites. Their huge volume, about 45,000 km^3 (Mohr, 1968), was erupted without any significant hiatus or known change in chemical composition. They postdate the colossal Paleogene flood-basalt eruptions, which were not associated with any silicic volcanism other than localized, end-phase activity of very minor extent. Williams and McBirney point out the evident inadequacy of fractionation processes in individual magma chambers to provide uniform and voluminous ignimbrites and go on to discuss the feasibility of an anatectic source. They note that partialiy melted xenoliths of suitably composed source rock are very scarce in the ignimbrites of New Zealand (Battey, 1966) and Central America, and the same holds for the Ethiopian ignimbrites.

Some welded tuff units of the Gariboldi Pass caldera complex, in the main Ethiopian rift (Cole, 1969), contain blocks of very fresh alkali syenite and granite, but the appearance of these plutonic rocks is quite distinct from comparable rocks of the Pre-Cambrian Basement. This distinction is confirmed chemically (Table 4), where the Ethiopian silicic volcanics are enriched in iron and alkalis compared with the Pre-Cambrian granites.

An alternative to fractionation and anatexis has been briefly suggested by Battey (1966) and Sigurdsson (1967), who consider a hypothesis of gradual accretion of silicic material at the base of the crust, originating from slow fractionation or partial melting processes in the mantle. Battey relates this process to a continuing "progressive differentiation [of the Earth] into core, mantle and crust." It can be conceived that in the ocean ridge-rift zones, where crustal spreading and magmatic ascent are relatively rapid, silicic accretion would be dissipated. But under the African swell-rift zones, where crustal dilatation is of the order of 1 mm/yr, accretion could become significant. And where, in the later stages of African rift development, crustal separation has finally begun to occur, the resultant increased heat flow could enable a sudden, large-scale remelting of this accreted material.

CONCLUSIONS

Progressive changes in basalt chemistry across the Arabo-Ethiopian swell are related to crustal thinning and shallowing of the zone of melting under the Afar rift. The progressive range of composition is from the Tana basanites to the Afar olivine basalts, the latter with tholeiitic affinities. The most useful discriminants appear to be Na/K and Ti. No abrupt chemical gradients occur at the plateau-rift margin, which supports the geological evidence that this margin does not mark an abrupt limit to continental crust, despite the young volcanism associated with some major fractures of the margin. It is therefore suggested that the continental crust of the plateaus may thin progressively riftward, in association with intense fracturing under the rift floor (Mohr, 1967, 1970b).

The Ethiopian rift zone began its development as a broad, downwarped trough during the Jurassic (Mohr, 1967), and the great bulk of the Ethiopian volcanics actually predate the graben faulting of the rift during the Pliocene-Pleistocene. Nevertheless, the existence of progressive chemical changes across adjacent tectonic zones, independent of the ages of the basalts concerned, suggests a steady-state rift phenomenon such that the depth of melting (and presumably crustal thickness) tends to remain constant despite any lateral carriage by crustal spreading. A coupling of crust and uppermost mantle is implied.

The intermediate volcanics of the Ethiopian plateau and the rift/rift margins are strongly contrasted, being chemically undersaturated and oversaturated, respectively. The boundary between these two types appears to lie just outside the zone of broad downwarping into the rift and is therefore related to tectonic and not to crustal-composition factors. The Yemen plateau intermediates are mildly oversaturated, in keeping with the weaker alkaline nature of the Yemen volcanic province as a whole compared with Ethiopia and East Africa.

The silicic volcanics show rather weak progressive chemical changes from plateau to rift. Again, Na/K is the most useful discriminant, but unlike the basalts, this is due to riftward enrichment in Na. Field and chemical evidence combined show that the genetic problems of the Ethiopian silicics are the same as for other major world occurrences. Fractionation, direct partial melting, and sialic anatexis all appear inadequate, and melting of an accreted syenitic layer at the base of the crust is postulated (see also Harkin, 1960).

The traverse across the northern sector of the Arabo-Ethiopian swell, inclusive of the Red Sea disruption, has a volcanic geochemistry confirming the thesis that this is a region of uplift and sea-floor spreading. But the amount and manner of crustal thinning appear to differ from the simplistic model of sharply bounded plates separated by a suture filled with purely oceanic crust.

Finally, it can be noted that although the Ethiopian and Yemen plateaus were originally contiguous at the time of the Paleogene flood-basalt eruptions, their volcanic geochemistries are sufficiently distinct to require a different thermal regime, or possibly a chemically heterogeneous mantle, beneath the two plateaus.

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TABLE 1. AVERAGE BASALT COMPOSITIONS (WITH STANDARD DEVIATIONS) FROM WESTERN TO EASTERN SECTORS OF THE ARABO-ETHIOPIAN SWELL TRAVERSE. TOTAL Fe IS EXPRESSED as Fe*O. (DATA FROM MOHR, 1970c.)

Wt. %	1	2	3	4	5	6	7	8
SiO_2	46.2 ± 2.1	47.1 ± 1.6	47.6 ± 1.7	48.8 ± 1.6	48.7 ± 0.4	47.5 ± 1.2	45.8	45.5 ± 3.3
TiO_2	1.8 ± 0.6	2.1 ± 0.7	2.2 ± 0.9	2.5 ± 0.8	1.9 ± 0.2	2.0 ± 0.6	3.1	3.0 ± 1.5
Al_2O_3	15.3 ± 1.1	15.1 ± 2.6	13.7 ± 3.6	12.7 ± 1.8	13.1 ± 0.2	14.8 ± 2.3	16.4	13.4 ± 2.7
Fe*O	11.7 ± 1.2	12.1 ± 2.0	12.0 ± 1.0	12.4 ± 2.3	14.2 ± 0.5	13.3 ± 3.1	12.3	14.0 ± 2.8
MnO	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.2	0.2 ± 0.0	0.3 ± 0.0	0.3 ± 0.1	0.2	0.4 ± 0.4
MgO	8.8 ± 1.9	7.3 ± 2.6	8.0 ± 1.8	6.8 ± 1.8	7.8 ± 0.5	5.1 ± 1.3	6.0	6.2 ± 3.1
CaO	9.9 ± 0.7	10.1 ± 1.8	10.7 ± 1.2	10.8 ± 1.0	10.6 ± 0.2	10.7 ± 1.7	11.3	11.6 ± 3.0
Na_2O	2.9 ± 0.8	2.9 ± 1.0	2.8 ± 0.7	2.9 ± 0.5	2.5 ± 0.4	2.3 ± 0.6	2.9	2.3 ± 1.2
K_2O	1.6 ± 0.7	1.4 ± 0.3	1.1 ± 0.4	0.7 ± 0.3	0.2 ± 0.0	1.5 ± 0.8	1.1	1.2 ± 0.7
P_2O_5	0.3 ± 0.1	0.3 ± 0.2	0.2 ± 0.1	0.4 ± 0.1	0.5 ± 0.0	0.5 ± 0.2	—	0.5 ± 0.4
H_2O^+	1.3 ± 1.0	1.5 ± 0.9	1.4 ± 0.8	0.8 ± 0.5	0.3 ± 0.2	2.0 ± 0.6	0.8	1.9 ± 0.5
Na_2O/K_2O	1.8	2.1	2.5	4.1	13	1.5	2.6	1.9
QZ	-34	-28	-25	-17	-16	-18	-29	-25
Q	—	—	—	—	—	—	—	—
Ne	6.9	4.0	3.0	—	—	—	0.3	2.8
Hy	—	—	—	3.9	13.1	1.9	—	—
Ol	23.3	20.3	19.8	14.4	14.2	16.8	4.1	17.9

1) 10 Tana basalts.
2) 20 North Ethiopian plateau basalts.
3) 6 Afar margin basalts.
4) 25 North Afar basalts.
5) 2 Red Sea central-trough basalts.
6) 11 Danakil horst basalts.
7) 1 Jebel Zukur Island basalt.
8) 29 Yemen plateau basalts.

TABLE 2. AVERAGE INTERMEDIATE VOLCANICS COMPOSITION (SEE CAPTION TO TABLE 1)

Wt. %	1	2	3	4	5	6
SiO_2	59.9 ± 2.9	60.6 ± 3.5	64.8 ± 0.6	60.8 ± 3.8	58.0 ± 1.3	59.7 ± 3.5
TiO_2	0.6 ± 0.3	0.7 ± 0.4	0.4 ± 0.2	1.6 ± 0.4	0.8 ± 0.2	0.4 ± 0.4
Al_2O_3	17.9 ± 2.6	17.4 ± 1.0	13.9 ± 2.4	12.2 ± 1.5	17.7 ± 1.1	15.0 ± 1.7
Fe*O	5.2 ± 2.0	5.3 ± 2.5	5.1 ± 0.3	10.1 ± 3.1	6.6 ± 0.7	8.8 ± 3.0
MnO	0.2 ± 0.1	0.2 ± 0.0	0.2 ± 0.1	0.2 ± 0.1	0.4 ± 0.4	0.7 ± 0.4
MgO	0.7 ± 0.1	0.6 ± 0.4	0.4 ± 0.2	2.0 ± 0.8	1.1 ± 0.3	1.3 ± 1.1
CaO	2.1 ± 1.2	1.9 ± 1.0	1.6 ± 0.6	4.6 ± 1.1	4.3 ± 0.5	3.6 ± 2.2
Na_2O	6.6 ± 2.1	7.9 ± 1.2	6.0 ± 0.3	4.8 ± 0.3	6.4 ± 1.9	5.3 ± 1.1
K_2O	5.5 ± 1.3	4.4 ± 1.1	4.9 ± 0.3	2.6 ± 0.9	2.6 ± 1.1	3.4 ± 1.1
P_2O_5	0.1 ± 0.0	0.2 ± 0.2	0.1 ± 0.1	0.5 ± 0.2	0.5 ± 0.3	0.5 ± 0.3
H_2O^+	1.2 ± 0.3	0.8 ± 0.2	2.6 ± 0.6	0.6 ± 0.2	1.6 ± 0.1	1.3 ± 0.1
Na_2O/K_2O	1.2	1.8	1.2	1.8	2.5	1.6
QZ	-29	-32	30	18	-13	1
Q	—	—	8.7	7.2	—	1.4
Ne	6.9	7.6	—	—	0.1	—
Hy	—	—	6.9	14.4	—	16.7
Ol	5.8	5.2	—	—	8.8	—

1) 4 Tana intermediates.
2) 6 North Ethiopian plateau intermediates.
3) 3 Afar margin intermediates.
4) 6 North Afar intermediates.
5) 4 Danakil horst intermediates.
6) 6 Yemen plateau intermediates.

TABLE 3. AVERAGE SILICIC VOLCANIC COMPOSITIONS (SEE CAPTION TO TABLE 1)

Wt. %	1	2	3	4	5	6
SiO_2	71.7 ± 1.9	73.6 ± 3.1	70.8 ± 1.7	71.0 ± 1.8	73.5 ± 3.7	73.3 ± 3.5
TiO_2	0.4 ± 0.2	0.4 ± 0.2	0.3 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.3 ± 0.2
Al_2O_3	13.2 ± 0.8	12.6 ± 2.3	12.1 ± 1.7	13.0 ± 0.9	11.9 ± 1.4	11.2 ± 2.2
Fe*O	3.9 ± 1.4	2.6 ± 1.4	4.2 ± 1.2	3.1 ± 1.0	3.3 ± 1.4	3.9 ± 2.0
MnO	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.1 ± 0.0	0.5 ± 0.4
MgO	0.4 ± 0.2	0.3 ± 0.1	0.3 ± 0.3	0.3 ± 0.1	0.2 ± 0.1	0.5 ± 0.4
CaO	0.9 ± 0.5	0.4 ± 0.3	1.1 ± 0.4	1.3 ± 0.4	1.0 ± 0.9	1.3 ± 0.9
Na_2O	3.7 ± 0.8	4.6 ± 1.0	5.3 ± 0.9	5.7 ± 0.7	4.1 ± 0.9	3.6 ± 1.4
K_2O	4.2 ± 0.8	4.1 ± 0.6	4.6 ± 0.4	4.2 ± 1.0	4.4 ± 0.6	4.1 ± 1.4
P_2O_5	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	—	0.3 ± 0.4
H_2O^+	1.4 ± 0.9	1.2 ± 0.4	1.1 ± 0.7	0.8 ± 0.2	1.2 ± 0.6	1.0 ± 0.5
Na_2O/K_2O	0.88	1.1	1.2	1.4	0.93	0.88

1) 4 Tana silicics.
2) 12 North Ethiopian plateau silicics.
3) 7 Afar margin silicics.
4) 6 North Afar silicics.
5) 6 Danakil horst silicics.
6) 13 Yemen plateau silicics.

TABLE 4. CHEMICAL COMPARISON OF ETHIOPIAN CAINOZOIC RHYOLITES AND PRE-CAMBRIAN GRANITES

Wt. %	1	2
SiO_2	72.3	73.6
TiO_2	0.2	0.1
Al_2O_3	11.2	13.2
Fe_2O_3	3.1	1.5
FeO	1.8	1.0
MnO	0.2	0.0
MgO	0.3	0.4
CaO	0.9	1.6
Na_2O	4.8	4.2
K_2O	4.2	3.7
P_2O_5	0.1	0.1
H_2O^+	0.9	0.6
	100.0	100.0

1) Average composition of 115 Cainozoic rhyolites from Ethiopia and Yemen.

2) Average composition of 21 Pre-Cambrian granites from Ethiopia and Yemen.

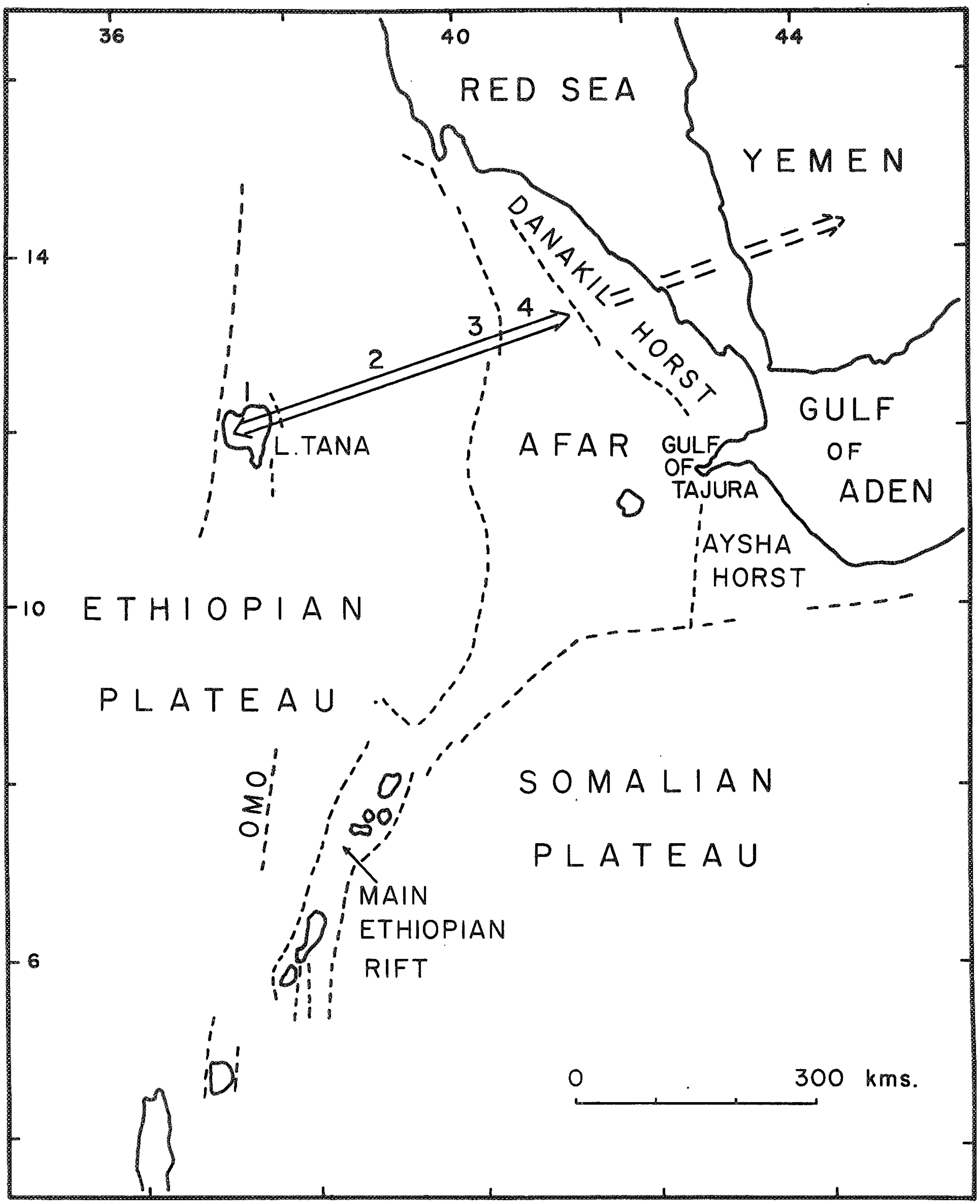

Fig. 1. Locality map of the Afar region and its three converging rift systems, showing the area of volcanics traversed by the present study (double arrow).

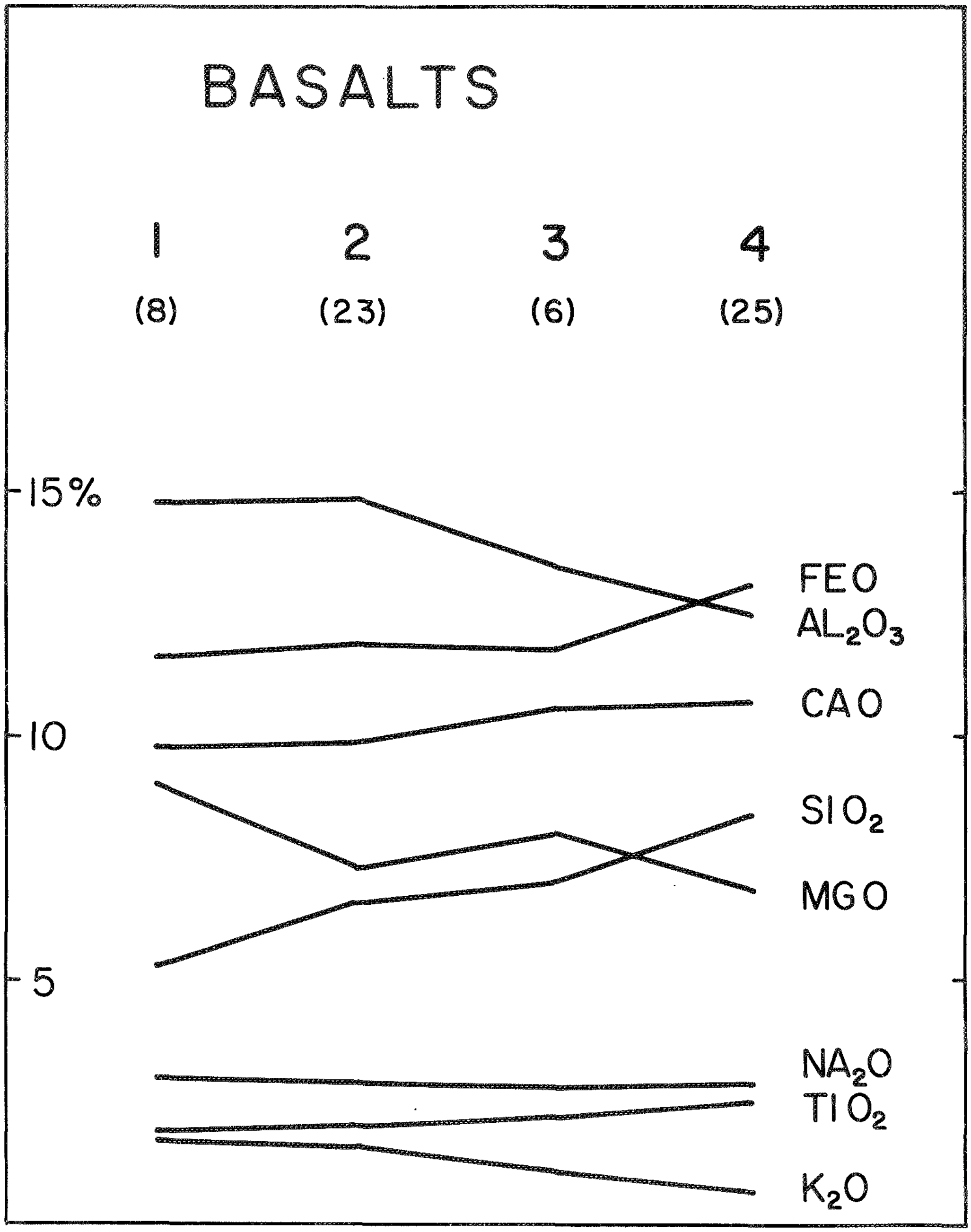

Fig. 2. Diagram showing variation of average oxide percentages for basalts from 1) Lake Tana basin, 2) northern Ethiopian plateau, 3) plateau-Afar marginal zone, to 4) Afar. Values in parentheses indicate numbers of specimens used in obtaining averages. Total iron is expressed as FeO, and SiO_2 values are additional to 40. 0%.

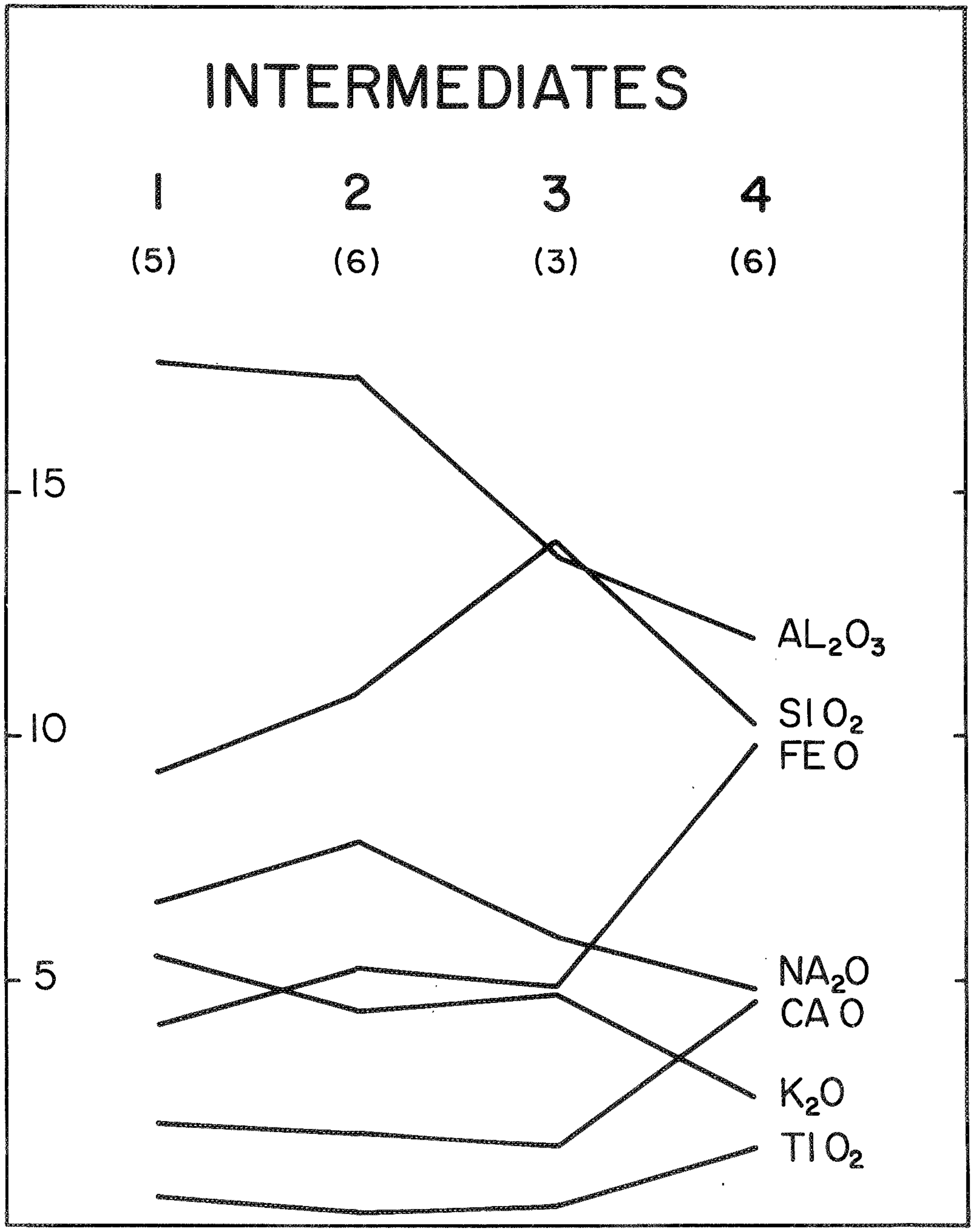

Fig. 3. As for Fig. 2 except data refer to intermediate volcanics. SiO_2 values are additional to 50.0%, and MgO is omitted for sake of clarity.

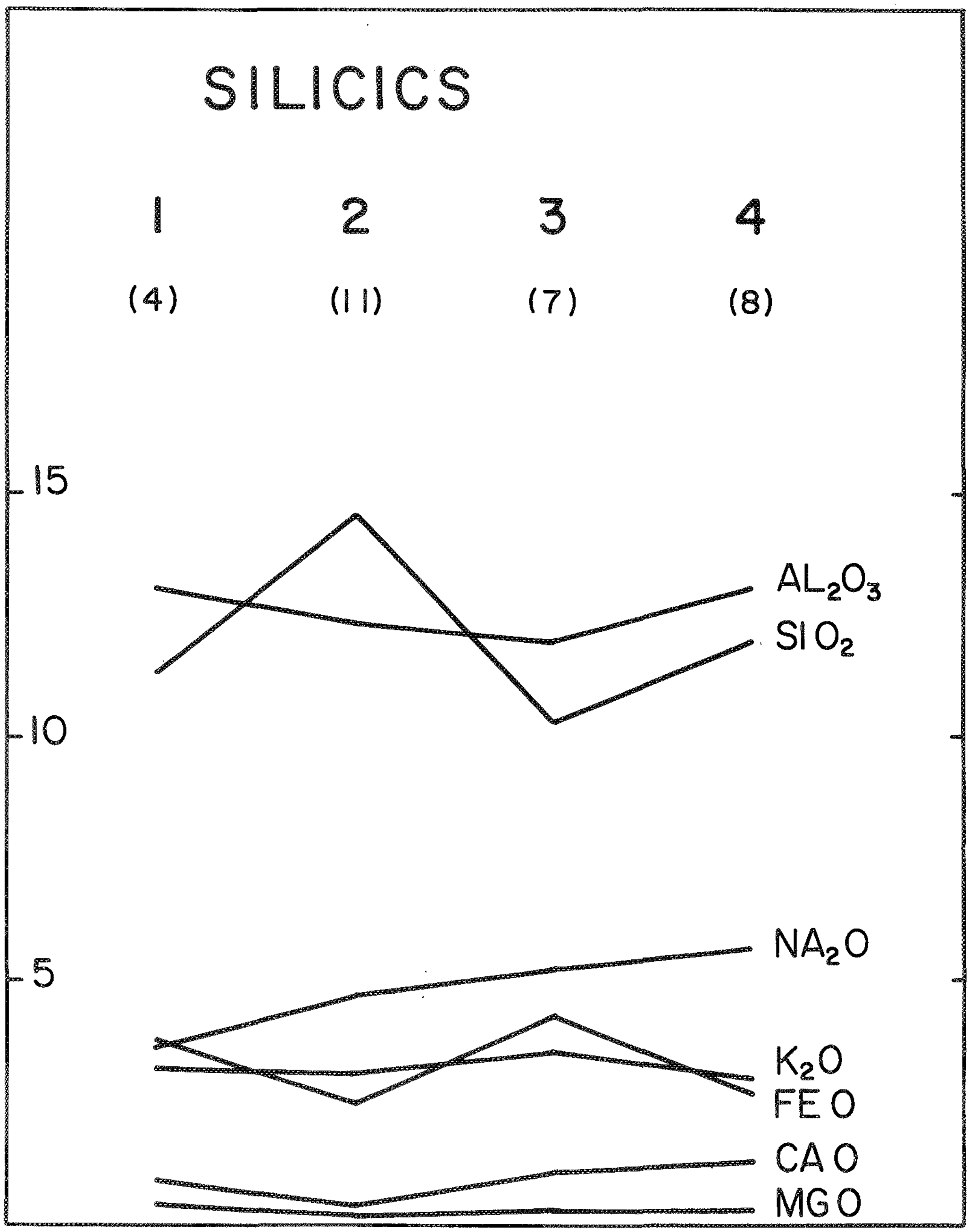

Fig. 4. As for Fig. 2 except data refer to silicic volcanics. SiO_2 values are additional to 60.0%.