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Sr ISOTOPIC COMPOSITION OF AFAR VOLCANICS AND ITS IMPLICATION FOR MANTLE EVOLUTION

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Investigations of Rb-Sr systematics of basalts from the Afar depression (Ethiopia) indicate the presence of a heterogeneous mantle source region. The Sr isotopic compositions of the basalts from the Afar axial and transverse ranges identify source regions which are enriched in LIL elements and radiogenic Sr (axial ranges) and others which are relatively depleted (transverse ranges). Sr isotopic composition of basalts from the Red Sea, Gulf of Aden and Gulf of Tadjoura, which range from 0.70300 to 0.70340 are also reported and compared with the more radiogenic Afar region, which is characterized by $^{87}Sr/^{86}Sr$ ranging from 0.70328 to 0.70410.

Available geochemical and isotopic data suggest that a relation exists between magma composition and the advancement of the rifting process through progressive lithosphere attenuation leading to continental break-up. However, the petrogenetic process is not simple and probably implies a vertically zoned mantle beneath the Afar region. Sr isotopic evidence suggests that the vertically zoned mantle is more radiogenic and enriched in LIL elements in its upper part.

1. Introduction

Until a few years ago basalts erupted at mid-ocean spreading ridges (MOR) were considered to represent a geochemically fairly homogeneous group.

This led to the recognition of a typical "oceanic" basalt, the so-called MOR basalt, or abyssal tholeiite, characterized by low concentration of large ion lithophile (LIL) elements, a light-REE depleted pattern and very low Sr isotopic ratio [1]. This "magma type" was considered to be exclusive to oceanic ridges and has been used as a criterion for the recognition of the oceanic character of present day or past (ophiolites) basaltic rocks. In contrast, basalts from seamounts and islands near ridges usually show a more alkalic nature and display distinct geochemical and isotopic variations (e.g. [2]), represented by volcanics with a varying degree of enrichment in LIL elements and emphasized also by the relative abundance of fractionated volcanic rocks. Geochemical differences between ridge and island basalts, particularly the isotopic differences, are too large to be explained simply by different degrees of partial melting from a homogeneous mantle source.

Alternative models involving complex mixing processes between two different mantle sources were therefore proposed to account for the geochemical trends observed approaching an oceanic island. The

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most popular of these is the mantle plume model of Schilling [3], initially proposed to explain the Reykjanes-Iceland sector of the Mid-Atlantic Ridge and then applied to many other sectors of oceanic ridge systems [4–7].

However, very recent detailed studies of specific ridge segments, including vertical sampling of the ocean floor basaltic pile by the Deep Sea Drilling Project, have shown that:

(1) Basalts erupted at the same site are not chemically homogeneous [8] and therefore there is no unique "typical" composition for MOR basalts.

(2) In some cases, such as the FAMOUS and Reykjanes areas [9–12], the range of variation is of the same order of magnitude as that observed longitudinally along the ridges, approaching an island.

Furthermore, these data indicate that the compositional spectrum of the ocean ridge basalts cannot be explained by mixing of melts from two distinct homogeneous sources. Thus, their origin is more complex, implying the existence of marked lateral and vertical inhomogeneities in their mantle sources.

The aim of this paper is to discuss, mainly in the light of Sr isotopic data, the geochemical variations observed in basalts erupted within and near the Afar rift, where a complex junction between oceanic and continental rifts occurs [13–15]. Marked geochemical variations in basalt composition were known from previous studies in this area, recently summarized in Barberi and Varet [14], and various models have been proposed to account for them, including the application of the Iceland mantle plume model to Afar [5].

2. Main structures of Afar

The Afar depression is considered to be an actively spreading area in an early stage of development [14]. Seismic work in the main part of the depression [16–18] indicates that Afar is approaching an oceanic type of structure, similar to that in Iceland or close to the Mid-Atlantic Ridge, with anomalously low mantle velocities found at rather shallow depth. Structures analogous to oceanic spreading ridges, transform faults and "leaky" fracture zones have been identified in Afar (Fig. 1, see Barberi and Varet [14] for a detailed description). They were formed during the past 3–4 m.y. and have been used along with the available magnetic and seismic data to attempt a plate boundary reconstruction in Afar [14].

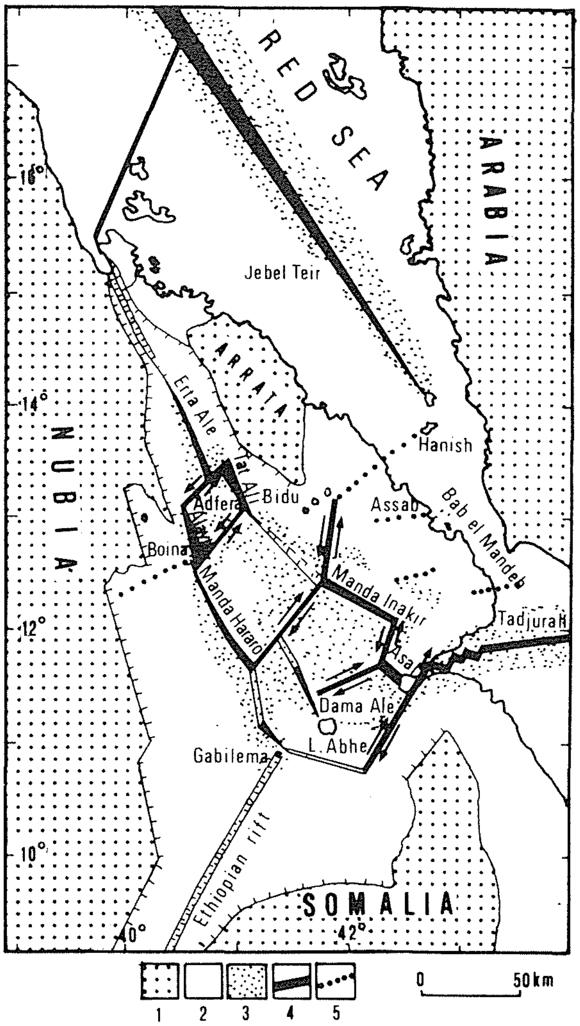

Fig. 1. Schematic structural map of Afar, from Barberi and Varet [14], indicating the location of the sampled volcanic units. 1 = continental basement; 2 = continental rift material; 3 = oceanic crust formed during last 3–4 m.y. (stratoid series); 4 = axis of spreading (axial ranges); 5 = transverse volcanic ranges.

The floor of Afar consists almost entirely of volcanic rocks. Various volcanic units have been distinguished [14]:

(1) The Afar stratoid series, dominantly basaltic, erupted through fissures aligned in a NNW to WNW direction during the period 3.5–0.5 m.y. [19,20]. This volcanic activity has been attributed to the

earliest episode of spreading within Afar [14].

(2) The axial ranges, volcanic structures which display topographical, seismic and gravimetric analogy with mid-ocean spreading ridges [14]. These volcanic units are less than 1 m.y. old and are presently active. They are typically produced by basaltic fissure eruptions occurring along axes aligned in a NW [21] (in northern Afar) to WNW [22,23] (in central and southern Afar) direction. Axial ranges are considered [14] as the surface expression of accreting plate boundaries connecting the Red Sea and the Gulf of Aden rifts, an interpretation now widely accepted [24].

(3) The transverse volcanic structures, localized on the Afar margin (Fig. 1) and aligned with offsets of the continental margin and with offsets of the axial ranges. These transverse structures are marked by alignments of scoria cones and basaltic flows without associated rifts, along an E-W to NE-SW direction [25–27], transverse to the main tectonic trend of the depression. They are of late Quaternary age and are considered as the equivalent of oceanic fracture zones [28].

Oldest Lower Miocene/Pliocene volcanic units and Lower Miocene peralkaline granitic bodies outcrop mainly on the Afar margin (Fig. 1) [19,29]. They have been related to the initial stages of continental rifting in Afar.

3. Magmatic evolution in Afar

The Afar depression is located in the area of junction of three major rift zones: two oceanic (Red Sea and Gulf of Tadjoura) and one continental (East African rift). Approaching Afar some modifications are observed in the petrology of each rift branch [30]. Magmas are typically alkalic in the East African continental rift and become progressively less alkalic approaching Afar, where transitional basalts are dominant [31]. A further gradation from transitional basalts, or tholeiites with moderate to low K content, towards "abyssal" "MOR-type" tholeiites, is observed passing from the proto-oceanic structure of Afar to the typically oceanic rift branches of the Gulf of Aden/Gulf of Tadjoura [32] and the Red Sea [31].

Geochemical differences have also been observed for basalts erupted within the short Afar spreading segments (axial ranges) [21,22]. These compositional differences (from low-K tholeiites to transitional basalts) are often emphasized by the occurrence of different volcanic rock sequences produced by fractional crystallization of basaltic magmas, typically erupted from central volcanoes located at the crossing of different tectonic trends and/or at zones displaying low spreading rate [14]. Further compositional differences are observed for basalts erupted along the transverse fractures of the Afar margins. These basalts, characterized by abundant K, Ti, P and LIL elements, are clearly of alkaline affinity (Fig. 2) and contain frequent ultramafic inclusions [20,25–27, 33].

Using the available petrological and geochemical data, samples were selected for a Sr isotopic study in order: (1) to obtain information on the isotopic composition of basalts from all Afar spreading segments; (2) to compare the isotopic composition of basalts erupted from different tectonic setting within Afar (axial ranges, rift margin and transverse fractures); (3) to investigate compositional variations in the Afar source region; (4) to compare Afar basalts with those from neighbouring rift branches of the Red Sea, the Gulf of Aden/Gulf of Tadjoura and the continental East African rift.

All the analyzed samples are less than 1 m.y. old, except those from the stratoid series, which was erupted between 3.5 and 0.5 m.y. [19,20]. Therefore we investigate here the variation of basalt composition within the framework of the present structural setting of Afar and not its evolution with time. Samples were selected from the most basic and aphyric rocks of the region, regarded as most appropriate for studying the initial composition of the parental magmas. In addition, some chemically evolved rocks were analyzed to evaluate the genetic relation, if any, with the basaltic magmas.

4. Analytical data

Analytical results are reported in Table 1, with an indication of rock type, locality and tectonic setting of the analyzed samples. Location of the sampled volcanic units is also indicated in Fig. 1. Petrography and chemical data for both major and some trace ele-

TABLE 1

Chemical and isotopic data for volcanic rocks from Afar and neighbouring oceanic structures

Sample No.	Rock type	K (%)	SiO_2 (%)	$\frac{K_2O + Na_2O}{Na_2O}$	Rb(ppm)	Sr(ppm)	La/Tb	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Erta Ale axial range									
CH-49	basalt				3.4	187		0.0052	0.70348 ± 5
CH-48	basalt	0.21 [1]	48.78	1.11	11.5	350	20.8 [2]	0.095	0.70365 ± 4
G-65	basalt	0.55 [1]	50.30	1.22	13.6 [1]	347 [1]	33.7 [2]	0.11	0.70375 ± 5
F-49	basalt	0.44 [1]	50.22	1.20	10.7 [1]	293 [1]		0.10	0.70391 ± 5
D-2	basalt	0.41 [1]	48.75	1.15	19 [2]		32.1 [2]		0.70410 ± 4
F-12	ferro-basalt	0.97 [1]	50.71	1.34	25.0 [1]	317 [1]	32.5 [2]	0.23	0.70354 ± 9
D-117	ferrobasalt	0.62 [3]	49.86	1.26	22.2	362		0.18	0.70365 ± 16
Alayta axial range									
D-38	basalt	0.29 [3]	47.23	1.14	7.5	306		0.071	0.70361 ± 5
F-98	basalt	0.36 [1]	46.20	1.17	7.4 [1]	349 [1]	24.6 [2]	0.061	0.70382 ± 4
D-35	basalt	0.50 [3]	46.23	1.22	13.1	401		0.095	0.70380 ± 5
F-147	trachyte	1.25 [1]	53.68	1.39	36.0 [1]	404 [1]		0.26	0.70371 ± 6
Boina volcanic centre									
G-495	basalt	0.66 [4]	46.75	1.30	18 [4]	382 [4]	28.0 [4]	0.14	0.70368 ± 7
S-52	basalt	0.91 [4]	46.03	1.37	24 [4]	490 [4]	35.5 [4]	0.14	0.70375 ± 5
S-40	basalt	0.52 [4]	48.36	1.26	13 [4]	343 [4]	28.4 [4]	0.11	0.70381 ± 4
D-236	trachyte	2.20 [4]	61.48	1.50	56 [4]	280 [4]	31.8 [4]	0.57	0.70371 ± 5
D-210	rhyolitic trachyte	2.71 [4]	59.44	1.66	79 [4]	323 [4]	42.5 [4]	0.71	0.70373 ± 8
Tat'Ali axial range									
G-113	basalt	0.54 [3]	42.10	1.30	9.1	117		0.15	0.70353 ± 5
F-114	basalt	0.58 [3]	48.91	1.25	14	341	42.1 [2]	0.12	0.70366 ± 5
Adfera									
D-47		0.25 [3]	47.73	1.14			30.4 [2]		0.70372 ± 8
Manda Inakir axial range									
B-511	basalt	0.30 [5]	45.94	1.13	3 [6]	608		0.014	0.70359 ± 4
B-536	basalt	0.63 [5]	46.13	1.25	14	448		0.090	0.70360 ± 3
B-549	basalt	0.69 [5]	44.66	1.24	13 [6]	541		0.070	0.70355 ± 7
B-570	basalt	0.63 [5]	44.02	1.23	12 [0]	475	28.2	0.073	0.70370 ± 8
Asal axial range									
6875	basalt	0.41 [7]	46.90	1.18	8.6	442		0.059	0.70373 ± 4
6872	basalt	0.33 [7]	46.00	1.14	5.5	386		0.041	0.70370 ± 5
6870	basalt	0.18 [7]	48.20	1.09	16.7	422	28.8 [7]	0.11	0.70404 ± 6
6868	basalt	0.33 [7]	45.70	1.15	4.7	343	20.9 [7]	0.040	0.70361 ± 5
6890	basalt	0.29 [7]	47.60	1.14	6.1	382	23.8 [7]	0.046	0.70392 ± 5
6945	basalt	0.39 [7]	46.40	1.15	7.5	284	20.4 [7]	0.076	0.70349 ± 4
Manda Hararo axial range									
S-214	basalt				8.6	320	20.5 [2]	0.078	0.70373 ± 5
S-161	basalt	0.49 [3]	46.12	1.20					0.70382 ± 5
S-69	basalt				9.8	326	22.9 [2]	0.083	0.70399 ± 6
S-170	(Kurub) basalt				7.7	327	21.3 [2]	0.068	0.70387 ± 5
Dama Ale volcano									
H-169	basalt	0.43 [3]	48.84	1.16	8.9	262		0.098	0.70335 ± 4
H-150	basalt								0.70341 ± 8
H-115	ferrobasalt	0.71 [3]	50.12	1.23	23 [3]	104	31.2 [2]	0.64	0.70335 ± 5
Gabilema axial range									
H-288									0.70332 ± 4

TABLE 1 (continued)

Sample No.	Rock type	K (%)	SiO_2 (%)	$\frac{K_2O + Na_2O}{Na_2O}$	Rb(ppm)	Sr(ppm)	La/Tb	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Assab "transverse" range									
B-6	alkali basalt	1.08 [8]	47.38	1.40	35 [8]	678	50.6 [8]	0.15	0.70328 ± 5
B-19	alkali basalt	1.09 [8]	47.09	1.37	40 [8]	650	65.7 [8]	0.18	0.70338 ± 5
B-258	alkali basalt	0.69 [9]	47.11	1.26	20 [9]	548	39.9 [8]	0.11	0.70355 ± 4
B-230	alkali basalt	1.29 [9]	47.43	1.44	36 [9]	600	48.8 [8]	0.17	0.70341 ± 4
B-298	alkali basalt	0.91 [9]	45.95	1.35	25 [9]	571	39.1 [8]	0.13	0.70361 ± 5
B-281	mugearite	2.44 [9]	55.82	2.70	69 [9]	670	69.2 [8]	0.30	0.70338 ± 4
B-236	trachyte				68 [9]	271		0.73	0.70369 ± 4
B-251	trachyte	2.56 [9]	61.43	1.58	60 [9]	298	38.5 [8]	0.58	0.70392 ± 6
Afar stratoid series									
B-496	basalt	0.61 [5]	46.98	1.24	9	385		0.068	0.70367 ± 4
D-543	basalt	0.48 [3]	47.77	1.17	12.5	387		0.093	0.70361 ± 6
S-60	basalt	0.46 [3]	47.08	1.20	17	289	26.7 [2]	0.17	0.70376 ± 12
C-300	basalt	0.83 [3]	52.74	1.29	17.7	356		0.14	0.70370 ± 15
Red Sea central trough									
MR-V62	basalt	0.21 [3]	50.01	1.10			8.6 [2]		0.70305 ± 4
Gulf of Aden									
MR-V51	basalt	0.12 [10]	49.06	1.06			5.7 [2]		0.70300 ± 5
Gulf of Tadjoura									
MR-V60	basalt	0.31 [10]	46.09	1.14					0.70340 ± 6
Ethiopian rift									
H-40	basalt						24.0 [2]		0.70405 ± 4

[1] Barberi et al. [36]; [2] Treuil and Joron [35]; [3] Unpublished analyses, University of Pisa; [4] Barberi et al. [34]; [5] De Fino et al. [23]; [6] Civetta et al. [20]; [7] Stieltjes et al. [22]; [8] Ottonello et al. [33]; [9] Civetta et al. [27]; [10] Richard [32].

ments have been already published [20,22,23,27, 29,31,33–36].

Sr was extracted by standard cation exchange technique and the Sr isotopic analyses were made on a V.G. Micromass-30 mass spectrometer at the Department of Geology and Mineralogy, Oxford University. Details of the chemical procedure and instrumental technique have been given previously [37,38]. $^{87}Sr/^{86}Sr$ presented here have been normalized to a value of 0.70800 for the Eimer and Amend $SrCO_3$. The quoted error (2σ) is the standard deviation of the mean. Rb and Sr, when not available from the literature, were determined by X-ray fluorescence spectrometry with a precision better then 5%.

Results will now be discussed grouping together samples with the same structural setting.

5. Discussion of results

5.1. Axial ranges

These volcanic suites are essentially composed of transitional basalts, locally with a tendency towards tholeiitic composition (Fig. 2) [21,23,31,35,38,39]. In most of the units, fractionation occurred towards iron- and titanium-rich intermediate rock types and more rarely to rhyolitic final products, often slightly peralkaline [40]. From north to south they are discussed below.

Erta Ale. This unit is made up of several volcanic centers aligned along a fissure trending in a NNW (Red Sea) direction, displaying geochemical variations along its length [31]. Volcanic products are more

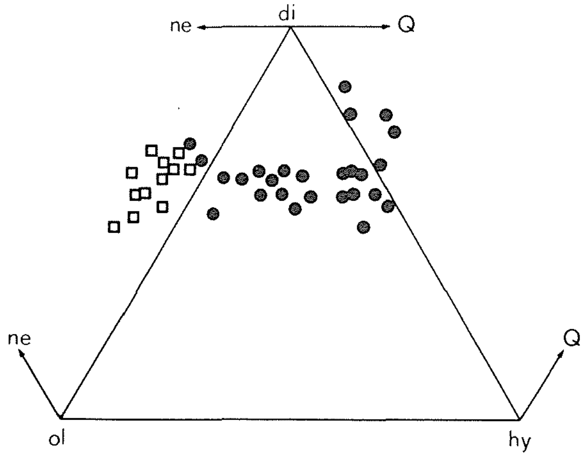

Fig. 2. Normative mineralogy of typical basalts from axial and transverse ranges of Afar. Axial range basalts: solid circles; transverse range basalts: open squares.

alkaline in its northern part where the spreading rate is lower [14,31]. Towards the north of the range, cumulo-volcanoes are developed and more fractionated products also occur [21,41]. Eight basalts and ferrobasalts have been analyzed; $^{87}Sr/^{86}Sr$ ratios range from 0.70348 ± 5 to 0.70410 ± 4, with Sr becoming more radiogenic from north to south. The large scatter of data suggests a range of $^{87}Sr/^{86}Sr$ in the primary liquids. Note that two basalts (samples CH-48 and G-65), with contrasting petrological and geochemical characters [41], have the same $^{87}Sr/^{86}Sr$ ratio.

Alayta. This unit forms a shield volcano built on NNW fissures and surrounded by more recent basaltic fissure activity. Products of the volcano range from transitional basalts to iron- and titanium-rich intermediate rock types, whereas the more recent fissure activity consists solely of undifferentiated transitional basalts [36,42]. Three basalts and one trachyte have been analyzed from the two parts of the range. The range of variation of $^{87}Sr/^{86}Sr$ from 0.70361 ± 5 to 0.70382 ± 4 is smaller than in Erta Ale. The trachyte gives 0.70371 ± 6, within the range of the basalts, consistent with its proposed origin by crystal fractionation [36].

Tat'Ali. This range lies at the same latitude and parallel to Alayta and is, therefore, considered as a coupled spreading segment [14]. Tat'Ali is a fissure in its northern part, where intense tectonic activity (gaping fissures and normal faults) is associated with eruption of usually picritic transitional basalts. In its central and southern part, central volcanoes are developed, which erupted more fractionated products [42]. Two samples from Tat'Ali gave $^{87}Sr/^{86}Sr$ values of 0.70353 ± 5 and 0.70366 ± 5.

Boina. This volcano is located between Alayta and the Manda Hararo axial ranges (Fig. 1) and may be considered to have been emplaced at the intersection with a short leaky transform fault [14]. Differentiation processes affected the most recent lavas of this centre, where a complete sequence of volcanic products, ranging from transitional basalts to pantellerites, was erupted in a short time interval [34,39]. Five samples, from picritic basalts to rhyolitic trachytes, have been analyzed. The range of variation of $^{87}Sr/^{86}Sr$ is from 0.70368 ± 7 to 0.70381 ± 4. The $^{87}Sr/^{86}Sr$ ratios of the analyzed trachytes and rhyolites are within range of the basalts.

Manda Hararo. This range, located in central Afar, is made almost exclusively of basalts erupted along NNW fissures. Basalts vary from low-K transitional basalts to more alkaline types. Three samples have been analysed from the range itself and one additional sample has been selected from nearby Kurub volcano, which displayed similar rock types. $^{87}Sr/^{86}Sr$ ratios, from 0.70373 ± 5 to 0.70399 ± 6, are well outside the analytical errors.

Manda Inakir. Located in eastern Afar this range is built along fissures aligned in a WNW to NW direction [23]. It consists of transitional basalts, with a slight alkalic affinity, fractionated locally up to mugearitic types. Although subdivided into two parts (southeastern Inakir shield and western Manda fissure activity) all the products of this range have been assigned to a single fractionation trend on the basis of petrological and geochemical data [23,29]. $^{87}Sr/^{86}Sr$ ratios of the five analyzed samples range from 0.70355 ± 7 to 0.70370 ± 8.

Asal. This easternmost range of Afar is clearly connected with the Gulf of Tadjoura/Gulf of Aden spreading segments [15,43]. It consists of a spectacular symmetrical graben with present-day axial activity [44]. In spite of its small dimension, this axial range displays marked chemical variation from basalts with alkalic affinity emitted during the earlier rift activity to recent low-K tholeiites and related iron-rich differentiates in the central part of the graben [22]. Six samples of basalts, covering the whole temporal sequence and compositional spectrum have been analyzed and display a wide range of variations, 0.70348 ± 4 to 0.70404 ± 6, similar to that described above for Erta Ale. The most recent and the most tholeiitic basalts tend to have more radiogenic $^{87}Sr/^{86}Sr$.

Dama Ale. Recent volcanic activity occurs in central Afar in the area around the junction of the Red Sea/ Gulf of Aden (NNW to WNW) and the East African rift (Lake Abbe and Kalo plain region). Three samples of basalts have been analyzed from the Dama Ale shield volcano where more fractionated products including rhyolites, also occur. These basalts clearly are of tholeiitic affinity [45], and display identical $^{87}Sr/^{86}Sr$ with a mean value of 0.70337 ± 4. One additional sample was selected from the WNW-trending Gabilema range and gives 0.70332 ± 4.

5.2. Transverse volcanic units

These volcanic units (Ma'Alalta, Assab, Gufa, Edd), are developed along the margins of the Afar depression. They consist of basalts, all of alkaline character (Fig. 2) and with frequent ultramafic inclusions [20,26,27,33].

TABLE 2

$^{87}Sr/^{86}Sr$ of mineral separates from spinel-lherzolite (sample 3G-18) from the Assab range

Analyzed phase	La/Tb	$^{87}Sr/^{86}Sr$
Orthopyroxene		0.70443 (± 8)
Clinopyroxene	13.6	0.70427 (± 15)
Spinel		0.70410 (± 14)
Olivine	23.3	0.70496 (± 11)

La/Tb ratios, geochemical data and a detailed mineralogical description of 3G-18 lherzolite are in Ottonello et al. [33].

According to Civetta et al. [20] the occurrence of alkalic volcanism along the Afar margin could reflect an increase in the depth of magma generation with progressive distance from the area of spreading.

Eight basalts, hawaiites, mugearites and trachytes have been analyzed from the Assab range, on the eastern Afar margin (Fig. 1). $^{87}Sr/^{86}Sr$ ranges from 0.70328 ± 5 to 0.70392 ± 4. The more chemically evolved rock (trachyte B-251) gives the higher $^{87}Sr/^{86}Sr$ ratio.

Some of the analyzed samples contain ultramafic nodules including spinel lherzolites [33]. Trace element data [33] on the host basalts indicate that the primary alkaline melts had an independent differentiation history, namely fractional crystallization at intermediate pressure prior to inclusion of the mantle xenoliths. Minerals (ol, cpx, opx, spinel) separated from one spinel-lherzolite (sample 3G-18) described in Ottonello et al. [33] have been analyzed in order to clarify the genetic relationship, if any, between the host basalt (B-6) and the mantle-derived ultramafic inclusion. $^{87}Sr/^{86}Sr$ of these minerals (Table 2) are all higher (from 0.70410 ± 14 to 0.70496 ± 11) than the host basalts (0.70338 ± 5).

5.3. The stratoid series

This huge volcanic pile consisting mainly of basaltic flows, covers most of the Afar floor, especially its central part. The series consists of transitional basalts with minor iron-rich intermediate types. Locally, rhyolites are also found as ignimbrites sheets or related to small central volcanoes occurring at the top of the series [19,20]. Some regional variations in the geochemistry of the basalts have been observed, with a tendency to approach the composition of basalts erupted at the nearest axial range [46].

Basalts have been selected from various localities in this unit. They were chosen to investigate whether major variations occur between the earlier and recent volcanic activity. Such a variation would not be expected if the stratoid series represents an earlier activity of oceanic crustal accretion similar to that presently occurring in the axial ranges [14]. The five samples analyzed have a range of $^{87}Sr/^{86}Sr$ from 0.70361 ± 6 to 0.70376 ± 12, and thus do not display a wide range of variation. This, however, may be due to inadequate sampling.

5.4. Surrounding rifts

Samples dredged during the Valdivia cruise (1976) from the surrounding oceanic rifts have been analyzed for comparison. Three samples of tholeiites from the Red Sea trough (19°38.48′N, 38°41.59′E), from the Gulf of Aden (11°42.08′N, 42°56.01′E) and from the Gulf of Tadjoura (13°03.02′N, 40°23.01′E) give values of 0.70305 ± 4, 0.70300 ± 5 and 0.70340 ± 6, respectively. The first two samples are isotopically clearly different from the Afar values. One sample from the northern part of the African rift valley (sample H-40) has also been analyzed for comparison and its $^{87}Sr/^{86}Sr$ of 0.70405 ± 4 is one of the highest recorded.

6. Summary of Sr isotopic variations in Afar basalts

The salient features of the Sr isotopic results are:

(1) Afar basalts on the whole display more radiogenic $^{87}Sr/^{86}Sr$ ratios than the surrounding oceanic rifts of the Red Sea, Gulf of Aden and Gulf of Tadjoura. The values are higher than $^{87}Sr/^{86}Sr$ ratios

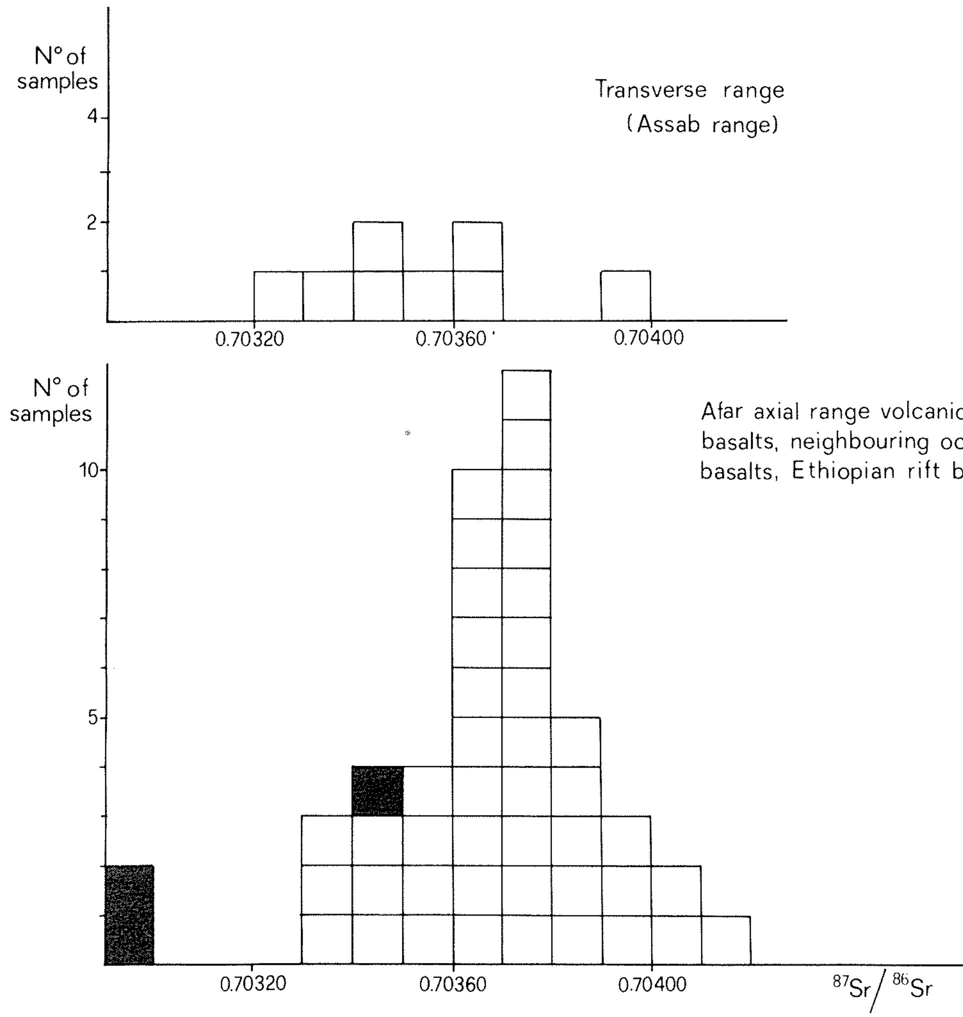

Fig. 3. Frequency distribution of Sr isotopic composition of Afar volcanics. Axial ranges, transverse ranges, stratoid series: open squares; Gulf of Aden, Gulf of Tadjoura, Red Sea basalts: solid squares.

reported for most mid-ocean ridges, which range from 0.7022 to 0.7035 [1]. Note, however, that data from the Mid-Indian and Sheba ridges [47] and the Gulf of Tadjoura rift (this paper) are close to the Afar values.

(2) $^{87}Sr/^{86}Sr$ ratios in the Afar basalts range from 0.70328 to 0.70410 and almost the whole range is observed within the two axial range units Erta Ale and Asal, and within the Assab transverse range. Most of the samples from the axial ranges and from the stratoid series, however, have $^{87}Sr/^{86}Sr$ ratios between 0.70360 and 0.70380 (Fig. 3).

(3) In those axial ranges where petrographical and geochemical studies have suggested that the rock sequence was derived from a single parental liquid, $^{87}Sr/^{86}Sr$ agree within analytical error. This is best observed at Boina volcano where the ratios agree for all analyzed basalts to rhyolites with a mean value of 0.70374, and at Dama Ale and Manda Inakir, where the mean values are respectively 0.70337 and 0.70361. This constancy allows us to exclude any significant Sr contamination process affecting these volcanics, which would affect mainly the low-Sr highly fractionated rocks.

(4) A wide range of Sr isotopic variations is observed among the basaltic rock types of the Erta Ale, Manda Hararo and Asal ranges, whilst in the other axial ranges the Sr isotopic compositions are within the analytical errors for each individual range. This is the case for Tat'Ali, Alayta, Boina, Dama Ale and Manda Inakir.

(5) No significant regular regional variation can be recognized among the various axial ranges.

(6) The isotopic composition of the axial ranges and the stratoid series volcanics fit quite well a Gaussian distribution about a mean value of 0.70370 (Fig. 3). Data from the stratoid series correspond to the most frequent values found for the axial ranges basalts.

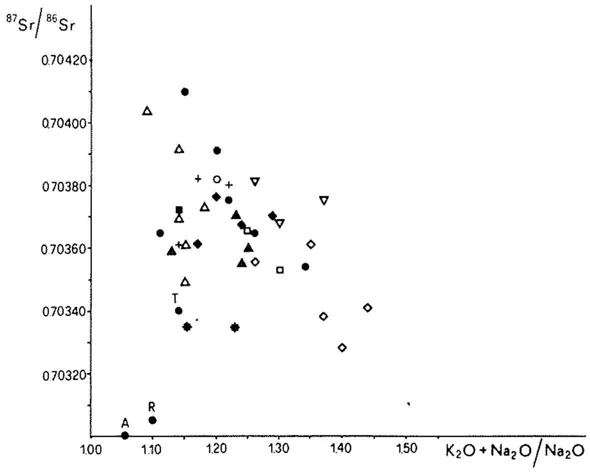

Fig. 4. $^{87}Sr/^{86}Sr-(K_2O + Na_2O)/Na_2O$ plots of Afar basalts and neighbouring oceanic basalts. ● = Erta Ale; + = Alayta; □ = Tot'Ali; ■ = Afdera; ▽ = Boina; ▲ = Manda Inakir; ○ = Manda Hararo; △ = Asal; * = Dama Ale; ◇ = Assab; ◆ = stratoid series; ▼ = Ethiopian rift. A: Gulf of Aden; T: Gulf of Tadjoura; R: Red Sea.

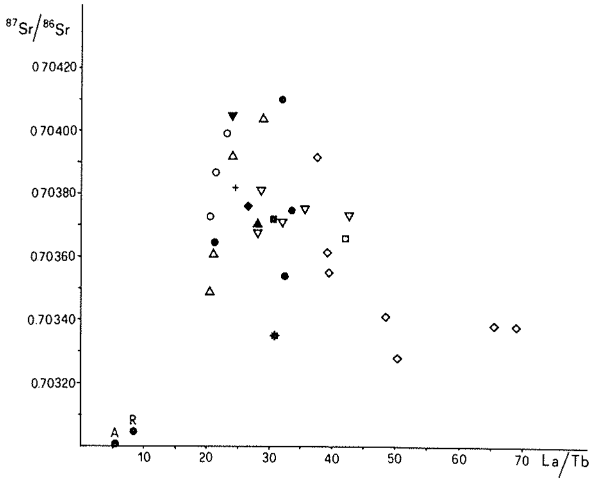

Fig. 5. $^{87}Sr/^{86}Sr$-La/Tb plots of Afar volcanics (including all lava types) and neighbouring oceanic basalts. Symbols as in Fig. 4.

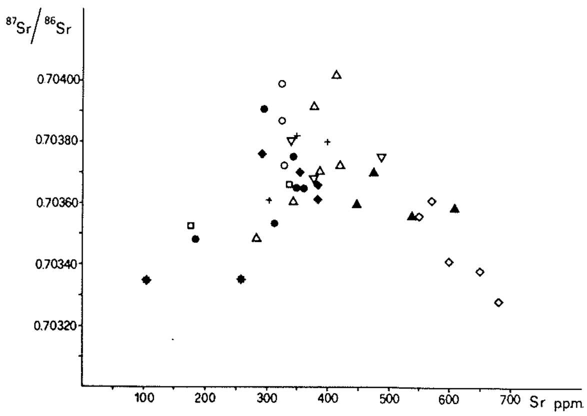

Fig. 6. $^{87}Sr/^{86}Sr$-Sr plots of Afar basalts and neighbouring oceanic basalts. Symbols as in Fig. 4.

(7) The samples from the Assab transverse range, on the eastern Afar margin, show a wide variation of $^{87}Sr/^{86}Sr$ from 0.70328 to 70392. However, the alkalic basalts from this range have lower $^{87}Sr/^{86}Sr$ from 0.70328 to 0.70365 than the transitional and tholeiitic basalts from the axial ranges (see Table 1). This is reflected in a broad negative correlation between $^{87}Sr/^{86}Sr$ and $K_2O + Na_2O/Na_2O$. La/Tb and Sr (Figs. 4–6), shown by the Assab alkaline rocks compared with the more radiogenic tholeiites and transitional basalts from the axial ranges.

(8) Low $^{87}Sr/^{86}Sr$ from 0.70355 to 0.70340 are also observed for tholeiites erupted in the junction area of central Afar, whereas one of the highest values of 0.70405 ± 4 is found for a basalt from the Ethiopian rift valley.

7. Discussion

Before discussing the genetic significance of the Sr isotopic variations observed within and around Afar, it is emphasized that contamination with more radiogenic continental crustal material can be excluded for the following reasons:

(1) Afar is floored by a thin oceanic crust [14,16], or by strongly attenuated continental crust [17,48] fragmented along the plate margins (axial ranges), where new oceanic crust is generated and where the most radiogenic basalts are erupted.

(2) The lack of crustal xenoliths [14].

(3) The geochemistry and mineralogy of the volcanic rocks (see Barberi and Varet [14] for a review).

(4) The constant $^{87}Sr/^{86}Sr$ observed for crystal fractionation sequences (e.g. Boina, from basalts to rhyolites).

It is assumed, therefore, that $^{87}Sr/^{86}Sr$ ratios of the basalts represent those of the source regions [1], and reflect processes operating within the mantle.

The observed range of $^{87}Sr/^{86}Sr$ allows us to reject a model of genesis of Afar basalts by different degrees of partial melting from a homogeneous mantle source, as proposed by Treuil and Varet [35] and Treuil and Varet [31]. This model might be applied only to few basalts, which have different contents of LIL elements and identical $^{87}Sr/^{86}Sr$. The best example is provided by some of the basalts from Erta Ale (see previous description), but this genetic process could be more general if we considered together basalts belonging to different ranges. The existence, in Afar as a whole, and within single units, of basalts displaying widely different $^{87}Sr/^{86}Sr$ implies the existence of several geochemically distinct sources. However, the normal distribution (Fig. 3) of the isotopic ratios of the axial ranges and stratoid series volcanics suggests that their source regions can be considered as fairly homogeneous on a regional scale, and that the random isotopic fluctuations might reflect local heterogeneities or other processes of minor importance.

The absence of regular regional geochemical [14] and isotopic variations approaching the Red Sea, the Gulf of Tadjoura/Gulf of Aden and the East African rift, or within Afar, rules out the hot-plume model, proposed by Schilling [5], which implies regional variations resulting from mixing of melts from two extreme mantle sources, the one enriched and the other depleted in LIL elements. Although Afar basalts are characterized by higher $^{87}Sr/^{86}Sr$ than the Red Sea and Gulf of Aden samples, several lines of evidences conflict with the plume model. For instance, on a regional scale, the East African rift sample is more radiogenic than the major part of the Afar samples. On a smaller scale, basalts from the Dama Ale and Gabilema ranges in central Afar, located on the inferred centre of the mantle plume, have lower $^{87}Sr/^{86}Sr$ ratios than the surrounding Asal, Manda Hararo and Ethiopian rift rocks. Ages of spreading also argue against a mantle plume in Afar, as indicated by the progressively more recent spreading ages along the Gulf of Aden and the Gulf of Tadjoura ridges, as Afar is approached [32].

Any other model involving mixing between two homogeneous mantle-derived end members is not adequate to explain all the variations observed. Such mixing models would result in a hyperbolic correlation between $^{87}Sr/^{86}Sr$ and other element ratios or contents and this would apply to any element [49]. No simple hyperbolic correlations exist in any of the diagrams based on the available geochemical data for rocks considered in this paper (Figs. 4–6). More complex mixing processes involving heterogeneous sources are difficult to model and cannot be ruled out.

In conclusion, the geochemical data do not fit a unique genetic model for the Afar basalts, and there is strong evidence for heterogeneity in the mantle sources.

The most striking result of the Sr isotopic determinations is the inverse trend between $^{87}Sr/^{86}Sr$ and total alkalies, La/Tb and Sr content observed for most of the samples (Figs. 4–6). This trend is particularly evident in comparing the Manda Inakir and Assab samples, the latter being the most alkalic and least radiogenic of all the Afar basalts.

The Assab basalts were generated in mantle sources deeper than those of the transitional and tholeiitic basalts of interior Afar, as indicated by a crustal thickness higher than in the axial ranges [17], probably reflecting a less attenuated lithosphere. The occurrence in the Afar region of mantle-derived ultramafic xenoliths more radiogenic than the host basalts, implies a vertical zoning in the mantle, with at least one depleted layer (source of Assab basalts) overlain by a more radiogenic one, which is the source of the spinel-lherzolite xenoliths.

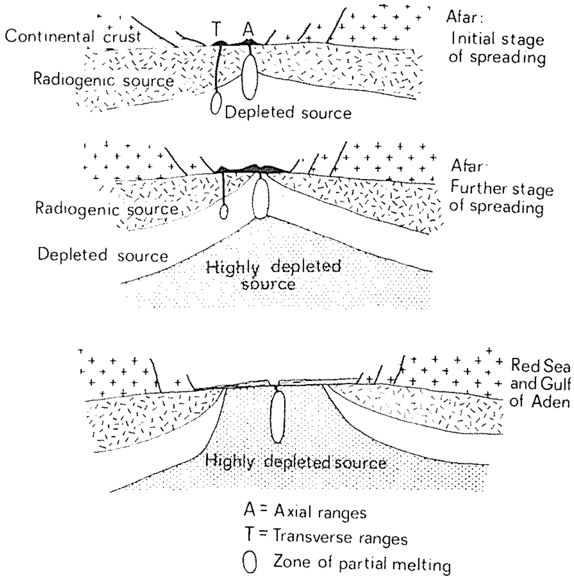

Fig. 7. Mantle evolution model from an initial (Afar) to an advanced (Red Sea, Gulf of Aden) stage of spreading, showing the uprising of a highly depleted mantle.

8. Mantle evolution beneath Afar

If Assab-type mantle layering is supposed to exist, or to have existed, underneath the entire Afar region, we must conclude that the axial tholeiites and transitional basalts originate by higher degrees of melting from this shallow mantle source, which is characterized by higher $^{87}Sr/^{86}Sr$. This is the only way to account for tholeiites with more radiogenic Sr isotope compositions. The alkali basalts from the Afar margin (Assab range) would then correspond to a deeper source, characterized by lower $^{87}Sr/^{86}Sr$ ratios and affected by lower degrees of melting (Fig. 7). Local mixing processes, either before or after melting, between these two sources could explain the inverse trend (Figs. 4–6) observed for the Assab samples.

The less radiogenic deeper layer may progressively rise and undergo higher degrees of melting, producing tholeiites with less radiogenic $^{87}Sr/^{86}Sr$ during progressive crustal attenuation by rifting. Tholeiites from Dama Ale and from the Gulf of Tadjoura (with the same $^{87}Sr/^{86}Sr$ of the Assab alkali basalts), erupted in areas where crustal spreading has been active since at least 3–4 m.y. [14,32], could be the expression of this stage of the process. The axial ranges (Erta Ale, Asal), where spreading has been active for a shorter period of time (less than 1 m.y.), could reflect a rapid transition from a more to a relatively less radiogenic source, judging by their wide range of $^{87}Sr/^{86}Sr$.

Following this line of reasoning, the tholeiites of the Red Sea and the Gulf of Aden may represent the last stage of this process, with a still less radiogenic mantle source located under the ridge axis and affected by a large degree of melting. This model is the exact opposite of the Schilling's mantle plume hypothesis and fits O'Hara's [50] suggestion that a depleted mantle rises more easily than an undepleted denser mantle.

Other petrogenetic processes of local importance may be superimposed on this trend. Come can be attributed to small-scale variations, in time or space, of the spreading rate, with consequent variations of the degree of melting from the same mantle source, whilst others may result from local mixing processes between the two extreme sources, as previously discussed. It is, however, clear that in a zone of mantle heterogeneity it may be misleading to expect a correlation between magma geochemistry and tectonic environment.

Isotopic evidence from Atlantic basalts [1] suggests a separate source for MORB and island alkali basalts. In contrast, the Afar isotopic data suggest that convection, with resulting rehomogeneization of MORB source material, has not occurred at this early stage in the Afar source region.

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