Dead Sea Region: Fault - Controlled Chemistry of Cenozoic Volcanics

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ABSTRACT. The 800 km long geosuture of the Dead Sea, particularly active in the Cenozoic time and representing the northernmost promontory of the Afro-Arabian rift system, shows intimate relations between tectonic and volcanic activities. The N–S striking rift was accompanied here not only by substantial horizontal sinistral displacement but also by sinistral fan-like rotation of Arabian plate opening ways for the ascent of magmas. In Jordan, these magmas fluctuate within the range of basaltic rocks only, including mostly alkali olivine basalts, basanites and less frequently olivine nephelinites. Nevertheless, systematic changes in the bulk rock chemistry with the position relative to the rift graben are obvious. The volcanics can be subdivided into within-rift, rift-proximal and rift-distal groups according to their distance from the rift. The amount of volcanic products rapidly increase with this distance. Alkalinity of the three volcanic groups decreases successively to the rift-distal group, the products become more acid, richer in Al_2O_3 and CaO and poorer in TiO_2 P_2O_5, FeO_{tot} and MgO and depleted in LREE. This reflects different depth reached by volcanic feeders and different grades of partial melting in the source area.

KEY WORDS: Cenozoic volcanics, basaltic rocks, Dead Sea, rift, Jordan.

Introduction

Two geologic features of the Dead Sea region are of special attractiveness: the large-scale faulting and the Cenozoic volcanism. These two conspicuous phenomena were treated by many authors, namely by Quennell (1956), Freud (1965), Bender (1968, 1975), Barberi et al. (1979), Ibrahim (1987, 1991), Guba and Mustafa (1988), Mattas and Bilik (1992) etc. All authors came to the conclusion that both phenomena are interrelated. Nevertheless, a closer concrete specification of these interrelationships still calls for publication of more data. The aim of the present paper is to bring new data on the chemistry of Cenozoic volcanics and to test to what extent was their composition affected by individual fault systems. This study was concentrated on the territory of the Hashemite Kingdom of Jordan with its closest neighbourhood.

Tectonic setting

The fault tectonics of the region includes three systems which, although genetically interrelated, substantially differ in their style, strike and depth reach. The first, most prominent category is represented by the Dead Sea Rift as the northernmost promontory of the World's mightiest continental geosuture – the 6,000 km long Afro-Arabian Rift System. This normal fault begins in the Aquaba Gulf in the south and ends on the Bitlis–Zagros Geosuture in eastern Turkey in the north. Its course, as stressed by Freud (1965), is neither straight nor arcuate, but bends sharply several times. It consists of four segments of which the Jordanian segment between the Dead Sea and Lake Tiberias, characterized by almost ideal S–N direction, is the one which the paper deals with. The rift here is markedly asymmetric not only from morphological point of view but also in the different thicknesses of the crust: this is thinner and partly oceanic in the W, thicker and entirely continental in the E. Cenozoic volcanics occur almost exclusively in the eastern flank. The second system of transform faults is a secondary product of the 60–100 km long sinistral strike-slip displacement along the Dead Sea Rift which produced a set of comparatively short W–E-striking fault-cracks in the eastern block. The origin of the third fault system, consisting of long, fan-like arranged diagonal cracks, is associated with the counterclockwise rotation (25° in total) of the whole Arabian Plate with the axis in the Aegean Sea.

The faulting started in the Upper Cretaceous (Freud 1965, for broader regional context see Garson and Krs 1976), culminated in several phases within the Tertiary and continued in the Quaternary with some manifestation even in historical time (Bowman 1995). As shown below, the timing of this activity overlaps in general with the volcanic activity.

Distribution of volcanics

Cenozoic volcanics of the Jordanian rift sector and its hinterland (with relevant Syrian and Saudi Arabian extensions), practically absent in the W-flank of the Rift, represent the northern sector of the North-Arabian volcanic province. They can be subdivided (Ibrahim 1987; Fediuk 1989) into three groups according to their distance from the Rift: within-rift, rift-proximal and rift-distal. In contrast to Ibrahim (1987), we restrict the within-rift category to occurrences situated strictly inside the graben. The three categories are present in distinctly unequal quantities as it is obvious from Fig. 1 and Table 1.

From tectonic point of view, the above mentioned three volcanic categories are associated with individual three fault systems defined in the preceding chapter as follows: within-rift volcanics with the main constrained normal rift fault (first fault system or the Dead Sea Rift proper), rift-proximal volcanics with the second strike-slip fault system and rift-distal volcanics with the third, rotational fault system.

	area km^2	output km^3	average rate km^3/m.y.
Within-rift basalts	2	0.10	0.007
Rift-proximal basalts	110	5.50	0.300
Rift-distal basalts	32,000	5,600.00	29.500

Tab. 1. Main quantitative parameters of three Cenozoic volcanic goups of Jordan.

Petrography

Volcanic rocks of all three groups are composed exclusively of basaltoids, while intermediate or acid rocks – in contrast with the situation in Saudi Arabia – are totally absent. Their mineralogy, as shown also by Van den Boom and Sawan (1966), Mattash and Bilik (1992), Ševčík and Hron (1997) etc., is quite simple, with 40 to 60 vol.% of plagioclase mostly of labradorite composition, quantitatively followed by 20 to 30% of augite to aegirine-augite and up to 10% of Ti-magnetite. Olivine (Fo_{82-74}) often exceeds 10% and is missing in few cases only. Nepheline, if present, is the sole feldspathoid occurring in basaltic rock of this region. It is more frequent in within-rift and rift-proximal basalts but rare or rather absent in rift-distal basalts, also called flood- or plateau-basalts. Volcanic glass can be currently found in small bodies or in peripheral parts of larger ones. Apatite is a common accessory present in higher quantities in within-rift and rift-proximal basalts. Iddingsite, calcite and/or zeolites occur as secondary minerals. Petrographic classification of these basaltic rock is discussed below in chapter Rock chemistry. Numerous localities with mantle-derived xenoliths (Fakhoury 1991, also containing older references) are known from rift-proximal as well as rift-distal basalts.

Volcanology, lithostratigraphy, age

More than 99 vol.% of Cenozoic volcanics of the area belong to the rift-distal basalts. They form a vast, continuous lava field with numerous volcanic cones, called Harrat ash Shaam, covering 32,000 km^2, approximately one-third of which is located in Jordan. The complex originated mainly by fissure eruptions. It is rather thin, 150 to 200 m on the average, with the maximum thickness reached by a borehole being 470 m (Ševčík and Hron 1997). Already Bender (1965) established a sequence of six lava flows here. Jordanian geologists, during their systematic detailed mapping 1 : 50,000 by Ibrahim (1993, 1996), Nawasreh (1994) and Tarawneh (1998), elaborated a morpholithostratigraphic scheme designating the whole volcanic complex of NE-Jordan as the Harrat ash Shaam Super-Group. They divided it into 6 volcanic Groups comprising 13 volcanic Formations (Tab. 2). Radiometric dating by Barberi et al. (1979) indicated the span 18.7 to 0.5 Ma but even less than 0.1 Ma is sometimes considered as the lower limit.

Rift-proximal basalts, confined mainly to Central Jordan (Saffarini et al. 1985, Ibrahim 1987), are – from volcanological point of view – more diversified in comparison with rift-distal basalts. They form mostly small individualized bodies: cones,

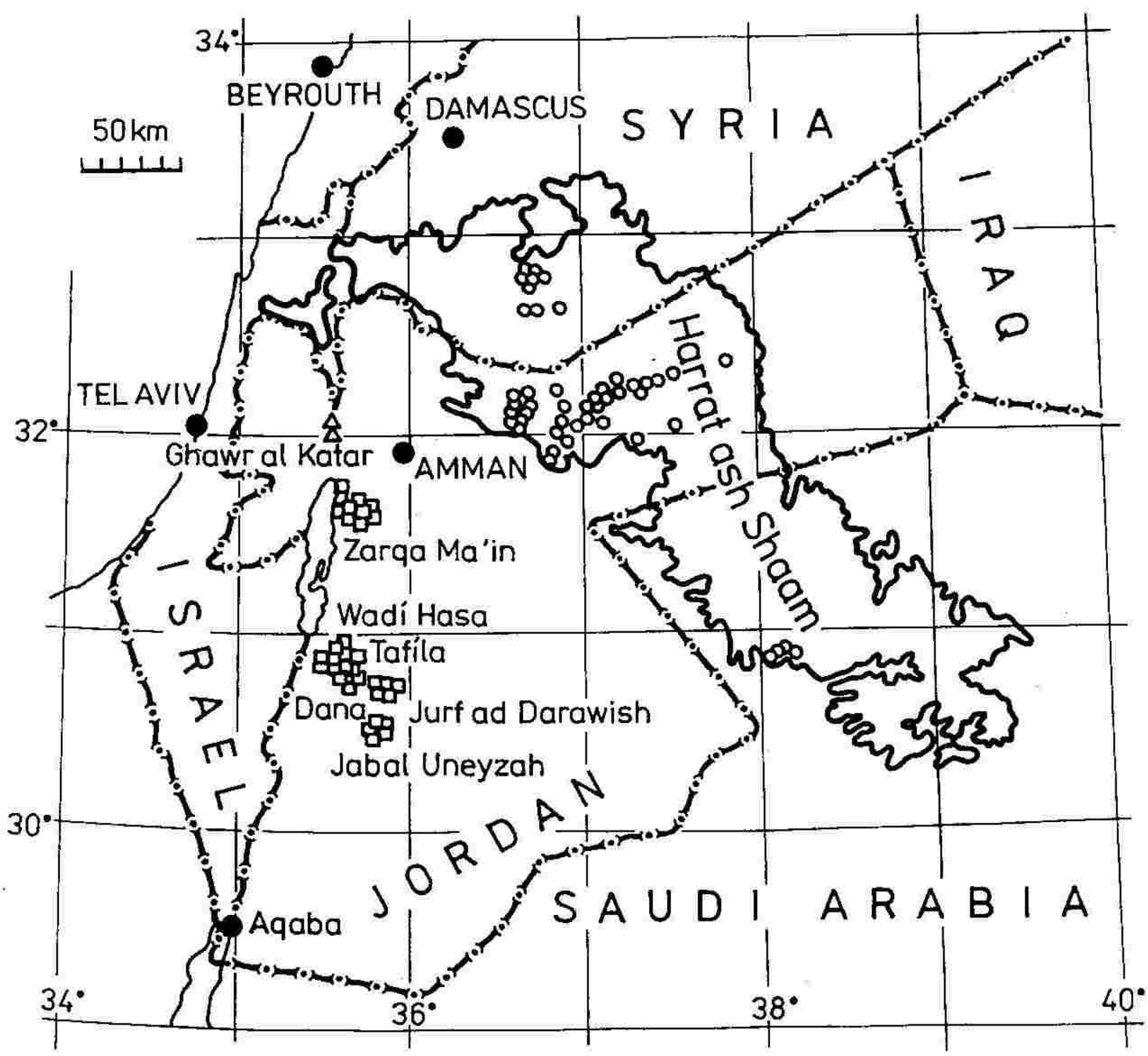

Fig. 1. Map of localities of analysed Cenozoic volcanics in the Dead Sea area. Triangles – within-rift basalts (n = 2), squares – rift-proximal basalts (n = 33), circles – rift-distal basalts (n = 48), relevant full symbols – average values.

HARRAT ASH SHAAM SUPER-GROUP (HSB)

Group	Age Ma	Formation	Thickness m
BISHRIYYA (BY)	0.5 - 1.45 (< 0.1 ?)	Fahda vesicular basalt (FA)	< 15
		Wadi Manasif basalt (WMF)	< 15
RIMAH (RH)	2.01 - 2.04	Aritayn volcaniclastic (AT)	10 - 150
		Hassan scoriaceous (HN)	15 - 40
ASFAR (A)	1.96 - 3.41	Mahadda basalt (M)	10 - 25
		Madhala olivine phyric basalt (MOB)	10 - 100
		Hashimyya aphanitic basalt (HAB)	> 10
		Ushaybib olivine-pyroxene phyric basalt (UB)	< 15
		Ufayhim xenolithic basalt (UM)	15 - 25
SAFAWI (SW)	8.45 - 9.3	Salaman flood basalt (SN)	10 - 50
		Abed olivine phyric basalt (AOB)	< 100
		Ali doleritic trachybasalt (AI)	10 - 30
QIRMA calcareous sandstone (QCS)			
WISAD (WD)	9.37 - 10.53		?

Tab. 2. Field lithostratigraphy of Jordanian flood basalts (Ibrahim 1993).

lava coulées, plugs, sills and dykes while large lava flows are absent. Within-rift basalts, as stressed already by Freud (1965), are surprisingly rare inside the Graben which can be attributed to the compressional regime of the normal rift faulting. They occur mainly in small subvolcanic bodies (necks, plugs). As to the age of both basalt categories, no data contradict the presumption that they are generally contemporaneous with rift-distal basalts (see above).

Methods

Several hundred of chemical bulk analyses of Cenozoic volcanics of the studied area are now available. Unfortunately many of them are incomplete, especially the Fe-oxidation stage and P_2O_5 or MnO determinations are often missing. Some other analyses are note reliable. Trace element and isotope data are still scarce. Nevertheless, the interpretation possibilities of the existing analyses do not seem to be fully exhausted yet.

The present paper makes use mainly of common major element data. 83 chemical analyses were chosen for this purpose: 26 unpublished archival data of one of the present authors (HAF), completed by new FeO and P_2O_5 determinations by the other (FF), 36 analyses kindly provided by Czech geologists and extracted from their expert reports (9x Kopecký et al. 1981; 27x Ševčík and Hron 1987) and 21 analyses adopted from published papers (10x Bender 1965; 7x Tarawneh 1996 and 4x Brown et al. 1989). Plots of all 83 analyses are used in the figures, however, only averaged data for individual groups of volcanics are referred to in Table 3 due to lack of space. The complete set of analyses is available upon request. Representative samples of three main groups of volcanics were analysed for REE.

Rock chemistry

Five diagrams (Fig. 2 to 6) illustrate the chemical character of three main groups of Cenozoic Dead Sea region basalts. Almost 98% of analysed samples plot above the dividing line into the alkaline field but the alkalinity of rift-distal basalts is rather low.

According to the TAS diagram of Le Maitre et al. (Fig. 2), 72% of rift-distal basalts can be classified as basalt, 15% as basanite–tephrite, 6% as picrobasalt, 6% as trachybasalt and one sample as transitional between trachybasalts and basaltic trachyandesites. The situation of rift-proximal basalts is as fol-

	Aa	Ab	A∅	Ba	Bb	Bc	Bd	Be	Bf	B∅	Ca	Cb	Cc	C∅	∅A+B+C
SiO_2	41.35	41.86	41.61	43.11	41.01	40.64	42.63	41.90	41.60	41.93	45.87	46.22	47.88	46.66	44.22
TiO_2	3.27	2.92	3.10	2.72	3.04	3.55	2.86	3.17	2.97	3.06	2.05	2.63	1.75	2.14	2.52
Al_2O_3	12.28	13.07	12.68	13.38	12.03	11.95	13.96	13.31	13.24	12.97	14.74	14.80	14.50	14.68	13.98
Fe_2O_3	6.20	5.87	6.04	3.96	6.39	5.32	5.98	5.19	5.02	4.97	4.54	4.60	4.18	4.44	4.74
FeO	9.12	9.31	9.22	8.71	6.25	8.61	9.13	7.88	8.13	8.43	6.92	7.61	6.88	7.14	7.65
MnO	0.27	0.24	0.26	0.17	0.16	0.18	0.18	0.16	0.17	0.17	0.18	0.17	0.12	0.16	0.17
MgO	8.69	8.21	8.45	11.05	10.19	12.21	7.72	8.38	9.86	10.39	8.06	8.42	8.02	8.17	9.03
CaO	10.02	9.34	9.68	8.35	11.46	8.48	10.03	10.95	10.95	9.51	10.90	9.87	11.13	10.63	10.22
Na_2O	4.21	4.35	4.28	4.10	4.00	4.50	3.38	3.98	3.52	4.06	3.06	3.60	3.79	3.48	3.58
K_2O	1.28	1.24	1.26	1.53	1.46	1.26	0.91	1.05	1.03	1.26	0.93	0.90	0.80	0.88	1.06
H_2O^+	1.90	1.43	1.67	1.50	1.61	2.09	1.55	2.22	2.19	1.87	1.34	0.52	1.15	1.00	1.46
P_2O_5	1.46	1.42	1.44	1.64	1.47	1.07	0.78	1.20	1.00	1.10	0.49	0.50	0.21	0.40	0.74
Σ	100.05	99.26	99.69	100.22	99.07	99.86	99.11	99.39	99.68	99.72	99.08	98.84	100.41	99.78	99.37

Tab. 3. Chemical analyses of Cenozoic basalts of Jordan and adjacent areas.
Aa – within-rift basalt, Ghawr al Katar N, n = 1 (Al Fugha unpubl. 1x); Ab – within-rift basalt, Gharw al Katar S, n = 1 (Al Fugha unpubl. 1x); A∅ – average of Aa+Ab, n = 2; Ba – rift-proximal basalts, Zarqa Ma'in, n =10 (Ševčík and Hron 1997 2x; Al Fugha unpubl. 8x); Bb – rift-proximal basalts, Wadi Hasa, n = 2 (Ševčík and Hron 1997 2x); Bc – rift-proximal basalts, Tafila, n = 8 (Ševčík and Hron 1x; Al Fugha unpubl. 7x); Bd – rift-proximal , Wadi Dana, n = 3 (Al Fugha unpubl. 3x); Be – rift-proximal, Jurf ad Darawish, n = 5 (Ševčík and Hron 1997 2x; Al Fugha unpubl. 3x); Bf – rift proximal, Jabal Uneyzah, n = 5 (Ševčík and Hron 1997 2x; Al Fugha unpubl. 3x); B∅ – average of Ba+Bb+Bc+Bd+Be+Bf, n = 33; Ca – rift-distal basalts of NE Jordan, n = 35 (Bender 1968 10x; Tarawneh 1996 7x; Ševčík and Hron 1997 18x); Cb – rift-distal basalts of S Syria, n = 9 (Kopecký et al. 1981 9x); Cc – rift-distal basalts of N Saudi Arabia, n = 4 (Brown et al. 1989 4x); C∅ – average of Ca+Cb+Cc, n = 48; ∅A+B+C, n = 83.

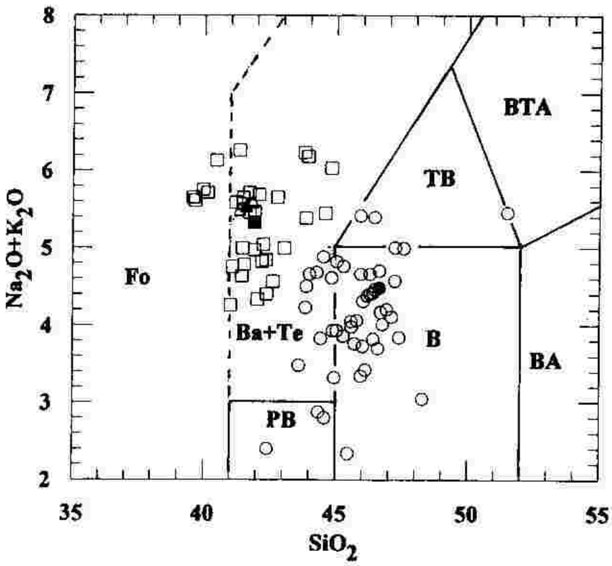

Fig. 2. Plots of 83 basalts from the Dead Sea region in the TAS diagram. Fields: Fo – foidite; Ba+Te – basanite + tephrite; PB – picrobasalt; B – basalt; TB – trachybasalt; BTA – basaltic trachyandesite; BA – basaltic andesite. Symbols as in Fig. 1.

	A within-rift	B rift-proximal	C rift-distal
La	47.90	41.50	27.60
Ce	82.40	74.20	50.90
Pr	10.50	9.30	6.00
Nd	31.20	28.90	20.60
Sm	6.64	6.42	4.36
Eu	2.06	1.93	1.72
Gd	5.28	4.97	3.97
Tb	0.64	0.58	0.40
Dy	3.08	2.97	2.39
Ho	0.49	0.50	0.42
Er	1.49	1.45	1.22
Tm	0.16	0.17	0.19
Yb	1.19	1.20	1.23
Lu	0.19	0.18	0.21
Σ REE	193.30	174.30	121.20
La/Yb	40.28	34.57	22.45
Eu/Eu*	1.01	1.05	1.26

Tab. 4. REE data of representative samples of three Cenozoic volcanic categories of Jordan.
A – within-rift basalt (olivine nephelinite), Ghawr al Katar, NW Jordan; B – rift-proximal basalt (nepheline basanite), Tafila, Central Jordan; C – rift-distal basalt (alkali olivine basalt), Jabal ar Rutayn, NE Jordan. ICP-MS analyses by Analytika Prague.

lows: one sample plots in the basalt field, far most samples correspond to basanite–tephrite, 18% to foidite. Within-rift basalt plots near the boundary of basanite – foidite fields. In the binary Al_2O_3 vs. SiO_2 diagram (Fig. 3), the cluster of rift-distal basalts overlaps to a limited degree only with the cluster of rift-proximal and within-rift basalts. Distal basalts are not only more acid but also richer in aluminium. The regression line for the whole set of plots in Fig. 3 is distinctly positive. Analogous pictures can be shown for CaO vs. SiO_2, which indicates a higher plagioclase fractionation in distal basalts. An opposite situation (Fig. 4) with a negative slope of regression line holds for the MgO vs. silica relation (as well as for K_2O or Na_2O vs. SiO_2). Within-rift and rift-proximal basalts are characterized by a higher MgO- (as well as alkalis-) and lower SiO_2 contents. A very sensitive discriminant is the TiO_2 vs. P_2O_5 relation (Fig. 5): the increase in both components in the series from distal across proximal to within-rift basalts is distinct. All analysed samples are olivine-normative, very often also nepheline-normative. The amount of both normative minerals increases towards distal and especially towards within-rift basalts.

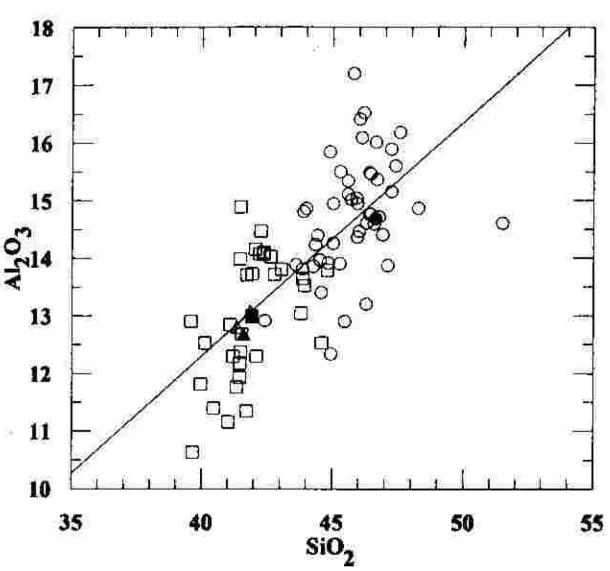

Fig. 3. Al_2O_3 vs. SiO_2 diagram with 83 plots of the Dead Sea region basalts and the regression line for the whole set of samples. Symbols as in Fig. 1.

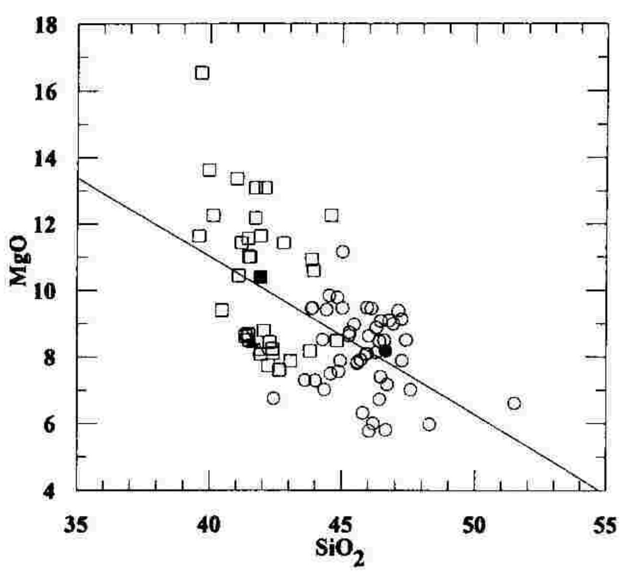

Fig. 4. MgO vs. SiO_2 diagram with 83 plots of the Dead Sea region basalts and the regression line for the whole set of samples. Symbols as in Fig. 1.

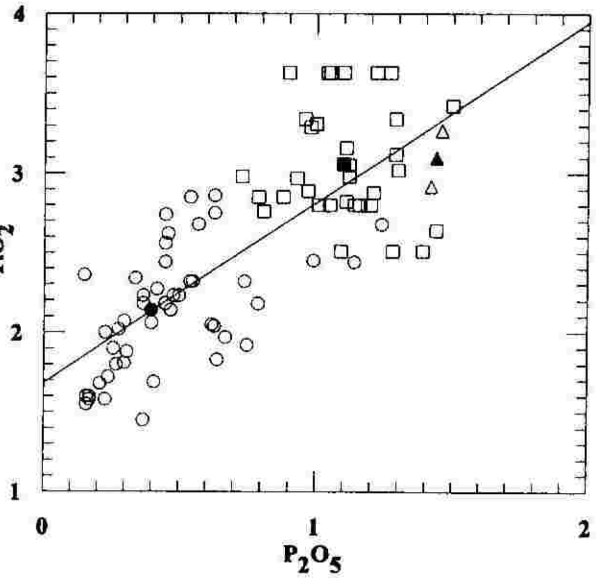

Fig. 5. TiO_2 vs. P_2O_5 diagram with 83 plots of the Dead Sea region basalts. Symbols as in Fig. 1.

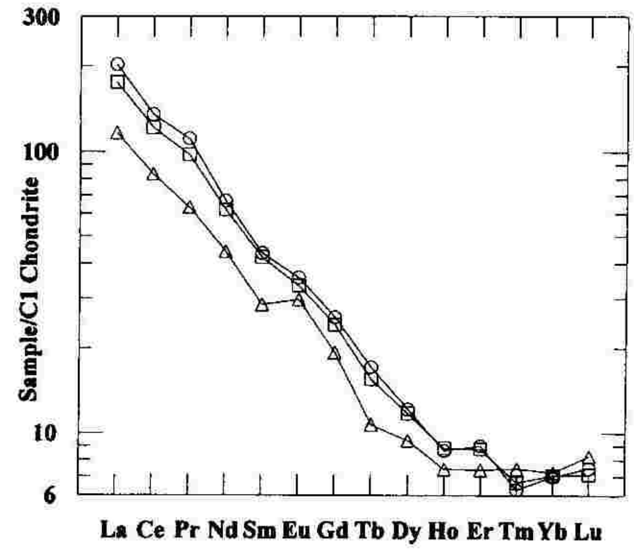

Fig. 6. Three representative C1 chondrite-normalized (Sun and McDonough 1989) REE patterns of the Dead Sea region basalts. For localities see Table 3, symbols as in Fig. 1.

Three representative samples, one rift-distal, one rift-proximal and one within-rift basalt, were analysed for REE-contents (see Tab. 4). C1 chondrite-normalized REE patterns are shown in Fig. 6. HREE abundance are very similar in all three samples. But as for the LREE contents, the values increase markedly from distal across proximal to within-rift basalts, the difference between the two last ones being rather small (cf. La/Yb ratios in Table 4). The rift-distal basalt shows a pronounced positive Eu-anomaly (1.3), obviously connected with the high plagioclase content. Such anomaly is practically missing from both other basalt samples. The geochemistry of the distal basalts resembles that of the "lateral basalts" of Bord and Bertrand (1995) in Saudi Arabia while proximal and within-rift basalts are similar to "axial basalts".

Conclusions

All the above mentioned data lead to the conception that the basalt chemistry and the distance from the rift are interconnected and that the style of faulting is decisive for the composition of volcanics. Within-rift basalts, which are the most alkaline and the most basic, are confined to the main faulting of the rift proper. Their extremely limited amount should be attributed to compressional regime producing very constrained pathways. Rift-proximal basalts, associated with sinistral strike slip along the eastern flank of the rift are more abundant and are characterized also by comparatively higher alkalinity. Rift-distal basalts, ascending along large-scale ruptures caused by sinistral fan-like rotation of the whole Arabian Plate, are by far the most frequent, their alkalinity is lower, their plagioclase fractionation accentuated and silica content elevated. Although originated at slightly different depth levels, all three categories are consanguineous, representing slightly differentiated products of a far to the north protruded channel of the Afar plume. The threefold series of within-rift, rift-proximal and rift-distal basalts reflects not too advanced stages of generally low partial melting in their chemistry.

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