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Editors
A. PILGER and A. RÖSLER
Geologisches Institut der Technischen Universität Clausthal, Germany

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extensive ground-surveys, that the quasi-oceanic Erta-ali spreading line in northern Afar jumps en-echelon southwards both to left and right, into the Tat-ali and Alaita spreading lines respectively, though Mohr (1967b, 1970a) has indicated that adapting, curvilinear faults play an important role in these jumps. The results of ERTS mapping indicate that en-echelon faulting on a mega-scale is distinctly rare in Afar, except in the southwest. The fault pattern of central Afar is not inconsistent with the rotation out of the Danakil block, leaving southwestern Afar under the influence of the Ethiopian rift stress-field.

The Danakil block is considered to have split from the stationary Aisha block in the late Pliocene-early Quaternary, and the resulting displacement along the Gulf of Tadjura due to continued rotation of the former is now about 75 km. Using Girdler & Styles' (1974c) new estimate for the opening rate of the Red Sea in the Afar region, of 1,8 cm/yr during the second spreading episode, revises the initiation of Danakil-Aisha separation from 2.5 m. y. ago (Mohr 1970a, 1972a) to 4.2 m. y. ago. This is in excellent agreement with the date of 5–4 m. y. ago, given by Girdler & Styles (1974c) for the recommencement of sea-floor spreading, on the basis of magnetic data.

The new data of Girdler & Styles (1974c), applied to Afar, can reconcile some previous discrepancies in the quantitative model of the plate tectonic evolution of this region. The rotation of the Danakil block through approximately 30^{o} is now seen to have been accomplished in a total of 11 m. y. (and not 20 m. y. – Mohr 1972a), which yields an average rotation rate about a Gulf of Zula pole of 0.0090 arc sec/yr. This revised value conforms quite well with an estimate independently derived from the average opening rate of the Red Sea basin in central Afar (2.3 cm/yr during the 11 m. y. of Red Sea floor spreading) of 0.0107 arc sec/yr. In these computations, of course, the angle of rotation of the Danakil block is critical, and indeed Tazieff et al. (1972) consider the angle to be appreciably less: on geological grounds they obtain a value of 18 ± 10^{o}, which Beyth (1973a) reduces even further to 9^{o}. It is important to realise that a rotation of only 20^{o} requires that a significant amount of sialic crust remains under the floor of Afar, and that this will then upset the plate tectonic picture at the Red Sea-Gulf of Aden junction. Nevertheless, there is a slim escape route for this model: internal deformation of the Ethiopian plateau has been by no means negligible (Mohr 1962a, Baker et al. 1972).

Acknowledgement

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Complete literature at the end of the volume, p. 391–416

Structural evolution of the Afar triple junction *

by

F. Barberi, G. Ferrara, R. Santacroce and J. Varet

With 9 figures and 2 tables in the text and on 3 folders

Abstract: Several new K-Ar age results have been obtained on volcanic rocks mainly from Central and Eastern Afar. Together with published radiometric data, they provide a coherent picture of the structural evolution of Afar. An early Miocene age (25 m. y.) for the initiation of the Afar rift is confirmed. Results from external Afar, particularly the area bordering the Red Sea and Gulf of Tadjurah allow to discuss the evolution during Mio-Pliocene. During this time a continental rift was formed, its development being characterized by periods of important volcanic activity (mainly comenditic and basaltic) separated by periods of apparent quiescence. Evidence is provided for a recent age (less than 3.5 m. y.) of the Gulf of Tadjurah opening.

The fissural volcanic series of dominant basaltic nature characterizing internal Afar (Afar stratoid series) is younger than 4 m. y.. It marks the transition to an oceanic type of structure which can be easily recognized on a geological basis by the individualization of axial volcanic ranges in the last million years. The nature and evolution of the Red Sea, the formation of the Gulf of Tadjurah and their relation with the Gulf of Aden are discussed in light of these data. A two-stage plate model is needed to account for the structural evolution of the Afar triple junction.

Introduction

The main conclusions of a recent paper summarizing the available radiometric age data on Northern Afar (Barberi et al. 1972a) were that (I) the initiation of Afar rifting dates back to Early Miocene (23–25 m. y.) and (II) individualization of spreading axes where new oceanic crust is generated is very recent (less than 1.3 m. y.).

The first conclusion was then confirmed by radiometric age dating in Eastern Afar (Red Sea and Somalian plateau margins: Civetta et al. 1974a; Chessex et al. 1974a). Contrasting with these data, rifting is considered to have lasted for at least 50 m. y. in the Ethiopian rift (Megrue et al. 1972) and for 41 m. y. in the Southern Red Sea (Girdler & Styles 1974c). The K-Ar age range obtained by Megrue et al. (1972) for dykes from the Ethiopian plateau margin covers the age range of Ethiopian plateau volcanics (Barberi et al. 1972a, table 4). These data therefore simply confirm an apparently well known fact of the Ethiopian geology and namely that beginning of volcanism on the plateau pre-dates the rifting[1]. The conclusion of Girdler & Styles (1974c) based on aeromagnetic interpretation, is strongly infirmed by the available age

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[1] New K-Ar age results on the plateau basalts reported at the Afar Symposium, allow however to cast some doubts on the validity of the older pre-Miocene ages.

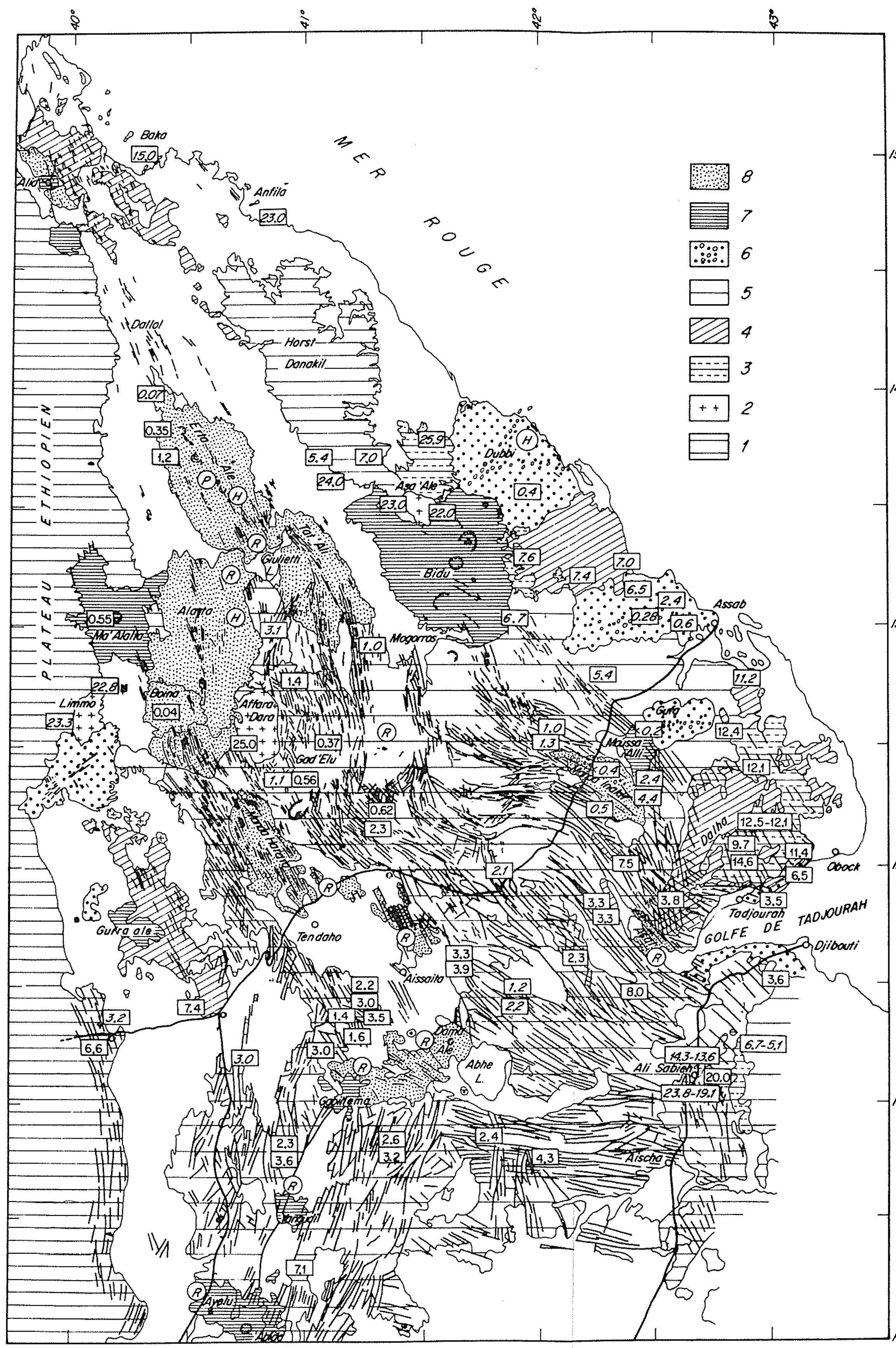


Fig. 1. Simplified map of Afar, redrawn from CNR-CNRS geological maps (1971 and 1974) with indication of available ages. (1) basement (metamorphic basement, mesozoic sedimentary cover, tertiary volcanics of the trap series. (2) Early Miocene peralkaline granitic bodies (3) Adolei and Mabla volcanic formations (4) Dalha formation (5) Afar stratoid series. Recent volcanic structures: (6) transverse volcanic structures (7) marginal volcanic complexes (8) axial volcanic ranges. P and A mean present and hystorical volcanic activity, R means recent (volcanics covering holocene lacustrine deposits). Dark, heavy lines are faults. Age data source: review by Barberi et al. (1972a); Civetta et al. (this volume); Chessex et al. (1974a); this paper.

data on volcanism from the western Red Sea margin (Frazier 1970) which are much younger than the 41 m. y. proposed by these authors for the same area.

On the other hand recent geological data on Southern and Eastern Afar (Black et al. 1972b; Marinelli & Varet 1973) have shown that volcanic activity since Early Miocene was not continuous as suggested by Barberi et al. (1972a) for Northern Afar. These data indicate that the structural evolution of the region is marked by several separated episodes of tectonic and igneous activity.

In order to provide a comprehensive picture of the various steps marking the evolution of Afar rift since its formation and to define the age of the Afar floor, new K/Ar age data have been obtained on relevant areas. The early stages of rifting have been reconstructed by studying the Afar margin and namely the area bordering the Red Sea. The age of the Afar floor has been obtained by an extensive dating of volcanic rocks from central Afar.

K-Ar age results

K-Ar age data have been obtained on 42 samples of volcanic rocks. Results are listed in table 1. They refer to whole rocks analyses, with the exception of two samples which consist of separated feldspar phenocrysts.

Samples were carefully selected on petrographic basis to avoid any trace of alteration. Only non vesicular, usually fine-grained samples with residual fresh glass (i. e. without any calcite, zeolite, clorite and other secondary minerals) were analysed. Many samples, collected for their "fresh" appearance in the field, were discarded after the microscope examination. Potassium determinations were made by flame photometry using a Perkin-Elmer photometer with lithium as internal standard. The assumed ratio of ^{40}K to total potassium is $1.19 \cdot 10^{-4}$. The argon analyses were made by isotope dilution, using a Reynolds type mass spectrometer statically operating. The following decay constants have been used for the age calculations:

$$\lambda e = 0.585 \cdot 10^{-10}/\text{year}; \lambda\beta = 4.72 \cdot 10^{-10}/\text{year}$$

The location of dated samples, together with previously available dates, is indicated in the simplified geological map of Afar (Fig. 1). Schematic sections illustrating the stratigraphical position of some representative dated samples are reported in Fig. 2. Their location is indicated in Fig. 3.

Geology of Eastern Afar margin (north T.F.A.I.)

Barberi et al. (1972a) have shown that central Afar is floored by a dominantly basaltic stratoid formation without any important break. As the Eastern margin is approached, older volcanic formations outcrop which are not found in internal Afar. Three main units can be recognized on the basis of relative stratigraphical position and nature of the volcanic products. These units are affected by extensional tectonics which differ in trend and intensity according to the age and the position relative to the axis of spreading (Fig. 4).

Table 1. Potassium-Argon Analytical Results.

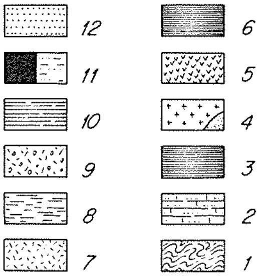
Sample	Rock type	Locality	Occurrence	K%	$^{40}Ar\%_{rg}$	$mlSTP\,^{40}Ar_{rg}/gK \cdot 10^{-5}$	Age m.y.
		Afar stratoid series					
C468	Hawaiite	Abana (N of Sardo)	NNW fault scarp	1.02	3.7	0.654	0.62 ± 0.06
C464	Hawaiite	Abana (N of Sardo)	NNW fault scarp	1.07	9.0	0.846	2.3 ± 0.2
C300	Basalt	NE Affara Dara (fig. 2.2)	Basis of a fault scarp affecting the basaltic sequence covering the granite	0.88	4.0	0.499	1.4 ± 0.14
C454–I	Rhyolite	S of Gad'Elu	Flow interstratified with basalts in the upper part of the Stratoid series	2.96	7.0	0.446	1.1 ± 0.05
C454–II				3.08	9.0	0.566	1.4 ± 0.07
S60	Basalt	SW of Dagaba plain	Basis of a NNW fault scarp	0.50	3.0	0.766	1.9 ± 0.2
D537	Basalt	Magenti Ale	Lava flow covering lacustrine deposits in the upper part of a fault scarp	0.61	4.0	0.536	1.4 ± 0.14
M27	Basalt	Meayle Lake (SE Magenti Ale)	Middle part of the NNW fault scarp	0.71	18.0	0.650	1.6 ± 0.05
D533	Hawaiite	Dit Bari (E Magenti Ale) (fig. 2.18)	Upper part of the NNW fault scarp	0.91	6.0	0.848	2.2 ± 0.2
M14	Basalt	E Magenti Ale	Middle part of the NNW fault scarp	0.14	4.7	1.17	3.0 ± 0.3
D543	Basalt	E Magenti Ale	Visible basis of the NNW fault scarp	0.53	10.5	1.36	3.5 ± 0.3
W156	Comendite	Babba Alou (Central T.F.A.I.)	Flow from a silicic center interlayered in the low-middle part of the Stratoid Series	3.51	9.3	0.812	2.3 ± 0.2
H427	Comendite	S Magenti Ale (fig. 2.17)	Flow from a silicic center interlayered in the low-middle part of the Stratoid Series	3.62	22.0	1.22	3.0 ± 0.1
B121	Basalt	Dobi graben (fig. 2.24)	Basis of the fault scarp, 700 m throw	0.59	10.0	0.827	2.1 ± 0.1
H349	Hawaiite	Adda'do graben (fig. 2.16)	Upper part of the western scarp	0.97	10.0	0.777	2.3 ± 0.1
H347	Basalt	Adda'do graben (fig. 2.16)	Visible basis of the western scarp	0.34	25.0	1.23	3.6 ± 0.05
H430	Basalt	Am'Adu graben (S of Lake Abhe)	Fault limiting to the North the Am'Adu E–W graben	0.56	9.0	0.866	2.4 ± 0.2
H327	Basalt	Askola graben (fig. 2.22)	Upper part of the western scarp of the graben	0.68	5.0	0.889	2.6 ± 0.2
H324	Basalt	Askola graben (fig. 2.22)	Lower part of the western scarp	0.38	15.0	1.27	3.2 ± 0.1

Table 1 continued.

Sample	Rock type	Locality	Occurrence	K%	$^{40}Ar\%_{rg}$	$mlSTP\,^{40}Ar_{rg}/gK \cdot 10^{-5}$	Age m.y.
		Afar stratoid series					
C220	Basalt	Afdera volcano	Visible basis of a fault scarp East of the volcano	0.70	9.0	1.21	3.1 ± 0.3
W151	Basalt	Northern end of Asal graben (2.19)	Visible basis of the W scarp of the graben (same occurrence as W7)	0.37	11.0	1.31	3.3 ± 0.1
W7	Basalt	Asal graben, N of Asal Lake (2.19)	Lava flow from a faulted basaltic sequence tilted toward SW discordant relatively to the uppermost flow of the Stratoid Series	0.66	7.0	1.33	3.3 ± 0.2
Z2	Basalt	Gamarri fault (fig. 2.20)	Top (1250 m alt.) of the scarp	0.77	11.0	1.32	3.3 ± 0.1
Z137	Basalt	Gamarri fault (fig. 2.20)	Visible basis (475 m alt.) of the scarp	0.73	6.0	1.57	3.9 ± 0.3
H448	Hawaiite	Dulul graben (fig. 2.15)	Visible basis of the fault scarp limiting to the South Dulul E–W graben	0.93	9.0	1.15	4.3 ± 0.2
		Dalha series					
TF 370	Basalt	Garab (Day region)	Top of the thick horizontal sequence of basaltic flows	0.68	18.0	0.920	3.8 ± 0.12
TF 3–I	Comendite	Ribta (fig. 2.9)	Lava flow overlying basalts and covered by alluvial deposits	3.74	66.0	1.40	3.5 ± 0.12
TF 3–II				3.74	61.0	1.29	3.2 ± 0.1
W 2	Trachyte	Sandera (fig. 2.9)	Lava flow tilted towards S and covered by horizontal stratoid basalts of Djibouti area	1.62	11.5	1.46	3.6 ± 0.15
W 82	Basalt	Hedalou (fig. 2.9)	Lava flow from the lower part of thick basaltic sequence tilted towards S and covered by rhyolitic flows	0.47	14.0	2.61	6.5 ± 0.2
D 558	Basalt	E Batie	Lava flow from the middle of a faulted block tilted towards E.	0.36	19.0	2.64	6.6 ± 0.2
H 393	Basalt	S Adda'Do (2.12)	Eastern scarp of the graben near the northern part of Ayelu volcano. 40 mts. of basaltic flows covered by thick silicic flows. Sample collected near the contact	0.53	8.5	2.83	7.1 ± 0.3

Table 1 continued.

Sample	Rock type	Locality	Occurrence	K%	$^{40}Ar\%_{rg}$	mlSTP $^{40}Ar_{rg}/gK \cdot 10^{-5}$	Age m.y.
		Dalha series					
D 555	Basalt	Mille River (2.13)	Upper flow of a fault scarp tilted towards W	0.20	10.0	2.96	7.4 ± 0.3
W 145	Basalt	Sakalol (fig. 2.11)	Lower part of a flow sequence tilted towards SE covered by Afar Stratoid Series with the intermediate of rhyolites	0.77	11.0	3.00	7.5 ± 0.25
W 19	Basalt	Unda Hemed (2.10)	Window of lava flows tilted towards E and covered by horizontal Afar Stratoid Series	0.49	15.0	3.17	8.0 ± 0.2
		Mabla Series					
W 60	Dark trachyte	Simbileyta (2.5)	Lava flow in the lower part of the thick rhyolitic series	2.27	69.5	3.87	9.7 ± 0.3
W 67	Comendite	Akkaba (fig. 2.8)	Rhyolitic flow covered by Dalha basalts tilted towards W, eroded and covered by Roueli basalts	4.08	77.0	4.55	11.4 ± 0.3
TF 176	Basalt	Goursa	Faulted block tilted towards W. Visible basis of a sequence of rhyolites with intercalated basalts	0.93	49.0	4.27	12.1 ± 0.35
W 25	Basalt	Simbililu (near Simbileyta) (fig. 2.5)	Lava flow covered by a dominantly rhyolitic sequence faulted and tilted towards W	0.82	47.0	4.26	12.1 ± 0.35
TF 305	Comendite	At'Anda (fig. 2.7)	Eroded rhyolitic lava pile surrounded by basalts of the Afar Stratoid Series	3.91	40.0	4.40	12.4 ± 0.35
W 34	Alkali feld spar plus quartz pheno-crysts from rhyolitic ignimbrite	Ali Dalaha (fig. 2.6)	Ignimbritic sheet overlying basaltic flows and covered by Dalha basalts	3.34	69.0	5.04	12.5 ± 0.35
TF 179	Basalt	Goursa	Faulted block tilted towards W. Lower flow of a basaltic sequence covering rhyolites	0.85	61.0	5.67	14.2 ± 0.4
		Adolei Basalts					
W47	Plagioclase phenocrysts from a basalt	Simbileyta (fig. 2.5)	Basis of a fault scarp with basalts covered by rhyolitic flows (9.7 m. y.)	0.39	16.0	5.83	14.6 ± 0.4
W 172	Hawaiite	Ali Sabieh (2.4)	Lava flow overlying Mesozoic sandstones	1.11	74.0	8.06	20.0 ± 0.6

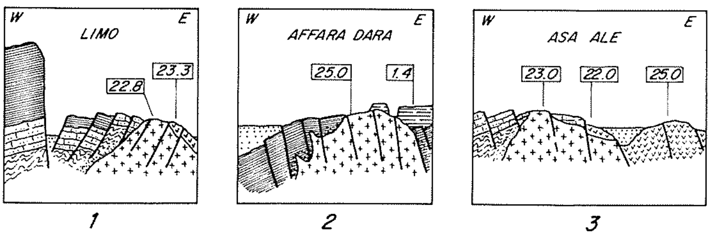


2a. Legend.

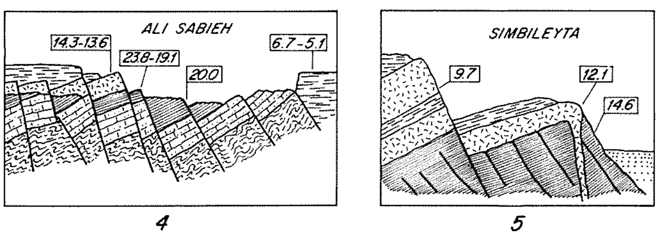
Fig. 2. Schematic sections illustrating the stratigraphical position of some representative dated samples.

2a. Legend:

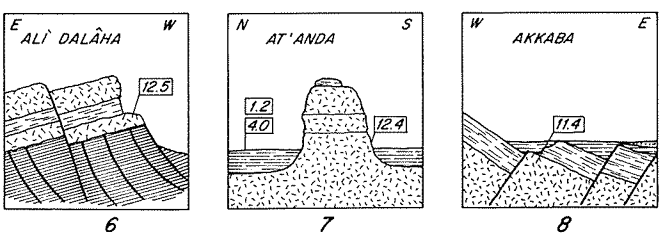
(1) metamorphic basement (2) mesozoic sedimentary cover (3) tertiary volcanics of the trap series (4) Early Miocene peralkaline granitic bodies, dots indicates formations affected by contact metamorphism (5) peralkaline rhyolites associated to Early Miocene granites (6) Adolei basalts (7) Mabla comenditic rhyolites (8) dominantly basaltic Dalha formation; basalts interstratified in Mabla formation in sections 5 and 6. (9) rhyolites covering the upper part of Dalha formation (10) Afar stratoid series (11) recent volcanic structures: axial and transversal (black) marginal complexes (dotted) (12) recent sedimentary deposits.



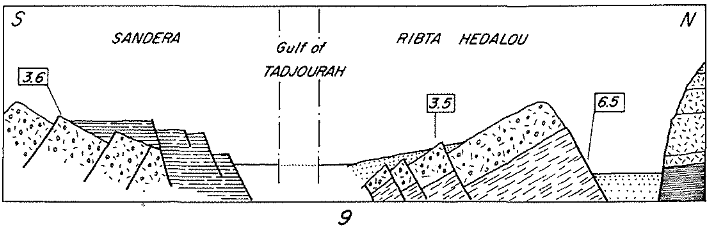
2b. Early magmatic events of Afar, peralkaline granitic intrusions.



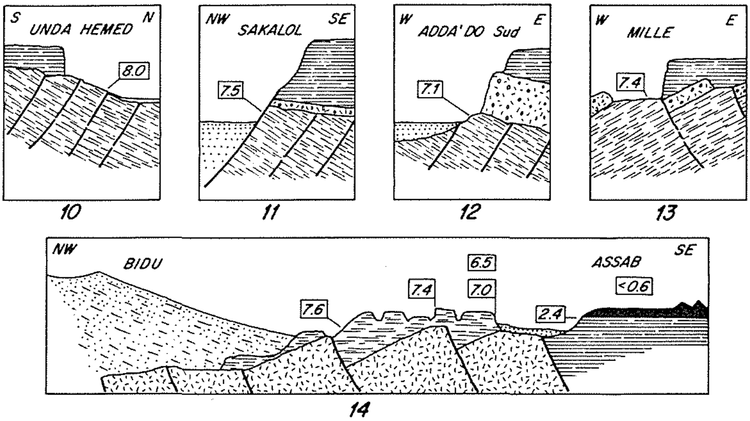
2c. Early magmatic events of Afar, volcanic activity on the eastern margin.



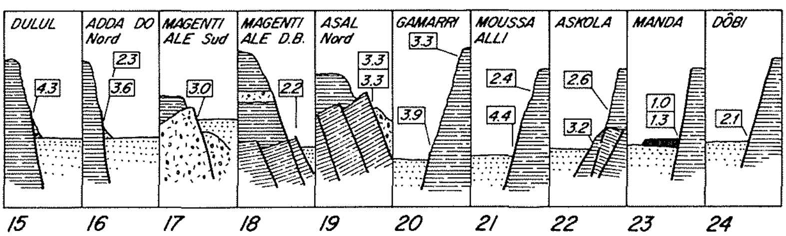
2d. Examples of Mabla formation outcrops



2e. Dates relevant to the Gulf of Tadjurah opening



2f. Outcrops of Dalha series away from the type area.



2g. Stratoid series of internal Afar.

Fig. 2 (continued). Schematic sections illustrating the stratigraphical position of some representative dated samples. Location of sections is indicated in Fig. 3. Names on the sections refer to CNR-CNRS maps (1971 and 1974).

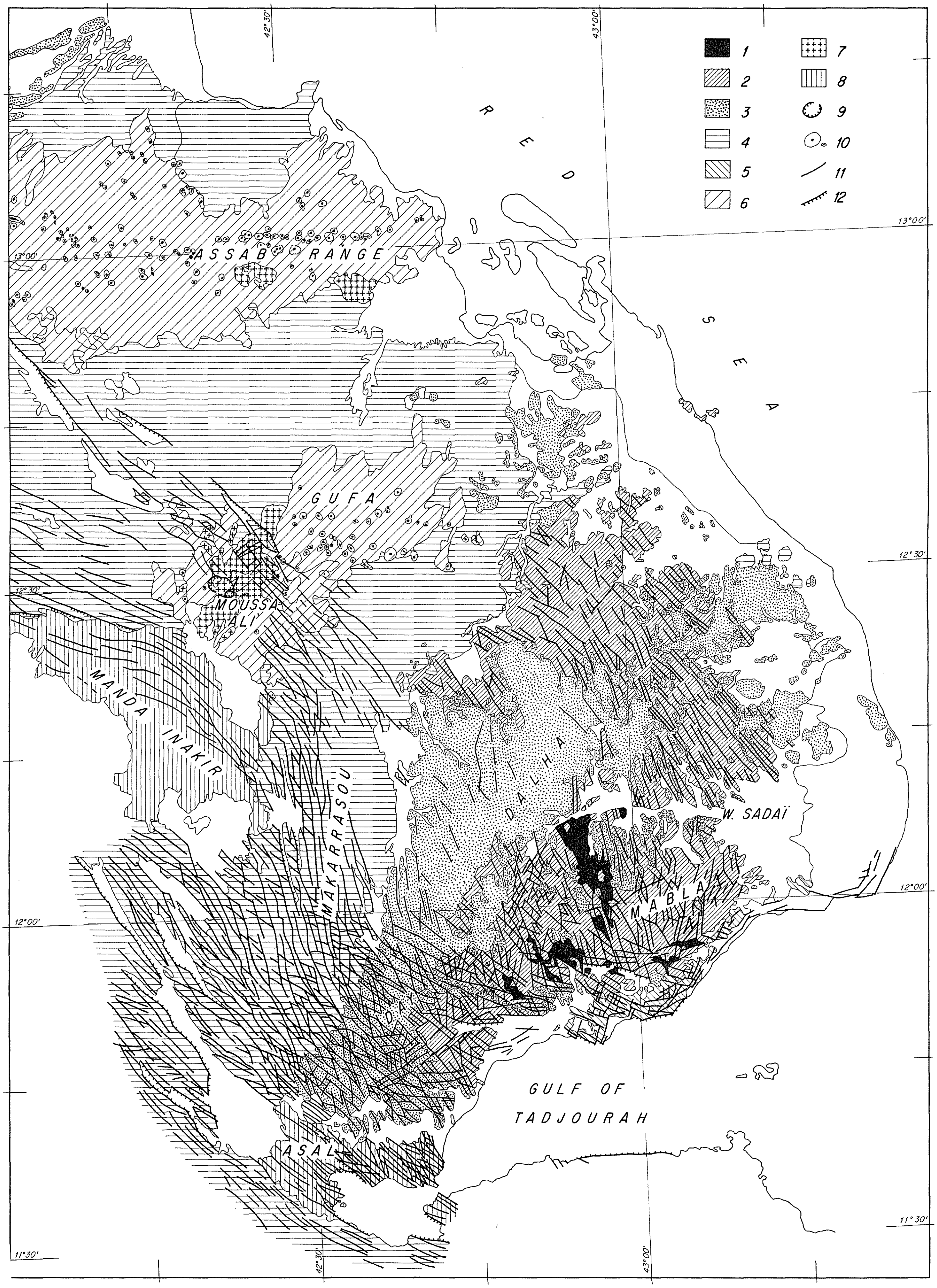


Fig. 4. Geological sketch map of Eastern Afar margin between Assab and Gulf of Tadjurah. (1) Adolei basalts (2) Mabla rhyolites (3) Dalha series (4) Afar stratoid series (5) Roueli submarine basalts, along the Gulf of Tadjurah coast (6) transverse volcanic structures (7) rhyolitic centres (8) axial volcanic ranges. (6, 7, 8) recent structures of Afar (9) calderas (10) spatter cones (11) faults and fissures (12) major faults.

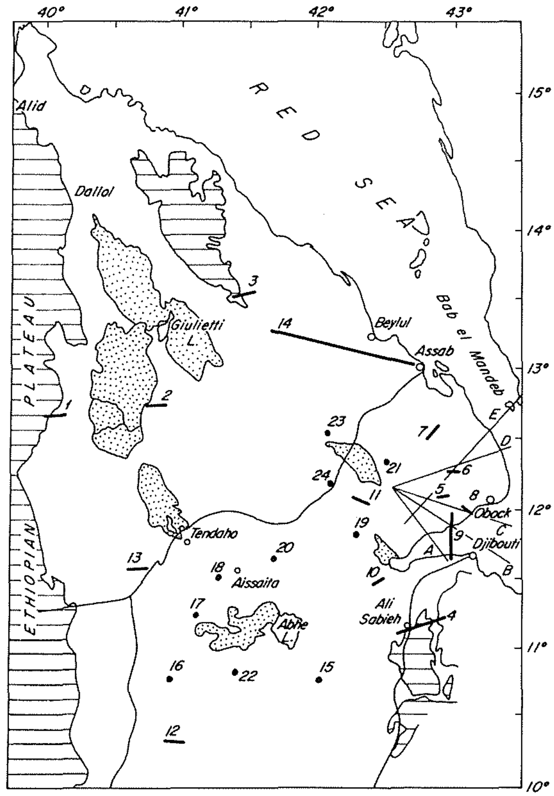


Fig. 3. Location of the schematic stratigraphical sections of Fig. 2 and geological profiles of Fig. 6. Basement is indicated by horizontal lines, dotted areas are axial volcanic ranges.

These units consist of two dominantly basaltic formations separated by a dominantly rhyolitic one. For the sake of simplicity we will call these formations respectively Adolei (old basalts), Mabla rhyolites and Dahla basalts. Similar sequences are found in other marginal areas, Ali Sabieh – Aischa and South East of the Danakil Alps (Black et al. 1972b; Civetta et al. 1974a; Chessex et al. 1974a).

The Adolei unit consists of basalts which are commonly deeply altered with formation of chlorite, calcite, zeolites and silica. They are affected by intensive tectonics, with frequent normal faults crossing each other. Collection of fresh samples suitable for K-Ar dating is extremely difficult. An age of 14.6 m. y. was obtained on plagioclase phenocrysts separated from one of these basalts (Fig. 2.5). An age of 20 m. y. was obtained for a basaltic flow overlying the sandstones near Ali Sabieh (Fig. 2.4). Ages from 22.3 to 16.3 m. y. are reported by Chessex et al. (1974a) for flows, dykes and sills of the same region; dykes are here known to be of NNW to NS direction (Black et al. 1972b).

Mabla series. This unit largely outcrops in the area North of the Gulf of Tadjurah and consists of thick flows, domes and ignimbrites of slightly peralkaline (comenditic) rhyolites, with some intercalated basaltic flows, pumice and cinerite deposits. It was mapped by Bannert & Kedar (1971) as pre-Tertiary basement on the basis of satellite photointerpretation, in spite of the geological map of Besairie (1946) which clearly indicated the rhyolitic nature of Mabla formation. North of the main wadi crossing this region, Wadi Sadai, the formation is affected by important normal faults (N 140^{o}) separating blocks which are tilted towards the Red Sea. Approaching the Gulf of Tadjurah the N 140^{o} tectonic trend is still the dominant one, but N–S directions are also found. Rhyolites were emplaced through fissures of both trends, as shown by alignments of domes and dykes.

This formation was affected by a phase of erosion before being covered by the Dalha basalts. Seven age determinations have been carried out on rhyolites from this unit and intercalated basalts (Fig. 2.7 and 2.8). Ages are ranging from 14.2 to 9.7 m. y. Ages around 14 m. y. have been obtained by Chessex et al. (1974a) for rhyolites covering the old basalts in the Ali Sabieh region.

D a l h a b a s a l t s. This unit consists of a series of basaltic flows with rare intercalations of ignimbrites and detritic deposits, and reaches a thickness of 800 meters. The whole formation is slightly tilted towards the NW (Fig. 5). Only in the Southern part, approaching Asal, it is affected by normal faults of dominantly NW to WNW direction (Fig. 4). The same faults also affect the Mabla formation, but only near the Gulf of Tadjurah. In the aeromagnetic map Girdler & Hall (1972) a negative anomaly overlaps Dahla outcrops. It might correspond to anomaly 4 (7 m. y.; see Laughton et al. 1970).

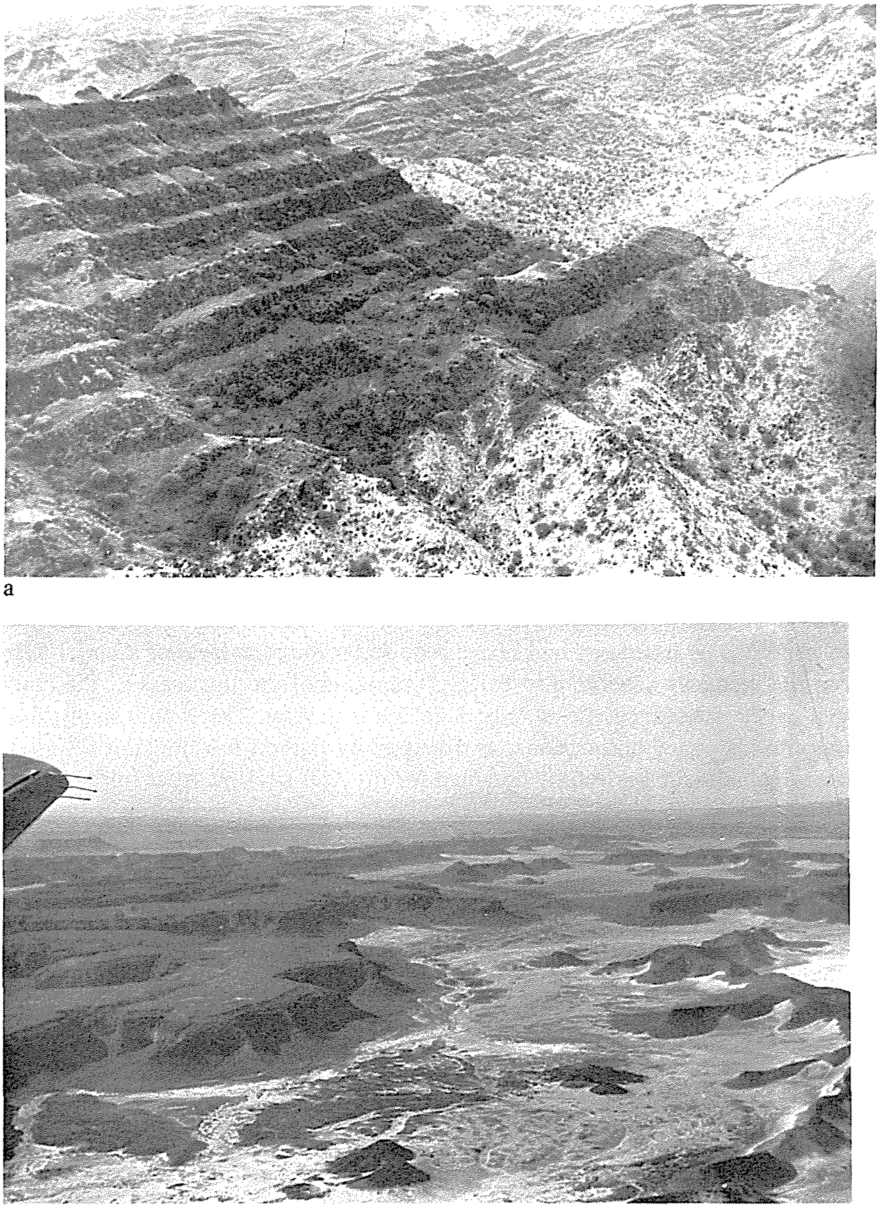
The Dalha unit is deeply eroded (as along the Red Sea coast) and is covered often in unconformity by the stratoid series of central Afar, with, in some cases, the intermediate of rhyolites (Adda'do, Ribta). Five age determinations have been obtained for Dalha series s.s. in T.F.A.I. outcrops, ranging from 8.0 to 6.5 m. y. (Fig. 2.9 to 2.11). Ribta rhyolite gave a 3.5 m. y. age and an age of 4 m. y. was obtained for the uppermost flow of the basaltic pile of Day. Eroded basalts covered by the stratoid series has been dated by Civetta et al. (1974a, 1975) in the Beylul region (Fig. 2.14). Results are the same as those we obtained in TFAI (7.6–6.5 m. y.). Near the Western Afar margin (Mille region, Fig. 2.13) an age of 7.4 m. y. has been obtained for basalts underlying the stratoid formation of central Afar. A similar age has been found for basalts at the bottom of an important fault in Southern Afar (Adda'do graben, Fig. 2.12). It is interesting to note that South of Tadjurah Gulf basalts covering in discordance rhyolites (15.3 m. y.) faulted in NNW direction, have given ages from 7.7 to 6.4 m. y. (Black & Morton 1974).

Age of the Afar floor

Recent volcanic units and Afar stratoid series

The Afar floor is characterized by the occurrence of recent volcanic units located both in axial and marginal positions (Fig. 1). Those located on or near the margins are clearly associated with transverse tectonics, whereas axial ranges are built on emissive fissures corresponding to the dominant tectonic trend (from NNW in Northern and Western Afar to NW in Eastern Afar). Axial ranges have been built during the last million years, as shown in Northern Afar (Barberi et al. 1972a) and in Manda Inakir range (Civetta et al. 1974a) and constitute the present axes of spreading in Afar.

Besides these volcanic units, Afar is floored by a thick dominantly basaltic stratoid formation, with some silicic centres towards the top. Rocks underlying this stratoid formation are not found in internal Afar, with the exception of Affara Dara Miocene granitic body which intruded preexisting volcanic formations (Fig. 2.3; Barberi et al.



a

b

Fig. 5. Dalha series of Eastern Afar. a) Tilted stratoid basalts covering Mabla rhyolites in North T.F.A.I. b) Eroded stratoid basalts near Beylul.

1972a). This stratoid formation is affected by innumerable vertical normal faults and open fissures, ranging from N to WNW directions with a dominant NW and NNW trend. Faulting was continuous during the emplacement of the stratoid series as indicated in several fault scarps by increase of the dip towards the basis. In some cases the dip changes are so marked that lavas outcropping at the basis of the fault scarps may be mistaken for an older formation. In various places, particularly in central Afar, the stratoid series is affected, especially in its lowest part, by deep weathering and alteration. The freshness of lavas therefore cannot be utilized as a field criterion to distinguish this series from older formations.

Due to the lack of data available on the stratoid series in Central Afar, 24 new age determinations have been carried out, mainly near the outcropping basis of this unit (Fig. 2.15 to 2.24). Other data were published by Barberi et al. (1972a) and Civetta et al. (1974a, 1975). These data clearly indicate that the stratoid formation was built in Plio-Quaternary time, as all together 37 age determinations fall in the range 4.4 to 0.37 m. y.[2].

Compared with the age of the Dahla formation, and considering that an important erosion episode separates the two units, an age near 3.5–4 m. y. is likely for the lower part of the Afar stratoid series. On the other hand in some areas (as Ribta and Day) there is no evidence for an interruption of magmatic activity between 6.5 and 3.5 m. y.

As internal Afar is not affected by any important erosion, the deepest outcropping rocks are found at the base of fault scarps. Sampling is therefore representative only of the uppermost part of the Afar floor, for a thickness of about 1 km. No direct information is available on the nature and age of rocks underlying the Afar stratoid series. No xenoliths of basement rocks have been so far found in lavas of internal Afar away from the margins. According to Ruegg (this volume) the thickness of the crust overlying a partly melted mantle is only 3 to 5 km in Afar. This would imply that entire Afar crust is young and oceanic, as discussed by Barberi & Varet (this volume).

The set of concordant age results obtained for the Afar stratoid series rules out the steril polemics about the stratigraphy of volcanic formations outcropping in internal Afar (Mohr 1973c; Barberi et al. 1973)[3]. These results have important structural implications, as they indicate that (I) the Afar floor is very recent and therefore surface tectonics is merely the expression of the most recent structural events and (II) only the study of the Afar margins may shed some light on the evolution of Afar rift during Mio-Pliocene.

[2] In light of these results the previously published age of 11.1 m. y. (Barberi et al. 1972a) for a rhyolite interlayered with basalts from the stratoid series of central Afar appeared anomalous. A new determination has been carried out on the same sample (C454, table 1). The obtained result (1.4 m. y.) indicates that the 11.1 m. y. was due to a trivial calculation error.

[3] An agreement was reached during the general discussion, which closed the Bad-Bergzabern Meeting, on the opportunity of avoiding, for the volcanic stratigraphy of Afar, such terms as Aden series. The use of the name "Afar stratoid series" was recommended.

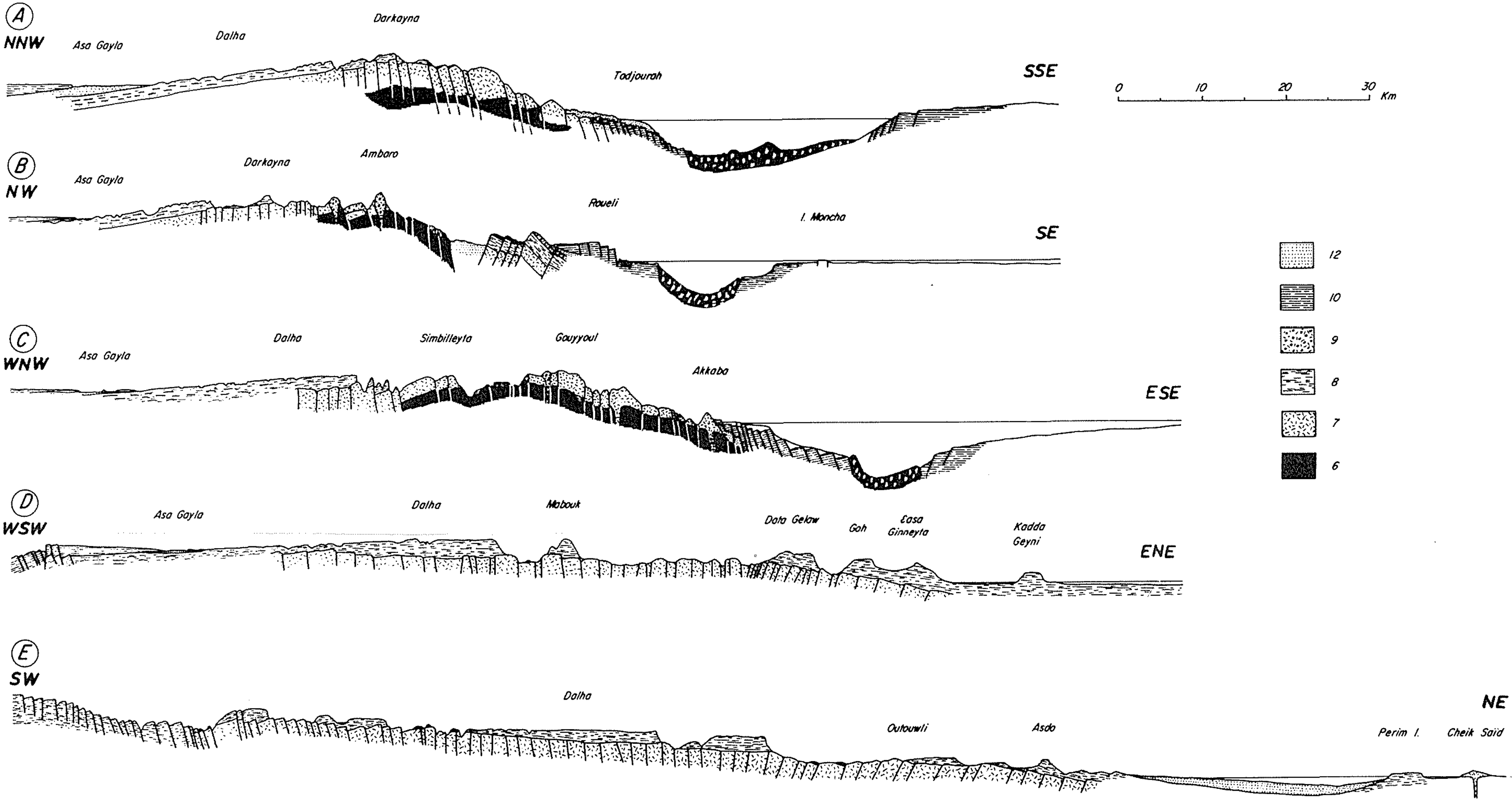


Fig. 6. Geological profiles of Eastern Afar margin. North of Gulf of Tadjurah. Location of the profiles is indicated in Fig. 3. Vertical exageration is 5 times the horizontal scale. Topography on land is from 1/100.000 IGN maps, on sea from Ruegg unpublished data. Legend as in Fig. 2. Note the striking differences between sections A, B, C crossing the tectonically active Gulf of Tadjurah trough and sections D, E crossing the stable Southern Red Sea region: uparching, erosion and faulting deeply affect the Afar margin as the Tadjurah spreading axis is approached, whereas Dalha formation is not faulted in the Southern Red Sea region. The newly formed oceanic crust of Gulf of Tadjurah is figurated.

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Main episodes of the Afar structural evolution

All data available (Bannert et al. 1970; Black et al. 1972a; Barberi et al. 1972a; Chessex et al. 1974a; Civetta et al. 1975) point to an early Miocene age for the initiation of the Afar rifting (Fig. 2.1 to 2.4), which affected a continental swelling interested by basaltic activity probably since Paleocene. Together with the development of rifting a change in the nature of magmatic products is observed. Transitional types of basalts with associated peralkaline rhyolites or granites (Barberi et al. 1972a) replace the undersaturated alkali basaltic rock association which apparently dominates on the Ethiopian plateau (Mohr 1968b; Gass 1970b).

The ancient basaltic activity of Afar, with associated minor intermediate and acid lavas lasted until 14.6 m. y.

The following step is marked by the eruption of huge masses of slightly peralkaline silicics in the period 14 to 9.7 m. y. It is important to stress out, that on both sides of the Gulf of Tadjurah, during the whole Miocene, volcanic activity was related to fissure systems with a Red Sea (NNW to N–S) trend. The picture of the volcanic activity of Afar during Miocene is typical of a continental rift as evidenced by comparing North TFAI area with the Northern termination of the East African Rift system:

– emplacement of important masses of salic volcanics through fissures of regional trend

– alkalic nature of volcanism

– lack of linear pattern of magnetic anomaly (see aeromagnetic map of Girdler & Hall 1972).

The third step was the emplacement of the dominantly basaltic Dahla series (8.0 to 6.5 m. y.). The occurrence of this formation and its tectonics (Fig. 6) defines two important episodes of the Afar evolution:

a) the lack of any tectonics on Dahla outcrops within a belt 70 km wide along the Red Sea coast (Fig. 4), suggests that the Eastern Afar margin became a stable region since Upper Miocene ($\approx$ 8 m. y.). The same consideration is valid for the Western margin of the Gulf of Aden, where unfaulted stratoid basalts outcropping East of Ali Sabieh have been dated (6.7 to 5.1 m. y.) by Chessex et al. (1974a). The lack of recent tectonic activity along the Red Sea margin of Afar, supported by the lack of seismic activity in the Bab El Mandeb (Fairhead & Girdler 1970), also suggests that the Southern Red Sea has been a stable region since the end of Miocene. Therefore the region of Eastern Afar-Southern Red Sea, comprised between the Tadjurah trough and Hanish islands, has to be considered as an accretion of the Arabian plate[4]. Further support to this interpretation is found by matching paleomagnetic data from Tarling (1970) and Schult (1974c). Magnetic anomaly patterns of the Red Sea and Gulf of Aden also confirm that spreading did not occur in recent times at the Bab El Mandeb region (see Fig. 7). The only recent volcanic activity observed within this area is

[4] The Southwesternmost portion of Gulf of Aden where no magnetic anomalies are observed may be considered of similar nature.

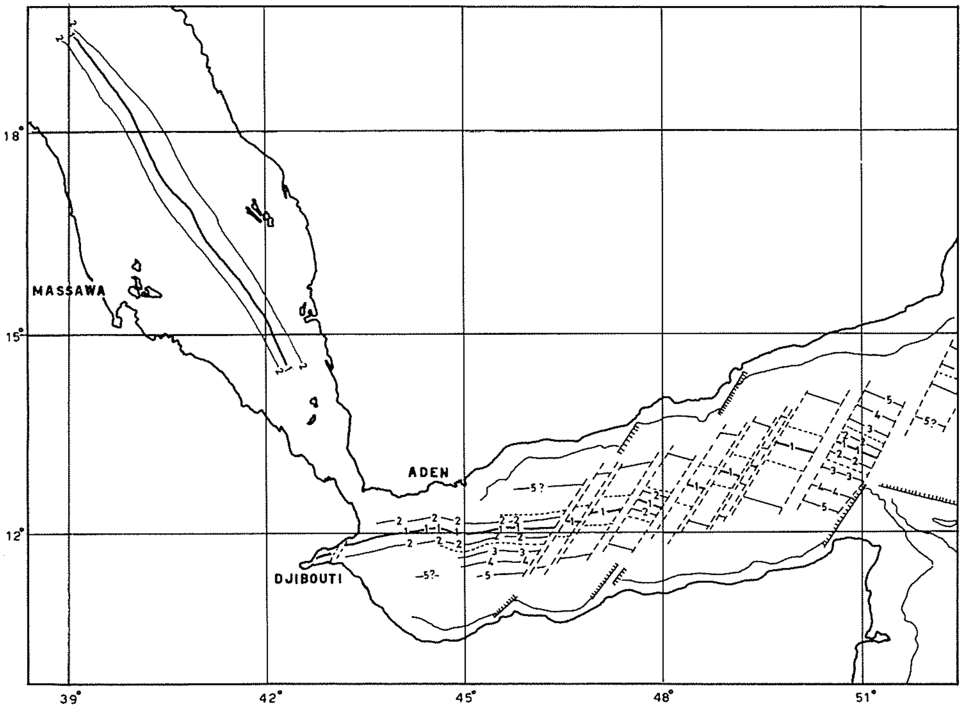


Fig. 7. Magnetic anomaly pattern of Red Sea and Gulf of Aden drawn matching data from Laughton et al. (1970) and Allan (1970). Axial lineations of Red Sea stop north of Hanish Islands, whereas axial magnetic anomalies of Gulf of Aden extend into the Gulf of Tadjurah and not into the Bab el Mandeb. See also details in Fig. 8B.

related to transverse tectonics (Barberi et al. 1974a). It is therefore difficult to conciliate these data with the 98 km of movement along a dextral transform fault in the Bab El Mandeb Strait, as proposed by Francheteau & Le Pichon (1972):

b) the important faulting affecting this formation in the vicinity of Asal and the Gulf of Tadjurah (Fig. 6) indicates that the sinking of the Gulf is more recent than the upper part of the Dahla formation. Ages obtained in both sides of the Gulf on rhyolites covering, in conformity with the basalts, the upper part of this formation and affected by the same normal faults, further indicate that the opening of the Gulf of Tadjurah is more recent than 3.5 m. y.[5]. After an important erosion episode recent basalts were erupted on both sides of the Gulf (Roueli and Djibouti areas). In recent

[5] Any model referring to the Gulf of Tadjurah opening should be restricted to the last 4 m. y. period; obviously the 243 km of opening proposed by Francheteau & Le Pichon (1972) are not compatible either with such a recent age of the Gulf, or with the width of oceanic crust emitted through the Gulf of Tadjurah fissures.

times (4 m. y. to present) the internal part of Afar has been affected by intensive tensional faulting with related volcanic activity. Tectonics and volcanism affect the margins only locally along transverse structural lineaments (Barberi et al. 1974a). It was during this time that Afar became an oceanic structure.

Discussion

As a whole, data point to a two-stage model for the evolution of the Afar rift: a long initial stage of continental rifting lasted about 20 m. y., followed by a stage (4 m. y. to present) during which the oceanic floor of Afar was formed.

Two-stage models have been also proposed for the opening of the Red Sea and Gulf of Aden. It is generally accepted (Phillips 1970; Phillips & Ross 1970; Vine 1966; Allan 1970) that the central trough of the Red Sea consists of oceanic crust emplaced during the last 4 m. y. Discussion persists on the nature of the floor at the Red Sea margins, which is interpreted either as thinned continental crust intruded by basaltic dykes (Drake & Girdler 1964; Girdler 1969) or as oceanic crust consisting of basalts with interlayered evaporites (Davies & Tramontini 1970). Most of the Authors agree on a lower Miocene (or Upper Oligocene) age for Red Sea formation (Gass 1969; Coleman et al. 1972; Coleman 1972; Brown 1970) with the evolution in two stages separated near 4 m. y. (Allan 1970; Lowell & Genik 1972).

A two-stage model, respectively Miocene (with an undated pre-miocene phase) and Plio-Pleistocene separated by a quiet period, has been also proposed for the formation of the Gulf of Akaba (Freund 1970; Freund et al. 1970). Similarly, a model of two stages, separated by a quiet period of sedimentation, was proposed for the Gulf of Aden by Laughton (1966b). Magnetic anomaly studies indicate that the formation of oceanic crust dates back to 10 m. y. in the Central and Eastern parts of the Gulf, whereas the Western part and its prolongation into the Gulf of Tadjurah is not older than 3 m. y. (Laughton et al. 1970; Fairhead & Girdler 1970) (Fig. 7).

Data from Afar and surrounding structures then fit fairly well into a common structural evolutive model whose main events are summarized in table 2. It basically comprises two stages of evolution. A first Miocene stage characterized by crustal attenuation, rifting and related volcanic activity; during this time Afar was not affected by the Gulf of Aden (E–W) tectonics.

The second stage is marked by generation of oceanic crust which started earlier (10 m. y.) in the Gulf of Aden (Fig. 7) than in the Red Sea, Afar and the westernmost part of the Gulf of Aden, where crustal separation is nearly contemporaneous probably around 4 m. y.[6] This stage is not observed in the Ethiopian Rift, but some evidence has been provided for acceleration of crustal attenuation process in the last few m. y. at the axis of the East African Rift (Girdler et al. 1969).

[6] Crustal separation might have been active earlier during the emplacement of Dalha series. Data on this series are presently too scanty to further define the evolution of the area.

Table 2. Evolution of the Afar triple junction.

Early Miocene (~ 25 m. y.)	Initial sinking of Red Sea, Gulf of Aden, Afar, Ethiopian Rift with formation of three arms of continental rifts
Miocene (25–10 m. y.)	Crustal attenuation and volcanic activity in the Red Sea, Afar, Gulf of Aden, Ethiopian Rift. Afar tectonics uniquely of Red Sea (NNW to NS) trend
Mio-Pliocene (10–4 m. y.)	Oceanic crust production in central-western Gulf of Aden. Eastern margin of Afar and Southern Red Sea become stable
Plio-Pleistocene (4 m. y. to present)	Sinking of Gulf of Tadjurah. Oceanic crust is generated in Red Sea, Afar, Gulf of Tadjurah. Red Sea and Gulf of Aden develop into a single accreting plate margin, through Afar axial ranges and Gulf of Tadjurah. Crustal attenuation and related volcanic activity continues in the third rift arm (Ethiopian Rift) where oceanic crust is not being formed.

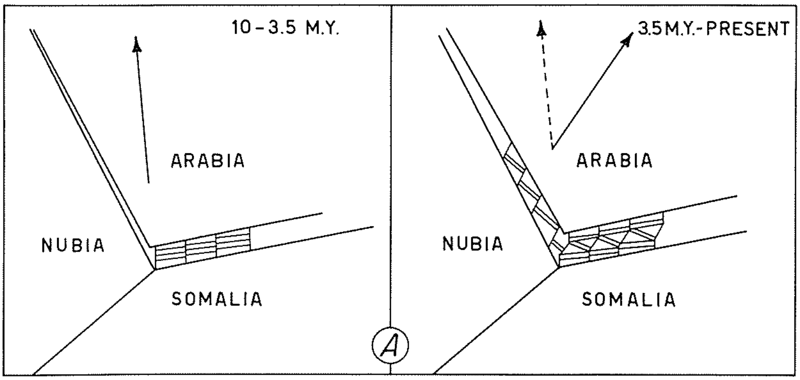
The analogy between Afar, Red Sea and Gulf of Tadjurah structural evolution furthermore suggests that the Red Sea floor away from the central trough and floor of Western Gulf of Aden away from the Tadjurah trough probably consist of materials similar to what is found on Estern Afar margin (North T.F.A.I.).

Data from Afar may help in reconstructing the relative motion of the Arabia, Somalia and Nubia plates since Miocene. A first point to be explained is the earlier formation of oceanic crust in the Gulf of Aden (West Sheba ridge) relative to the Red Sea and Afar. This might be accounted for by:

a) variation in the direction of spreading of the Arabian plate (change near 4 m. y. from approximately N to the present NE motion) (Fig. 8a). No data support this hypothesis, which is infirmed by the magnetic anomalies pattern in the Gulf of Tadjurah (Fig. 8b) and in the Gulf of Aden (Fig. 9b).

b) motion variation of the Somali plate, with a spreading rate higher in the 10–4 m. y. period than in the last 4 m. y.. This has to be rejected because it is contradicted by the recent acceleration of attenuation process at the East African Rift axis mentioned above. Another possibility would be a change in the direction of the relative motion of the Somali plate from S–SW to the present motion which is SE according to McKenzie et al. (1970) (Fig. 9a). This is in agreement with the change observed in the Gulf of Aden magnetic anomaly pattern (Fig. 9b) and could explain the recent formation of the Gulf of Tadjurah. It would however imply a presently unsuspected dextral shear component in the East African Rift during Pliocene.

c) variation in the spreading rate of Arabian plate which accelerated since 4 m. y. with a constant NE motion. This is the generally accepted model (Allan 1970; Phillips



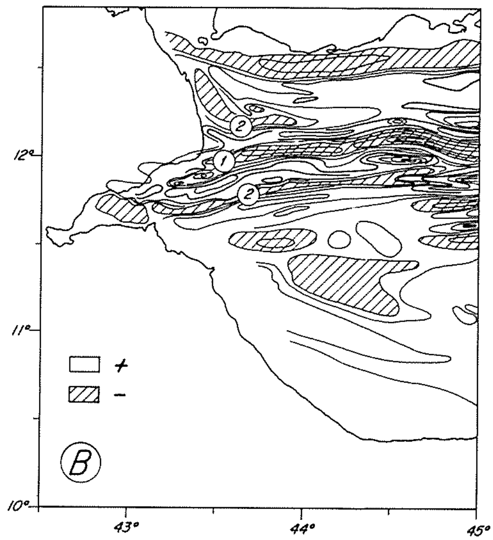


Fig. 8. (A) Hypothetical motions of Arabian plate which would account for the two-stages structural evolution of Gulf of Aden-Red Sea region.
Magnetic anomaly lineations and transform faults resulting from this model do not correspond to what is actually observed in Gulf of Tadjurah, as illustrated in (B) where magnetic anomalies are redrawn after Whitmarsh (1970).

1970; Tarling 1970; Lowell & Genik 1972). Earlier oceanic spreading of the Gulf of Aden with respect to the Red Sea would be simply related to the distance from the Arabia/Africa pole of rotation[7], whereas the Plio-Pleistocene increase of spreading rate would account for the Red Sea (and Afar) change from crustal thinning to crustal separation.

[7] This might be a consequence of the Westward migration of plate motion in the South Pacific and Indian oceans described by Bowin (1974) who considered the opening of the Gulf of Aden as the most recent extension of this migration and noted that "in the wake of the migration secondary adjustments in directions of plate motion appear to occur".

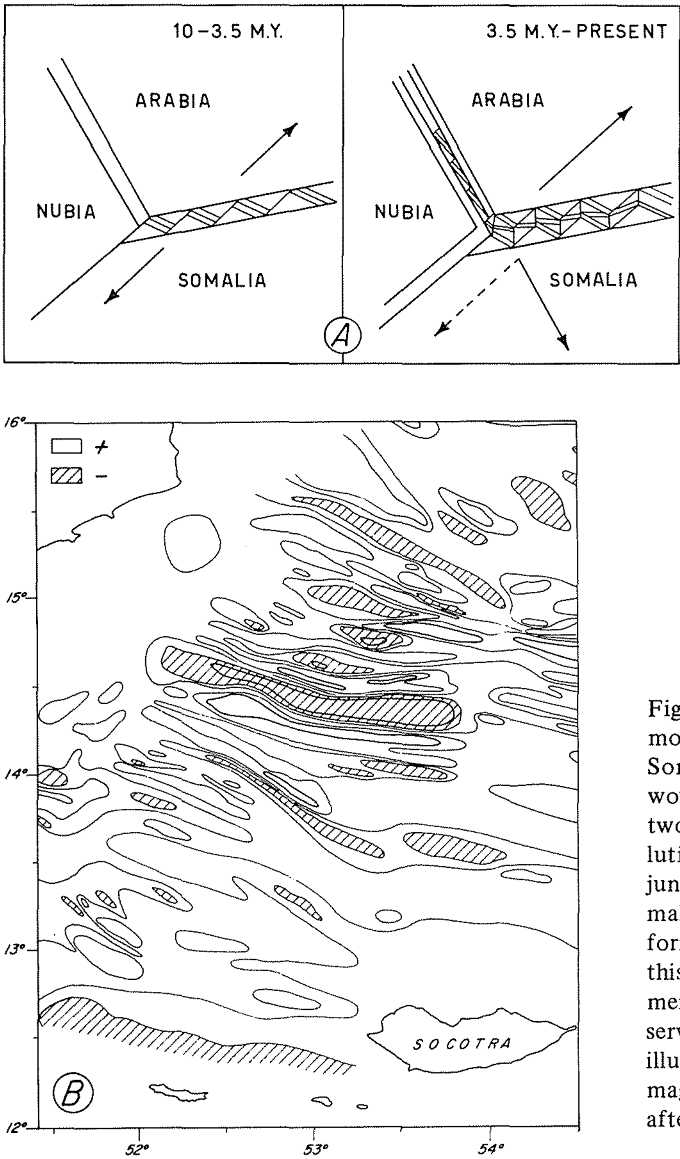


Fig. 9. (A) Hypothetical motions of Arabian and Somalian plates which would account for the two-stages structural evolution of the Afar triple junction. Magnetic anomaly pattern and transform faults resulting from this model are in agreement with what is observed in Gulf of Aden, as illustrated in (B) where magnetic anomalies are after Whitmarsh (1970).

This model can explain most features observed in the Afar triple junction but it does not account either for the dominant E–W magnetic anomaly pattern in the Gulf of Aden for the last few m. y., or for the recent opening of the Gulf of Tadjurah.

A combination of this model with a change of direction of relative motion of the Somali plate envisaged in b) better explains the geology of this region.

Complete literature at the end of the volume, p. 391–416