International Journal of Geosciences, **2013, 4, 1459-1466**
Published Online December 2013 (http://www.scirp.org/journal/ijg)
http://dx.doi.org/10.4236/ijg.2013.410143

Continental Flood Basalts and Rifting: Geochemistry of Cenozoic Yemen Volcanic Province

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Received August 2, 2013; revised September 6, 2013; accepted October 3, 2013

ABSTRACT

Rift formation is a crucial topic in global tectonics. The Yemen rift-related area is one of the most important provinces, being connected to the rifting processes of the Gulf of Aden, the Red Sea and Afar Triangle. In this paper, a review of the Yemen volcanic province and its relations with the Red Sea rifting are presented. Tertiary continental extension in Yemen resulted in the extrusion of large volumes of effusive rocks. This magmatism is divided in the Oligo-Miocene Yemen Trap Series (YTS) separated by an unconformity from the Miocene-Recent Yemen Volcanic Series (YVS). Magmas of the YTS were erupted during the synrift phase and correlate with the first stage of sea-floor spreading of the Red Sea and the Gulf of Aden (30 - 15 Ma), whereas the magmas of the YVS were emplaced during the post rift phase (10 - 0 Ma). A continental within plate character is recognized for both the YTS and YVS basalts. The YTS volcanic rocks are contemporaneous with, and geochemically similar to, the Ethiopian rift volcanism, just as the volcanic fields of the YVS are geochemically alike to most of the Saudi Arabian volcanics. YTS and YVS have analogous SiO_2 ranges, but YVS tend to have, on average, higher alkalis and MgO contents than YTS. Fractional crystallization processes dominate geochemical variations of both series. Primitive magmas (MgO > 7.0%) are enriched in incompatible elements and LREEs with respect to primitive mantle, but YVS are more enriched than YTS. To first order, the different geochemical patterns agree with different degrees of partial melting of an astenospheric mantle source: 25% - 30% of partial melting for YTS and 10% - 3% for YVS. Secondly, the higher degree of enrichment in incompatible elements of YVS reflects also greater contribution of a lithospheric mantle component in their source region.

Keywords: Continental Flood Basalts; Continental Rifting; Geochemistry; Yemen; Cenozoic

1. Introduction

The Tertiary continental magmatism of Yemen was associated to the early opening phases of the Red Sea and the Gulf of Aden, and was part of the Afro-Arabian rift system (AARS), which included the Ethiopian Rift and the Afar Triangle (**Figure 1(a)**).

During Late Eocene to recent, the geological evolution of North Africa was dominated by the development of the Red Sea-Gulf of Aden-East Africa Rift System that resulted in the separation of the Arabian plate. The opening of narrow, elongated oceanic domains along the Gulf of Aden and the Red Sea from Miocene times resulted in the separation and northwards drift of the Arabian plate, allowed by sinistral movement along the Levant-Dead Sea fault zone. Rifting initiated in the Early Oligocene in several small, en echelon E-W to ESE-WNW trending basins in the Gulf of Aden province. By the Oligocene-Miocene transition, rifting had spread to Afar and throughout the Red Sea system. The onset of continental rifting began ~22 Ma ago, and encompassed the whole length of the present-day Red Sea basin and Gulf of Aden [1]. Strong magmatic activity predated and accompanied rift tectonics, favouring extension by weakening the lithosphere. Oceanic spreading followed advanced continental rifting about 5 Ma ago with volcanic (mainly basaltic) activity [1].

In the late Oligocene-early Miocene through to the present time, large volumes of flood basalts emplaced at discrete eruptive centres along the western margin of the Arabian plate from the Gulf of Aden to the Mediterranean. These plateau basalts are concentrated on the Arabian side of the Red Sea without matching counterparts on the Nubian plate (**Figure 1(a)**), and represent one of the largest areas of predominantly alkali-olivine basalts in the world.

In Yemen, Oligo-Miocene to Recent (pre-/syn-rift) volcanic complexes were emplaced in the western and southwestern parts (**Figure 1(b)**).The area of this volcanism, which included Continental Flood Basalts, occupied approximately one-tenth of the total area of the country, and approximately 28% of the total area of the Arabian Plate volcanic rocks. The Yemen flood volcanics are characterized by: 1) large volumes of magmatic activity; 2) large-scale crustal extension; 3) mildly alkaline basalts and 4) bimodal distribution of basic and acid magma products. Volcanic products from Yemen are akin to coeval volcanic rocks from Djibouti, Ethiopia, and some parts of the Kenyan rift.

This work presents a review of petrological data for the rift-related volcanic rocks of Yemen.

2. The Yemen Continental Flood Basalts

The Cenozoic Yemen volcanic province can be divided into: 1) the late Oligocene-early Miocene *Yemen Trap Series* (YTS), separated by an unconformity from 2) the late Miocene-Recent *Yemen Volcanic Series* (YVS).

2.1. Yemen Trap Series (YTS)

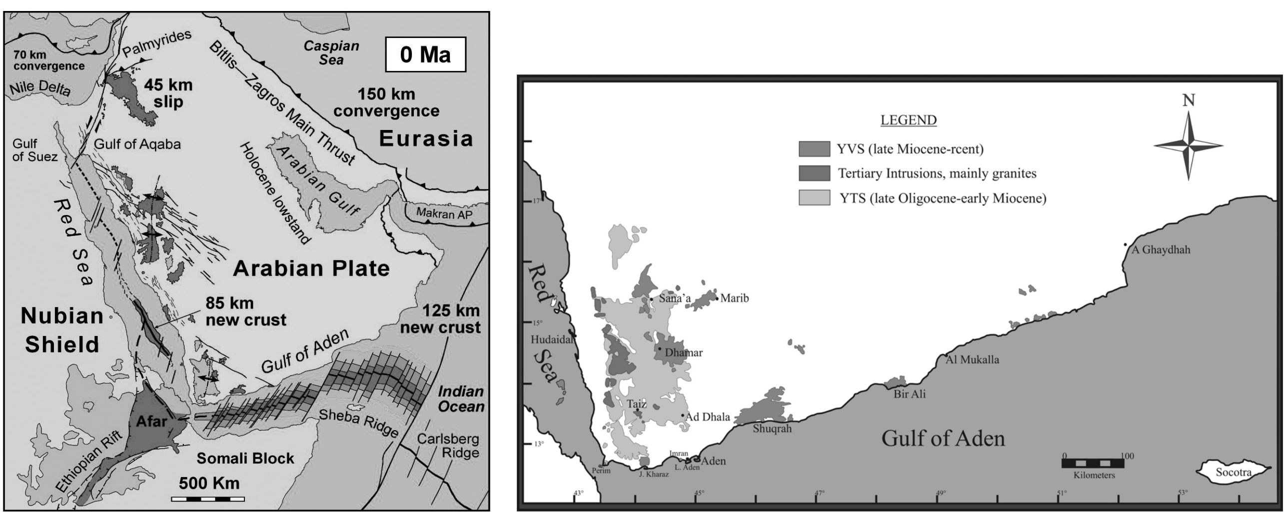
The YTS represent the lowest part of the Cenozoic Yemen volcanic province, and mainly overly the Cretaceous Tawilah Group sandstones and the Paleogene lateritic paleosols, and in some cases the metamorphic basement rocks. They had been developed during the Oligocene-early Miocenic pre- and sin-rift phases.

The YTS consists of thick bimodal volcanics, including alkaline to transitional basalts and peralkaline rhyolites and their associated ignimbrites, tuffs and rhyolitic obsidian flows, which cover an area of about 3000 km^2. The volume of acidic to basic volcanic products is greater than 0.5. Thickness of the YTS varies from >2000 m in the west down to hundreds to tens of meters in the east. The older units of this series are intruded by gabbro, alkali granite and syenite bodies. The majority of the felsic rocks are of peralkaline type (A/CNK > 1) with a comenditic character (normative-quartz > 20%) and are very poor in normative-mafic minerals.

Quoted ages for the YTS volcanism range from 31 to 16 Ma (see review in [1]). Within this large period, the peak of activity occurred between 30.9 and 26.5 Ma. In addition, some pre-Oligocenic ages [e.g. 2] could suggest early beginning of the volcanism in an Eocenic pre-Trap phase of magmatic activity, in agreement with Cenozoic igneous activity in the neighbouring Arabia and Gulf of Aden.

2.2. Yemen Volcanic Series (YVS)

The YVS was firstly defined by [3-5] on the basis of both geochronological and geochemical evidence. They were generated and developed through the post-rift stage (Miocene to Recent), and are separated by an unconformity



(a) (b)

Figure 1. (a) Generalized map of the Afro-Arabian rift system, comprising the Read Sea, the Gulf of Aden, the Ethiopian Rift and the Afar triangle. (b) Sketch map of the southwestern part of Yemen showing the main Tertiary magmatic rocks.

from the older YTS. Volcanic cones, domes, sheets and lava flows are the typical occurrences of this series. They are composed mainly of basaltic lavas, stratified basic tuffs and agglomeratic pyroclastics, and less common differentiated rock-types, except the Al-Lisi volcano (5 km E of Dhamar city), which is entirely composed of rhyolitic lava flows.

Published K-Ar ages for the YVS volcanism range from 11.3 to 0.04 Ma ([2] and references therein).

There are eight well-known volcanic fields situated along the Gulf of Aden coast. They are mainly composed of individual volcanoes characterized by central vent eruptions. There are geological, chronological and geochemical differences between those outcropping West- and East-of Aden [4]. The former (West-of-Aden) are older (10 - 5 Ma), include the Island of Perim, Jabal Kharaz, Jabal Al-Birkah, Ras Imran, Little Aden, and Aden, and are stratoid volcanoes characterized by transitional-mildly alkaline basalt to peralkaline rhyolite. The latter (East-of-Aden) are younger (5 - 0 Ma); include Shuqrah (Al Urkoob-Ahwar), Bir Ali, Ataq, as well as smaller basaltic fields in Hadramawt and Al-Mahrah in the farther east (Qusaier, Er-Raidah, Musayna'h-Hadhathem, Hesay-Thamnoon, and the southern part of Wadi Al-Masilah), and the inland volcanic fields (Marib, Amran, Dhamar). They are low cones (basalts and basic pyroclastics), mostly characterized by an alkaline affinity.

3. Geochemistry of the Yemen Flood Volcanism

The following sections present a review of geochemical and isotope data of the Oligocene-Recent volcanic rocks from Yemen [2,3,6-19], along with their age equiva- lent from Saudi Arabia and Ethiopia [20-23].

The chemical characterization of the Yemen flood volcanism is illustrated in the total alkali versus silica (TAS) diagram of **Figure 2**. The volcanic rocks from northern YTS (**Figure 2(a)**) range in silica from 40% to 75%, witha marked bimodal distribution (SiO_2 < 50% or >60%) and alkaline character in the mafic part of the sequence. The southern YTS (**Figure 2(b)**) have only mafic lithotypes with the same SiO_2 range of mafic northern YTS, but tend to be lower in alkalies and their rock types are mainly transitional olivine basalt.

The East-of-Aden YVS (**Figure 2(a)**) have only mafic lithotypes with alkaline connotation comparable to the mafic northern YTS, whereas the West-of-Aden YVS (**Figure 2(b)**), show instead a continuous variation of silica from basalt to rhyolite, and have transitional character comparable to the southern YTS.

On the basis of several tectonic discrimination diagrams, not shown, the YTS and YVS basalts have within continental plate (WPB) character.

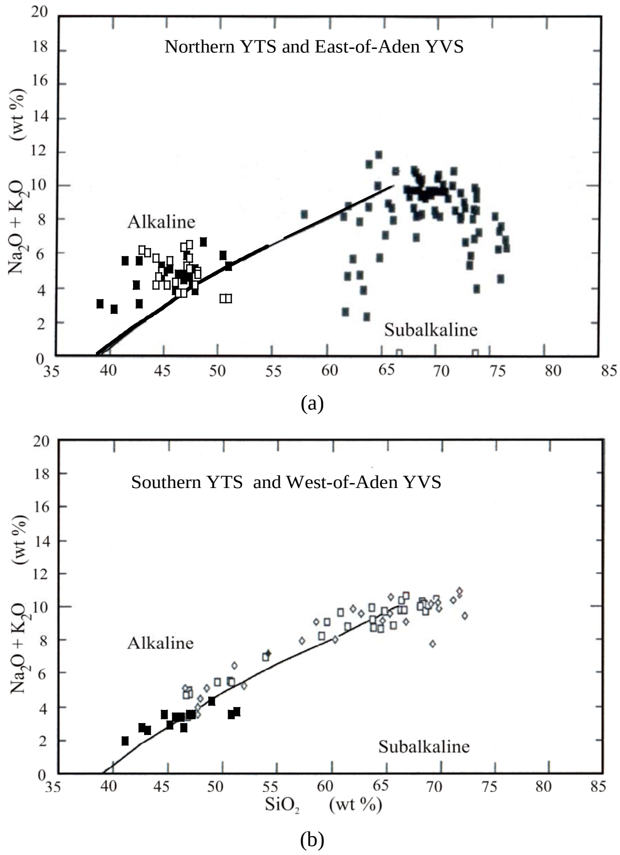


Figure 2. Total alkalis vs. silica diagram showing (a) the Northern YTS (closed squares) along with the East-of Aden YVS (open squares). (b) the Southern YTS (closed squares) along with the West-of-Aden YVS (open squares = Aden; open diamonds = Little Aden).

Binary diagrams of major elements versus MgO are reported in **Figure 3**. Despite the considerable scatter for most elements, the YTS and YVS have similar ranges of MgO, CaO and P_2O_5, even if YVS tend to have, on average, higher MgO contents (7.0% vs. 6.6, respectively). Al_2O_3, Na_2O and K_2O are higher, and TiO_2 lower, in the YVS than in the YTS. There is similarity in major element contents and distributions between the YTS and their age equivalent series in Ethiopia, and between the YVS and their age equivalent alkaline basalts in Saudi Arabia. Indeed, the Ethiopian basalts mainly overlap to the YTS, with rough positive correlation of CaO and rough negative correlations of Na_2O, K_2O, and P_2O_5 versus MgO. And the Saudi Arabian basalts tend to trace the YVS distributions, with rough positive correlation of CaO, rough negative correlation of Na_2O, and bell shaped patterns of K_2O, and Al_2O_3, versus MgO. The marked variation in MgO suggests olivine fractionation throughout the sequences.

Fractionating ol + plag could generate the decline in CaO observed with decreasing MgO, but this is inconsistent with the lack of decrease in Al_2O_3 observed with

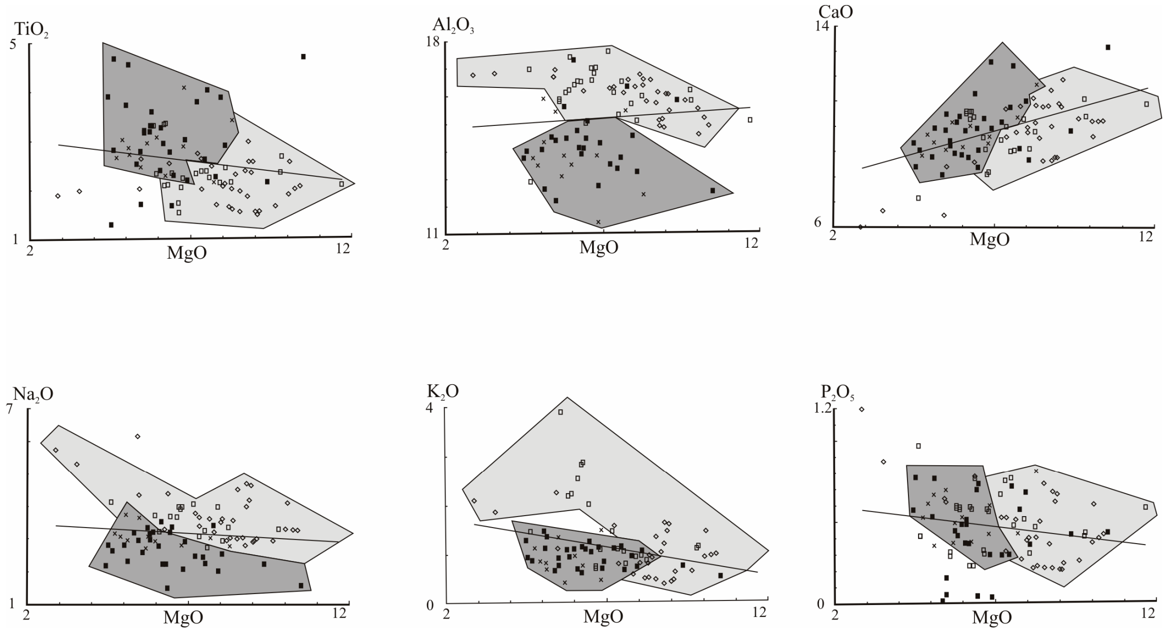


Figure 3. Major oxides versus MgO for YTS (closed squares) and YVS (open). The fields of Ethiopian (dark grey) and Saudi Arabian (light grey) basalts are shown for comparison.

decreasing MgO in most but the evolved samples. Thus, this decrease in CaO also requires significant clinopyroxene fractionation. In summary, differentiation trends indicate crystallization of ol + cpx throughout the fractionation sequence, with plagioclase also a significant fractionating phase only in the most evolved part of the series (MgO < 6 - 7 wt%).These conclusions agree with quantitative fractionation modelling [e.g. 12].

The West-of-Aden YVS, which show a continuous variation of lithotypes from basalt to rhyolite, were considered separatelyin the major elements vs. Differentiation Index plots of **Figure 4**. The samples show well-defined negative correlations of TiO_2, MgO, CaO, and FeO, and a tight positive correlation of alkalies, with DI. These variations, taken together, point to olivine + clinopyroxene fractionation.

Trace element normalized concentrations of two representative primitive basalts from YTS and YVS were reported in **Figure 5**. The YTS are enriched with respect to normalizing primitive mantle, with increase of Large Ion Lithophile Elements (LILE) over High Field-Strength Elements (HFSE), and pronounced negative spikes of K and Pb. The pattern of the YVS is similar to that of YTS, but with even higher LILE/HFSE.

4. Discussion

The Cenozoic Yemen volcanic rocks are rift-related, and their formation and evolution is the result of syn- and post-rift phases of the formation and development of the Gulf of Aden and the Red Sea. Magmas of the YTS were erupted during the syn-rift phase and correlate with the

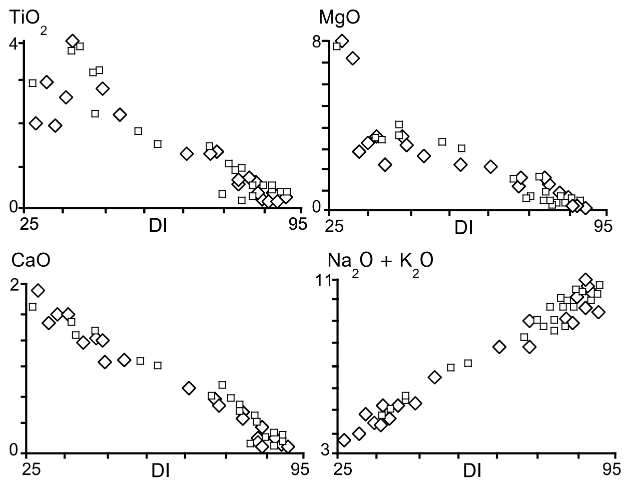


Figure 4. Major oxides versus DI (Differentiation Index) for the West-of-Aden YVS, which show a continuous variation of lithotypes from basalt to rhyolite. Open squares = Aden; open diamonds = Little Aden. DI is the normative weight ratio: (Qz + Or + Ab + Ne)/Total).

first stage of sea-floor spreading of the Red Sea and the Gulf of Aden (30 - 15 Ma), whereas magmas of the YVS were ascended during the post-rift phase (10 - 0 Ma). These differences in tectonic settings are reflected in analogue differences in geochemical characterization of the two rock series. YTS are bimodal, less alkaline, less enriched in incompatible elements and LREEs with respect to the YVS. The most primitive magma types in the YTS are transitional to alkali olivine basalts, in the YVS only alkali olivine basalt.

The geodynamic setting influences the magma-gen-

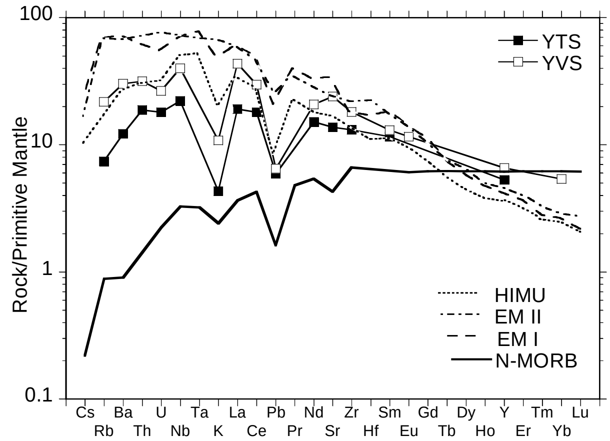


Figure 5. Spider diagrams displaying the normalized concentrations of trace elements ordered by increasing compatibility. Normalizing values after [24]. A representative pattern for MORB [24], and examples of HIMU (St. Helena, [25]), EM I (Tristan da Cunha, [25]), and EM II (Society Islands, [26]), are also reported for comparison.

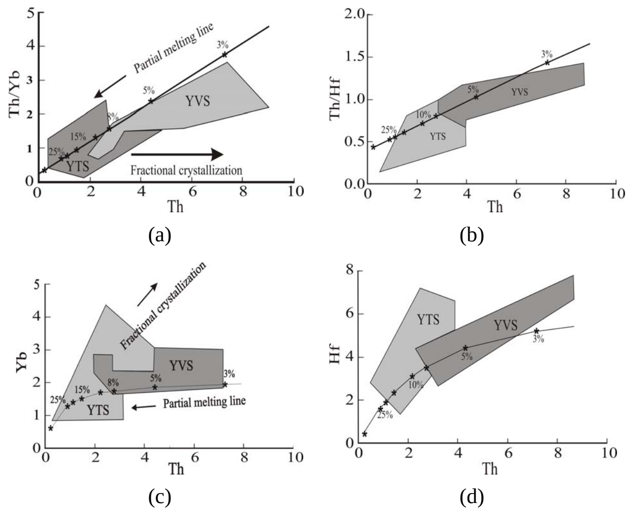


Figure 6. (a) Th/Yb versus Th; (b) Th/Hf versus Th; (c) Yb versus Th; (d) Hf versusTh reporting the fields of YTS and YVS mafic rocks, along with the result of calculations made with equilibrium partial melting model, starting from an astenospheric mantle composition. Numbers marked by asterisks along the solid lines are the degrees of partial melting.

eration process in the rift zones. In high-volcanicity rifts, the rates of crustal extension are higher, corresponding to higher degrees of lithospheric attenuation and hence more asthenospheric penetration into the lithosphere [27]. In this context, mafic magmas are derived by partial melting of asthenospheric mantle ascending beneath the rift axis, and possibly mixed with partial melts from the lithospheric mantle during their rise to the surface. The greater is the crustal extension rates and mantle upwelling, the higher are the partial melting degrees of the asthenosphere. Regarding the Yemen volcanism, major element geochemistry denoted the effects of fractional crystallization processes. In order to clarify the relative role of partial melting and fractional crystallization, trace element discrimination diagrams, availing the different behaviour of moderately and strongly incompatible elements, were used (**Figure 6**). The ratios of highly to mildly incompatible elements (Th/Yb and Th/Hf in **Figures 6(a)** and **(b)**) remain approximately constant during closed system fractional crystallization, whereas they decrease for increasing melting degrees. The distribution of the Yemen volcanic rocks suggests that YTS can be the result of higher degrees of partial melting of the mantle source with respect to YVS. This is confirmed by calculations made with equilibrium partial melting model [28], starting from an astenospheric mantle composition [29-32], which indicate 25% - 30% of partial melting for YTS and 10% - 3% for YVS (**Figure 6**). However, departure of the YTS trend from the partial melting trend (**Figures 6(c)** and **(d)**) corroborates a consistent role of fractional crystallization in the more differentiated part of YTS.

As regards the nature of the mantle source, previous studies identified several distinct mantle domains contributing to magma genesis in the AARS. To first order, these components include a mantle plume, broadly thought to consist of 1) an HIMU (High m) [e.g. 33] or FOZO (Focus Zone) [e.g. 15] component; 2) a depleted mantle reservoir, interpreted as the source region for N-MORB, and 3) one or two *enriched* (EMI = Enriched Mantle I - EMII = Enriched Mantle II) mantle components [15,33 among others]. In the spider diagrams of **Figure 5**, progressively higher contents of alkalies, incompatible elements and LREEsare evident passing from YTS to YVS. This could agree with alarger contribution of *enriched* mantle components in the source of the YVS with respect to the YTS.

Published Sr, Nd, Pb, and O isotope studies pointed out that part of the YTS and YVS underwent assimilation of heterogeneous Pan-African crust. This is consistent with the high heat flow that characterizes active rift zones, where elevated crustal temperatures give rise to the generation of acidic magmas by crustal melting, or mixing of crustal and mantle partial melts. On this basis, higher degrees of crustal contamination could be hypothesized as the agent of the enrichment in incompatible elements and LREEs of YVS with respect to YTS. To ascertain this hypothesis, the $(La/Sm)_N$ versus Ba/Nb patterns of the YTS and YVS, along with the Red Sea MORB, and the main mantle and crustal components, were reported in the plot of **Figure 7**. To minimize the effects of fractional crystallization, only samples with MgO > 7% were considered. It can be seen that crustal rocks have much higher Ba/Nb than all mantle components, whilst have $(La/Sm)_N$ higher than those of N-MORB, but similar to

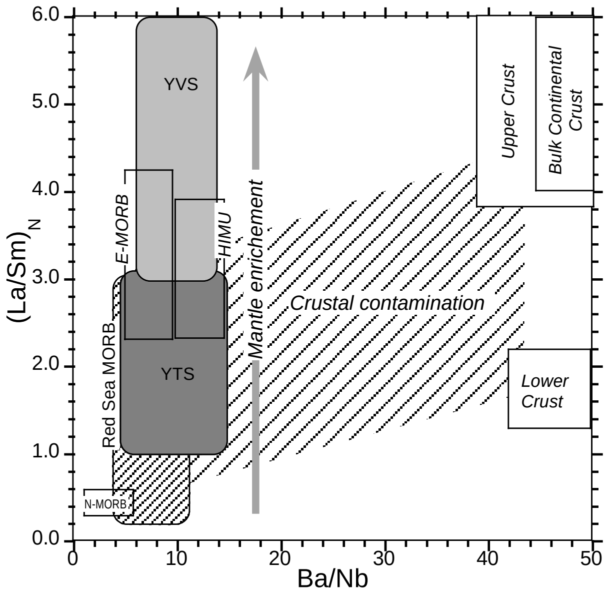


Figure 7. $(La/Sm)_N$ versus Ba/Nb plot reporting: YTS and YVS, Red Sea MORB [2 and references therein], N-MORB [24], E-MORB and HIMU [25,34], Upper Crust, Lower Crust, Bulk Continental Crust [35].

those of mantle sources like E-MORB or HIMU. Thus crustal contamination paths should afford a simultaneous increase of both Ba/Nb and $(La/Sm)_N$ (**Figure 7**). The ranges of Ba/Nb of basalts from both YTS and YVS show instead restricted variations, comprised in the range of mantle values, and do not show the increases expected for crustal contamination. As regards to the $(La/Sm)_N$, it is interesting to note that YTS are similar to the Red Sea MORB, and are displaced towards *enriched* components with respect to N-MORB. The YVS are still more *enriched* than YTS, and their $(La/Sm)_N$ encompass those of E-MORB, but without a concomitant increase of Ba/Nb, denoting a process of source enrichment rather than magma contamination.

Schilling [33] suggested, on the basis of combined Nd-Sr-Pb isotopes, that the Afar mantle plume material may consist mainly of HIMU component and explained the isotope variations of the Cenozoic basalts from the Gulf of Aden by three components mixing including Afar plume material (HIMU), depleted mantle (DM) and an hybrid *enriched* mantle (EM I-EMII). However, the typical HIMU signatures are not found in the Cenozoic Yemen volcanics [15]. Indeed, in the $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ plot (**Figure 8**), the Yemen flood volcanic rocks appear to plot within the mixing area of three components: Depleted mantle, Enriched Lithospheric Mantle (ELM, as defined by [15]), and C, an intermediate component between DM and HIMU. Although assimilation of heterogeneous crust has the major control on large-scale isotope variability, the least contaminated samples of the Yemen flood volcanics have radiogenic isotope ratios

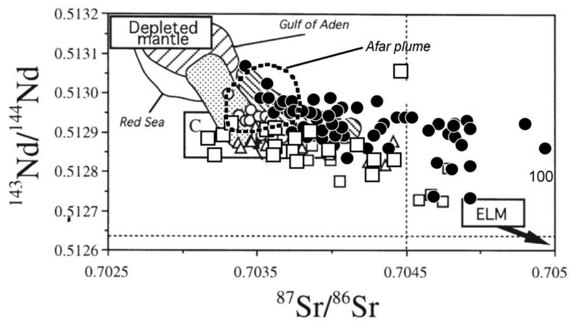


Figure 8. $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ plot reporting YTS (closed symbols) and YVS (open symbols). Shaded areas outline data of the Red Sea [36-39], Gulf of Aden, and Afar plume [33,40]. C: Common component defined by [41]. ELM: Enriched Lithospheric Mantle defined by [33].

that approach those inferred for the Afar plume (field circled with dashed line in **Figure 8**).

5. Summary and Conclusions

In summary, the following conclusions can be drawn:

1) The Cenozoic Yemen flood volcanic province can be divided in: Oligo-Miocenic bimodal transitional to alkaline Yemen Trap Series, YTS, and Miocene-Recent alkaline Yemen Volcanic Series, YVS. Magmas of the YTS were erupted during the synrift phase and correlate with the first stage of sea-floor spreading of the Red Sea and the Gulf of Aden (30 - 15 Ma), whereas magmas of the YVS were ascended during the post rift phase, consistent with the sea-floor spreading model (10 - 0 Ma).

2) The YTS are contemporaneous with, and geochemically similar to, the Ethiopian Trap Series, whereas the more alkaline YVS are geochemically similar to the Saudi Arabian volcanics.

3) A continental within plate character is recognized for both the YTS and YVS basalts. The two rock series have similar SiO_2 ranges, but YVS tend to have, on average, higher alkalis and MgO contents than YTS. Fractional crystallization processes dominate geochemical variations of both series.

4) Primitive magmas (MgO > 7.0%) from both series are enriched in incompatible elements and LREEs with respect to primitive mantle, but YVS are more enriched than YTS. To first order, the different geochemical patterns agree with different degrees of partial melting of the mantle source: 25% - 30% of partial melting for YTS and 10% - 3% for YVS. Secondly, the higher degrees of enrichment in incompatible elements of YVS reflect also a greater contribution of an *enriched* component (E-MORB) to the mantle source.

5) The large-scale Sr-Nd-Pb-O isotope variability of the Cenozoic Yemen flood volcanism is mostly accounted by crustal contamination. However, the least contaminated samples have radiogenic isotope ratios that ap-

proach those inferred for the Afar mantle plume.

6. Acknowledgements

We are deeply indebted to Gianluca Bianchini and an anonymous referee for their useful and invaluable suggestions. Particular thanks are due to Gyorgy Buda, University of Budapest, Hungary for providing all the possibilities to make this work successful. We also acknowledge Professors of the University of Idaho, USA, for their continuous help and cooperation.

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