

The petrogenesis of basic and ultrabasic alkaline rocks of western Makhtesh Ramon, Israel: geochemistry, melt and fluid inclusion study

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Abstract The basic and ultrabasic alkaline rocks of western Makhtesh Ramon, Israel crop out in numerous lava flows and subvolcanic bodies. The rock suite is composed of tephrite, basanite, basanitic nephelinite, analcinite, olivine nephelinite, and melilite-olivine nephelinite and in many outcrops is represented by glass-bearing varieties. Melt and fluid inclusions have been studied in olivine, clinopyroxene, and plagioclase phenocrysts. The EP, SIMS and microthermometry methods were used for inclusion study. The geochemical data obtained on glasses of melt inclusions (major, REE, trace elements, volatiles) are compared with the data on whole-rock and groundmass glass compositions. The compositions of melt inclusions reflect the different stages of rock crystallization: the initial products of crystallization are similar to whole-rock compositions whereas final portions of melts are usually enriched in SiO_2 , Al_2O_3 , and alkalis, and depleted in mafic components. The data on contemporaneous melt and CO_2 inclusions were used for the evaluation of the P – T conditions of rock generation. The following parameters were obtained: tephrite: $P = 6.3$ – 7.7 kbar and $T = 1,150$ – $1,250^\circ\text{C}$; basanite: $P = 6.6$ – 9.2 kbar and $T = 1,150$ – $1,250^\circ\text{C}$; olivine and analcime-olivine nephelinite: $P = 5.6$ – 8.2 kbar and $T = 1,150$ – $1,250^\circ\text{C}$; melilite-olivine nephelinite: 4.0 – 5.4 kbar and T mainly

between $1,150$ and $1,200^\circ\text{C}$. Magma genesis was restricted to P – T conditions of spinel- and plagioclase-lherzolite fields. These data suggest the shallowest depth of magma genesis occurred in Makhtesh Ramon compared to other occurrences of Early Cretaceous magmatism at the Middle East. Differences in the degree of batch partial melting of the same source rocks best explain the diversity of the igneous suite in western Makhtesh Ramon.

Keywords Melt and fluid inclusions · Basic and ultrabasic alkaline rocks · Makhtesh Ramon · Israel

Introduction

The alkali basalt and foid-bearing rocks are silica-undersaturated and rich in incompatible elements. Their genesis is commonly related to the limited partial melting of metasomatised mantle source (Barker 1996). The suggestion is primarily based on partial melting experiments with peridotite which show that the initial melting products are usually silica-undersaturated and enriched in incompatible elements relative to the products of higher degrees of melting. The formation of nephelinite and melilitite magma is further constrained by one or all of the following conditions: (a) a low degree of partial melting; (b) high pressure; (c) high partial pressure of CO_2 .

The basaltic rocks in Makhtesh Ramon are associated with the second event of Mesozoic volcanism identified in Israel. This magmatism corresponds to a Late Jurassic-Early Cretaceous event which is also known in the Middle East in Samaria-Galilee fields in

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Central Israel, and in Jordan, Lebanon, and Syria. Our previous data were mainly reported in domestic reports so the rock suite in Makhtesh Ramon, which shows special compositional features, is poorly known to the international community and is still referred to in the literature as olivine basalts and basanites (Bonen et al. 1980; Stein and Hofmann 1992; Abdel-Rahman 2002). Several scattered occurrences of alkaline rocks in Makhtesh Ramon were reported by Garfunkel and Katz (1967) and Bonen (1980). At present it is evident that this rock suite is composed of assemblages such as melilite-olivine nephelinite, olivine nephelinite, analcinite, basanitic nephelinite, basanite, and tephrite (Eyal et al. 2000, 2003).

The tephrite, basanite, nephelinite, analcinite, and melilite nephelinite rock sequence in western Makhtesh Ramon formed during a relatively short time interval. The rocks were likely generated from the same source and then followed the same path of descent. It seems that the rocks and rock sequence record both fractional melting processes within the mantle and fractional crystallization within the crust. The geochemical investigation of rock samples usually permits one to determine the processes governing the evolution of matter and to characterize geochemical constraints on the source region, whereas the P – T conditions of magma genesis remain basically problematic. This study combines our geological observations and geochemical data on rock samples with the data on melt and fluid inclusions hosted in olivine, clinopyroxene, and plagioclase phenocrysts. The study of melt and fluid inclusions in phenocrysts gives direct information on the compositions of melts at the earliest stages of magma crystallization and enables one to define the P – T conditions of magma genesis and crystallization.

Geological setting

A Jurassic to Cretaceous sedimentary section, about 350 m thick is exposed in Western part of Makhtesh Ramon. The lower part represented by Jurassic Inmar Formation (0–325 m, Goldberg 1970) consists of mainly sandstones with some clay lenses. The upper unit, Mahmal Formation (0–40 m, Katz 1968), consists of sandy dolomites and ferruginous sandstones. The base of the Early Cretaceous rests on major unconformity in the region. The Early Cretaceous sequence begins with the Arod Conglomerate (0–30 m), composed of mainly quartzite pebbles with some trachyte pebbles and cobbles, and is overlapped by the Hatira Formation (Shilo and Nevo 1955). The Hatira For-

mation is divided into three members: The Lower Sandstones (5–40 m), the volcanic section (0–215 m), and the Upper Sandstones (80–120 m). The uppermost part of the section forming the cliffs of Makhtesh Ramon consists of Cenomanian carbonates of the Hazera Formation.

The volcanic rocks in Makhtesh Ramon were re-exposed by erosion during the Neogene incision of Makhtesh Ramon (Avni 1993). The western part of Makhtesh Ramon is composed of the Early Cretaceous magmatic rocks (Lang and Steinitz 1989). The intra-continental alkaline magmatism in the western part of Makhtesh Ramon led to the formation of an alkaline rock suite (Eyal et al. 2000, 2003) including both plagioclase-bearing alkaline rocks (tephrite, basanite and basanitic nephelinite) and plagioclase-free alkaline rocks (olivine nephelinite, analcinite, and melilite-olivine nephelinite). These alkaline rocks comprise lava flows, volcanic structures and numerous subvolcanic intrusive bodies (Eyal et al. 2000, 2003).

Although the area is relatively small, it includes different types and excellent exposures of lava flows, pyroclastic rocks, eruption centers and intrusive bodies. Columnar jointing is characteristic for lava flows and subvolcanic intrusions. The main lava outcrops are located in Qarnei Ramon (Fig. 1). The flows overlie Lower Hatira sandstones that cover Arod Conglomerate, and are overlain by sandstones of the Upper Hatira Formation. The lava flows are composed of basanite, tephrite, and basanitic nephelinite.

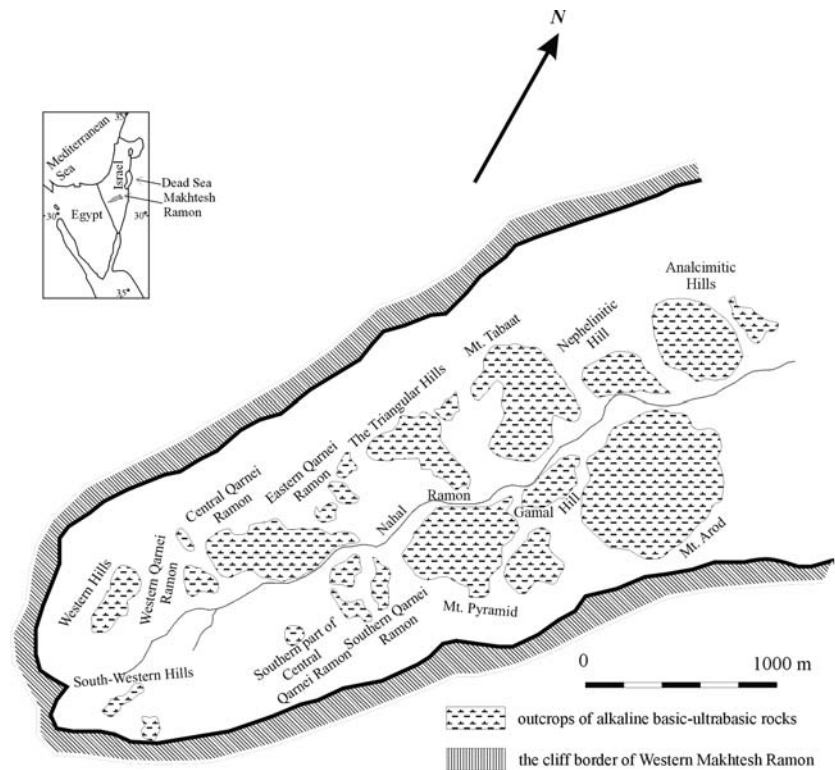
Relatively small outcrops of pyroclastic rocks are found in most parts of the study area and they include tuff, lapilli tuff, agglomerate and pyroclastic breccia. Many of the pyroclastic rock outcrops are located within eruption vents. The tuffs and lapilli tuffs commonly contain rounded fragments up to a few tens of cm in diameter, represented by all varieties of volcanic rocks, but mainly of basanite. The outcrops with the bigger blocks, up to 1.5 m, are found close to or in the eruption centers.

Three types of eruption centers were distinguished in the study area: volcano (Mt. Arod, Eyal et al. 1996), pyroclastic vents and phreatomagmatic vents.

There are about 50 different outcrops of subvolcanic bodies spread over most of the area. The subvolcanic bodies are more varied in composition than the lava flows and include in addition to tephrite, basanite, and basanitic nephelinite also olivine nephelinite, analcinite-olivine nephelinite, melilite-olivine nephelinite, nepheline-olivine analcinite, and melilite-olivine analcinite (Eyal et al. 2000, 2003).

Mt. Tabaat is an example of subvolcanic intrusive body, 800 m × 600 m, formed by olivine and melilite-

Fig. 1 Physiographic map of western Makhtesh Ramon to show outcrop areas of basic and ultrabasic alkaline rocks



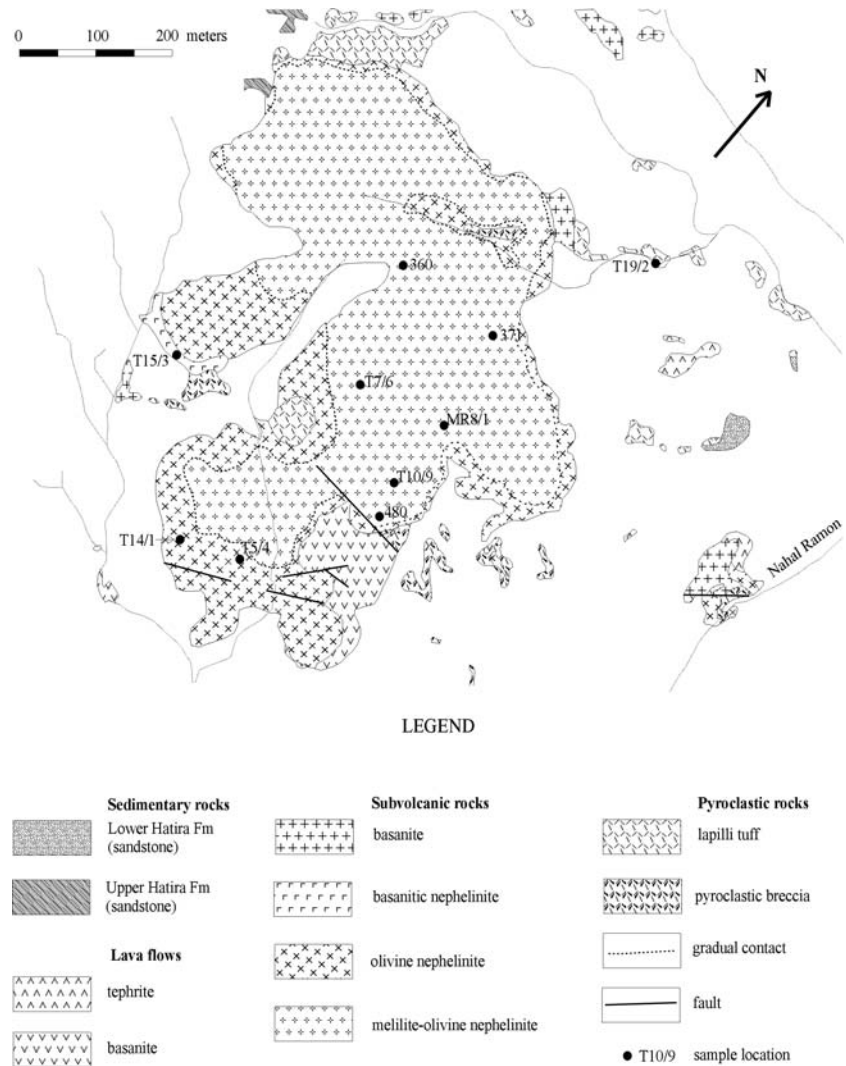
olivine nephelinite (Fig. 2). This subvolcanic body intruded the basanite flows, lappili tuffs, and pyroclastic breccias. The melilite-olivine nephelinites occur in the central part of intrusion, within an area of about $610 \text{ m} \times 500 \text{ m}$ (Fig. 2); the shape of melilite-olivine nephelinite body is similar in general to the shape of the whole Mt. Tabaat intrusion. The melilite-olivine nephelinites are finely crystalline to crystalline and surrounded on all sides by melilite-free olivine nephelinites with fine-grained and cryptocrystalline matrix. The thickness of the nephelinite rim is between 5 and 150 m. The transitions between melilite-bearing and melilite-free nephelinites occur in very short intervals (a few centimeters). In some cases such transitions may be observed within a single columnar prism.

The appearance of glassy varieties of rocks is one of particular features of the lava flows and subvolcanic bodies. In Mt. Pyramid the glassy rocks were found in a lava flow which was traced along the entire northern foot of the mountain. The flow is composed of basanite; in its upper part the olivine content decreases and the rock resembles tephrite. The total thickness of the flow is 43 m; the thickness of the upper part which was transformed into paleosol is 6 m. The part of the glassy-bearing tephrite that is located in the upper part of the flow grades into glass-free basanite in a few centimeters. The thickness of the glassy variety of ba-

sanite is between 6 and 13 m. The glass mainly makes up the intergranular space between the phenocrysts and microlites of plagioclase. The volume of groundmass glass in the rock is from 3 to 33%.

The glass-bearing varieties of alkaline rocks within subvolcanic bodies were found in nephelinite and analcinite intrusions such as Western Hills, Nephelinitic Hill, and Analcimite Hills. Glass-bearing nephelinite and analcinite are fine-grained and they always occur in the interior parts of subvolcanic bodies, and are always surrounded by fine-grained and cryptocrystalline glass-free nephelinite and analcinite. The transition from glass-bearing to glass-free varieties commonly occurs in distances of a few to tens of centimeters and the glass content changes gradually. The glass-bearing varieties occur both as isometric stock-like bodies and linear zones. Glass-bearing analcinite was found in several outcrops of Analcimite Hills. The area of the biggest glass-bearing outcrop is $210 \times 260 \text{ m}$. In other outcrops the linear glassy zones vary in thickness between 10 and 45 m and are up to 240 m long. In Western Hills, the subvolcanic elongated intrusion of nephelinite has a thickness up to 135 m and is 600 m long. The glass-bearing nephelinite is located in the central part of the intrusion and varies in thickness between 12 and 49 m. The common volume content of glassy groundmass is between 3 and 38%.

Fig. 2 Geological map of Mt. Tabaat, western Makhtesh Ramon



Sample description

The main rock-forming minerals of the studied rocks are olivine, clinopyroxene, plagioclase, titanomagnetite, nepheline, analcime and melilite. Alkali feldspar, calcite, amphibole, ilmenite, and biotite are sparsely present. Apatite is a typical accessory mineral whereas serpentine, chlorite and zeolites are main secondary minerals.

All the alkaline rocks are porphyritic. Phenocrysts (up to 30%) are mainly represented by olivine and clinopyroxene. Tephrites and plagioclase-rich basanites contain also plagioclase phenocrysts. Melilite-olivine nephelinites are characterized by the presence of melilite and nepheline microphenocrysts in the groundmass. The texture of holocrystalline groundmass is trachytic that is more typical of lava flows whereas hypidiomorphic is typical of subvolcanic bodies. Some melilite-olivine nephelinites have nephelinitic texture. Glassy alkaline

rocks contain glass in the groundmass and are characterized by their hypohyaline (hypocrystalline) texture.

The samples of alkali basic-ultrabasic rocks selected for the study are shown in Table 1. The main principles of sample selection were the abundance of olivine, clinopyroxene and/or plagioclase phenocrysts and that the samples should be typical of the different sequence of alkali basic-ultrabasic rocks known in Makhtesh Ramon. In such a way the collection representing the samples of tephrite, basanite, basanitic nephelinite, olivine nephelinite, and melilite-olivine nephelinite were prepared for the study. These are samples of subvolcanic bodies and lava flows of the western part of Makhtesh Ramon (Fig. 1) sampled at Western Hills, Southern Qarnei Ramon, Mt. Pyramid, Mt. Arod, Mt. Tabaat, Nephelinitic Hill, and Analcimitic Hills (Table 1). The well-preserved groundmass glasses suitable for geochemical analyses were found in several samples with high content of glass (Table 1).

Table 1 Studied samples

Number	Location	Rock	Type of magmatic body
Melt and fluid inclusions			
N2	Nephelinitic Hill	Anl-Ol nephelinite	Subvolcanic
N5	Nephelinitic Hill	Anl-Ol nephelinite	Subvolcanic
41/5	Mt. Pyramid	Basanite	Subvolcanic
41/4	Mt. Pyramid	Basanite	Subvolcanic
41/3	Mt. Pyramid	Tephrite	Lava flow
T5/4	Mt. Tabaat	Ol nephelinite	Subvolcanic
T15/3	Mt. Tabaat	Basanite	Lava flow
MR8/1	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
T19/2	Mt. Tabaat	Tephrite	Lava flow
T14/1	Mt. Tabaat	Ol nephelinite	Subvolcanic
T7/6	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
360	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
371	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
480/1	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
MR23/9	Western Hills	Ol nephelinite	Subvolcanic
MR15/3	S. Qarnei Ramon	Basanite	Lava flow
Fluid inclusions			
7/22a	Mt. Arod	Basanitic nephelinite	Lava flow
17/9	Mt. Arod	Basanitic nephelinite	Lava flow
17/8	Mt. Arod	Basanitic nephelinite	Lava flow
15l/2	Mt. Arod	Basanitic nephelinite	Lava flow
12b/2	Mt. Arod	Basanitic nephelinite	Lava flow
15f/1	Mt. Arod	Basanitic nephelinite	Lava flow
12a	Mt. Arod	Basanitic nephelinite	Lava flow
12/1	Mt. Arod	Basanitic nephelinite	Lava flow
4–1	Mt. Arod	Basanitic nephelinite	Lava flow
8–1	Mt. Arod	Basanitic nephelinite	Lava flow
T16/1	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
T10/9	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
32	S. Qarnei Ramon	Tephrite	Subvolcanic
Groundmass glasses (vol% of glass)			
N14(20.2%)	Nephelinitic Hill	Anl-Ol nephelinite	Subvolcanic
N15(11.3%)	Nephelinitic Hill	Anl-Ol nephelinite	Subvolcanic
P6c(30.5%)	Mt. Pyramid	Tephrite	Lava flow
M7/11(30%)	Analcimite Hills	Ol analcimate	Subvolcanic
M7/6(26%)	Mt. Tabaat	Ol-Mel nephelinite	Subvolcanic
MR23/8b(31%)	Western Hills	Ol nephelinite	Subvolcanic

Anl analcime, *Mel* melilite, *Ol* olivine

The major and trace element contents of several rock samples are shown in Table 2. The major differences between tephrite-basanite-nephelinite rock suite are represented, for example, by Mt. Tabaat rock series. In the melilite-olivine nephelinite-olivine nephelinite-basanite-tephrite rock series the contents of SiO₂ and Al₂O₃ increase gradually whereas MgO, CaO, and FeO+Fe₂O₃ are gradually decreased. In the same way the trace element content decreases from melilite-olivine nephelinite to tephrite.

Description of phenocrysts hosted melt and fluid inclusions

Olivine is mainly observed in phenocrysts that are present in all studied rocks. Their content in basanite,

olivine nephelinite and melilite-olivine nephelinite is more than 10 vol% and up to 26 vol%. Tephrites comprise between 5 and 10 vol% of olivine. Olivine phenocrysts are commonly form euhedral or subhedral tabular crystals up to 8 × 10 mm. Corrosion of the olivine phenocrysts by the melt with the formation of embayed crystals is common. Part of the phenocrysts contains inclusions of groundmass and ore minerals. Corona texture with clinopyroxene borders is observed rarely, mainly in subvolcanic varieties, but the resorption by clinopyroxene was not found (Eyal et al. 2000). The typical electron probe data on olivine phenocrysts are shown in Table 3. Olivines usually correspond to Fo_{85–73}. A few studied olivine phenocrysts in olivine nephelinite and melilite-olivine nephelinite are more Mg-rich and correspond to Fo_{89–90}. Olivine alteration to total

Table 2 Major and trace element geochemistry of whole-rock samples

Sample	T19/2	T15/3	T14/1	MR23/9	T16/1a	41/3	41/4	41/5	MR15/3	7/22a	N2
SiO ₂ (wt%)	46.90	44.20	40.20	40.80	39.70	46.30	44.20	44.10	44.40	43.00	40.40
TiO ₂	2.26	2.29	2.65	2.57	2.39	2.59	2.38	2.38	2.29	2.82	2.72
Al ₂ O ₃	15.50	12.25	12.20	11.90	11.60	14.60	12.60	12.60	12.25	13.60	11.90
Fe ₂ O ₃	4.35	4.06	4.32	4.08	6.65	3.40	4.19	3.83	4.06	3.17	3.88
FeO	5.90	7.93	7.86	8.12	6.62	8.84	7.67	7.82	7.93	8.62	8.01
MnO	0.24	0.17	0.21	0.20	0.25	0.18	0.17	0.17	0.17	0.18	0.18
MgO	6.29	12.95	10.71	11.24	11.50	8.21	12.25	12.93	12.95	9.55	12.67
CaO	8.77	8.83	12.52	12.90	12.97	8.50	10.00	9.73	8.83	10.66	12.13
Na ₂ O	3.31	2.50	3.88	3.12	4.00	3.19	2.66	2.13	2.50	3.81	3.01
K ₂ O	1.59	1.05	1.00	0.91	1.46	0.70	1.16	1.07	1.05	1.52	0.94
P ₂ O ₅	0.69	0.53	1.11	1.14	1.11	0.61	0.56	0.54	0.53	0.98	0.81
LOI	3.78	2.64	3.39	3.32	1.54	3.29	2.29	2.85	2.64	2.46	3.59
Total	99.58	99.60	99.95	100.30	99.79	100.41	100.13	100.35	99.60	100.37	100.24
CO ₂	<0.20	0.26	<0.20	<0.20	<0.20	<0.20	0.37	0.44	0.26	0.48	<0.20
La (ppm)	41	23	89	78	105	32	31	28	31	63	51
Ce	88	48	175	156	200	69	68	63	65	127	106
Pr	9.4	5.6	18.6	16.7	20.6	7.7	7.6	7.1	7.5	13.9	11.7
Nd	36	22	68	62	73	33	30	28	30	52	44
Sm	6.5	4.1	11.1	10.6	11.8	6.1	5.8	5.5	5.7	9.0	7.8
Eu	2.6	1.6	4.1	3.9	4.2	2.6	2.3	2.2	2.2	3.4	2.9
Gd	6.1	3.9	10.1	9.5	10.8	5.7	5.5	5.2	5.2	8.2	7.1
Tb	0.89	0.59	1.4	1.3	1.4	0.87	0.84	0.80	0.77	1.2	0.99
Dy	4.6	3.0	6.5	6.3	6.7	4.5	4.3	4.0	4.0	5.3	4.8
Ho	0.85	0.53	1.1	1.1	1.2	0.82	0.78	0.72	0.73	0.93	0.84
Er	2.3	1.4	3.0	2.9	3.2	2.2	2.1	2.0	2.0	2.4	2.2
Tm	0.30	0.17	0.36	0.36	0.39	0.27	0.25	0.24	0.24	0.28	0.26
Yb	1.9	1.1	2.2	2.1	2.4	1.7	1.6	1.5	1.5	1.7	1.6
Lu	0.26	0.16	0.31	0.30	0.36	0.24	0.23	0.22	0.22	0.26	0.22
Ba	700	415	970	850	1000	470	370	390	410	650	615
Sr	1350	560	1150	1270	1200	880	575	620	560	1000	800
Th	4.5	2.9	12	10	16.7	3.4	3.8	3.5	3.8	7.8	5.7
U	1.4	0.8	3.0	2.8	4.7	1.1	1.2	1.0	1.1	2.3	1.7
Rb	31	17	102	15	47	6.6	24	21	11	19	18
Nb	71	41	151	129	206	52	57	52	55	107	89
Ta	3.6	2.5	7.9	7.1	10.4	3.0	3.3	3.1	3.2	6.3	5.1
Pb	3.1	1.8	5.6	4.8	5.7	2.6	2.3	1.8	2.2	4.6	2.8
Y	24	19	29	27	32	22	20	20	19	23	23
Co	53	75	58	70	70	62	71	73	78	62	65
Ni	153	358	206	219	246	171	293	304	364	175	255
Cr	175	267	269	344	282	193	366	254	281	257	458
V	165	190	210	220	200	170	220	220	190	215	235

Mt. Tabaat: *T19/2* tephrite; *T15/3* basanite; *T14/1* Ol nephelinite; *MR23/9* Ol nephelinite; *T16/1a* Ol-Mel nephelinite; Mt. Pyramid: *41/3* tephrite; *41/4*, *41/5* basanites; S. Qarnei Ramon: *MR15/3* basanite; Mt. Arod: *7/22a* basanitic nephelinite; Nephelinitic Hill: *N2* Anl-Ol nephelinite

pseudomorphs is common, mainly as serpentinization and partly as chloritization.

Clinopyroxene is observed both in groundmass and among phenocrysts. The clinopyroxene phenocrysts may compose up to 23% of rock volume, but some samples of lavas and subvolcanic rocks contain less than 1 vol% of clinopyroxene phenocrysts. Clinopyroxene forms mainly euhedral or subhedral tabular phenocrysts, usually up to 4.5 mm × 6.0 mm. Tabular phenocrysts exhibit usually zoning due to the change in their color. The crystal cores are mostly formed by colorless or grayish augite (Table 3) or more rarely by green Na-rich augite, whereas their rims are composed

of pale rose to rose titanium augite. Tabular clinopyroxene phenocrysts are frequently twinned with simple twins. Corrosion of tabular phenocrysts by the melt with the formation of embayed shapes was noted. Phenocrysts can contain inclusions of groundmass and ore minerals (Eyal et al. 2000).

Plagioclase is present mainly in groundmass and only partly among phenocrysts. Plagioclase phenocrysts (up to 10 vol%) are typical for tephrites with Pl > Cpx > Ol among phenocrysts. Basanites contain frequently less than 1 vol% of plagioclase phenocrysts or devoid of them. Plagioclase phenocrysts are mainly observed as large laths or partly as euhedral and subhedral tabular

Table 3 Electron microprobe data on typical phenocrysts hosted melt inclusions

Sample Phenocryst	41/3 Ol	41/5 Ol	T5/4 Ol	MR8/1 Ol	T19/2 Cpx	41/5 Cpx	MR8/1 Cpx	41/3 Pl	41/3 Pl
SiO ₂ (wt%)	39.44	39.78	39.56	38.60	46.92	50.05	52.07	56.33	54.70
TiO ₂	0.03	0.02	0.02	0.05	2.50	1.40	0.28	0.25	0.09
Cr ₂ O ₃	0.06	0.05	0.02	0.02	0.12	0.21	0.88	0.00	0.00
Al ₂ O ₃	0.00	0.00	0.00	0.00	8.46	5.60	6.00	27.16	28.46
FeO	17.12	17.34	17.76	23.46	8.60	6.63	3.30	0.34	0.34
MnO	0.19	0.16	0.29	0.30	0.13	0.10	0.05	0.00	0.01
MgO	42.84	42.28	42.12	37.38	12.26	15.35	15.74	0.05	0.06
CaO	0.23	0.24	0.28	0.14	20.27	20.03	20.05	9.06	10.30
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.07
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.10
Na ₂ O	0.00	0.00	0.00	0.00	0.78	0.63	1.49	6.24	5.45
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.35
Total	99.91	99.87	100.06	99.94	100.04	99.99	99.86	100.18	99.94
a.p.f.u.									
Si	1.001	1.010	1.005	1.008	1.797	1.843	1.887	2.536	2.474
Ti	0.001	0.000	0.000	0.001	0.067	0.040	0.008	0.008	0.003
Cr	0.001	0.001	0.000	0.000	0.003	0.006	0.024		
Al					0.359	0.243	0.257	1.443	1.517
Fe	0.363	0.369	0.377	0.513	0.259	0.204	0.100	0.014	0.014
Mn	0.004	0.003	0.006	0.006	0.004	0.002	0.002		0.000
Mg	1.622	1.600	1.597	1.457	0.657	0.843	0.852	0.003	0.004
Ca	0.006	0.006	0.008	0.004	0.781	0.790	0.778	0.436	0.500
Ba								0.001	0.001
Sr								0.006	0.003
Na					0.054	0.044	0.105	0.544	0.478
K								0.015	0.019
Fo	0.812	0.808	0.800	0.731					
Fa	0.182	0.185	0.189	0.258					
La	0.003	0.003	0.004	0.002					
En					0.330	0.420	0.425		
Fs					0.130	0.101	0.050		
Wo					0.392	0.393	0.388		
An								0.434	0.499
Ab								0.512	0.469
Or								0.006	0.019

crystals. The size of tabular phenocrysts is from 0.12 mm × 0.16 mm up to 2.7 mm × 4.2 mm. They are sometimes twinned with simple twins, have anomaly blue–brown color and are always characterized by normal zoning. Based on optical data the rims of large phenocrysts and small phenocrysts are formed by An_{55–65}. The cores of large phenocrysts are composed of An_{55–75}. In some cases the plagioclase phenocrysts are partly corroded by alkaline melt with the formation of embayed and even skeletal shapes and may comprise small groundmass inclusions (Eyal et al. 2000). Commonly plagioclase is practically unaltered (Table 3).

Methods of study

Fresh olivine, clinopyroxene, and plagioclase phenocrysts containing silicate melt and fluid inclusions were carefully selected from doubly polished thin sections of

rocks. Experimental investigations of melt inclusions were performed using the Vernadsky high-temperature heating/quenching stage (Sobolev et al. 1980) installed at the Ben-Gurion University (BGU), Israel. Operating up to 1,600°C, the heating stage permits visual observation of inclusions during the heating, and has a very high rate of quenching (200–300°C per second). Experiments with olivine-hosted melt inclusions were executed with constant flow of pure argon into the heating stage. Argon was first purified in a heated copper tube at a temperature of 700°C. Experiments with clinopyroxene- and plagioclase-hosted melt inclusions were performed at ambient atmosphere. The heating experiments were conducted at atmospheric pressure under visual observation. The phase reactions in melt inclusions were observed during sequential heating. The rate of heating at temperatures higher than 1,000°C was about 20° per minute. At the final step of heating the inclusions were rapidly quenched

and the resulting glassy melt inclusions were suitable for further microprobe studies. The accuracy of high-temperature measurements is $\pm 10^\circ\text{C}$.

Fluid inclusions (only CO_2 -rich inclusions were found) were studied at temperatures between -190 and 35°C with a FLUID INC. heating-freezing stage. The accuracy of temperature measurements is about $\pm 0.5^\circ\text{C}$. In CO_2 inclusions the melting temperature (T_m) of solid CO_2 characterizes the purity of the system. For pure CO_2 the melting temperature is -56.6°C ; a lower melting point usually indicates the presence of CH_4 and/or N_2 . The homogenization temperature of CO_2 ($T_h\text{CO}_2$) indicates the density of the carbon dioxide. The highest $T_h\text{CO}_2$ is 31.2°C , which corresponds to the critical point of CO_2 .

The analyses of phenocrysts, glasses and solid phases of silicate melt inclusions, and groundmass glasses were performed at the Analytical Centre of the Institute of Geology and Mineralogy (IGM), Novosibirsk, Russia. Camebax electron microprobe with accelerating voltage of 20 kV, probe current of 30 nA, beam of 2–3 μm , and measuring time of 40 s was used. The accuracy of major element determination was better than 1–2% of total value.

Whole-rock major element analyses were made using a combination of wet chemical methods, AAS and titration at the Geological Institute, Ulan-Ude. Analyses are accurate to within 2–5%.

Whole-rock trace element content was determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) (Jobin Yvon JY-48) in the laboratory of the Geological Survey of Israel. The trace elements were analyzed in solution prepared by fusing powdered rocks with lithium metaborate ($\text{Li}_2\text{B}_2\text{O}_4$) and dissolving the resultant glasses in nitric acid.

Secondary ion mass spectroscopy (SIMS) analyses for trace elements, water and fluorine in melt inclusions and groundmass glasses were carried out on the Cameca IMS-4f ion microprobe operated at the Institute of Microelectronics and Informatics RAS, Yaroslavl. The measurement procedures for trace element and H_2O analysis were similar to those described in detail by Smirnov et al. (1995) and Nosova et al. (2002). The method of ion probing of fluorine was published in Portnyagin et al. (2001). The standard glass NIST 610 was used for the testing of all measured data before and after all types of analysis.

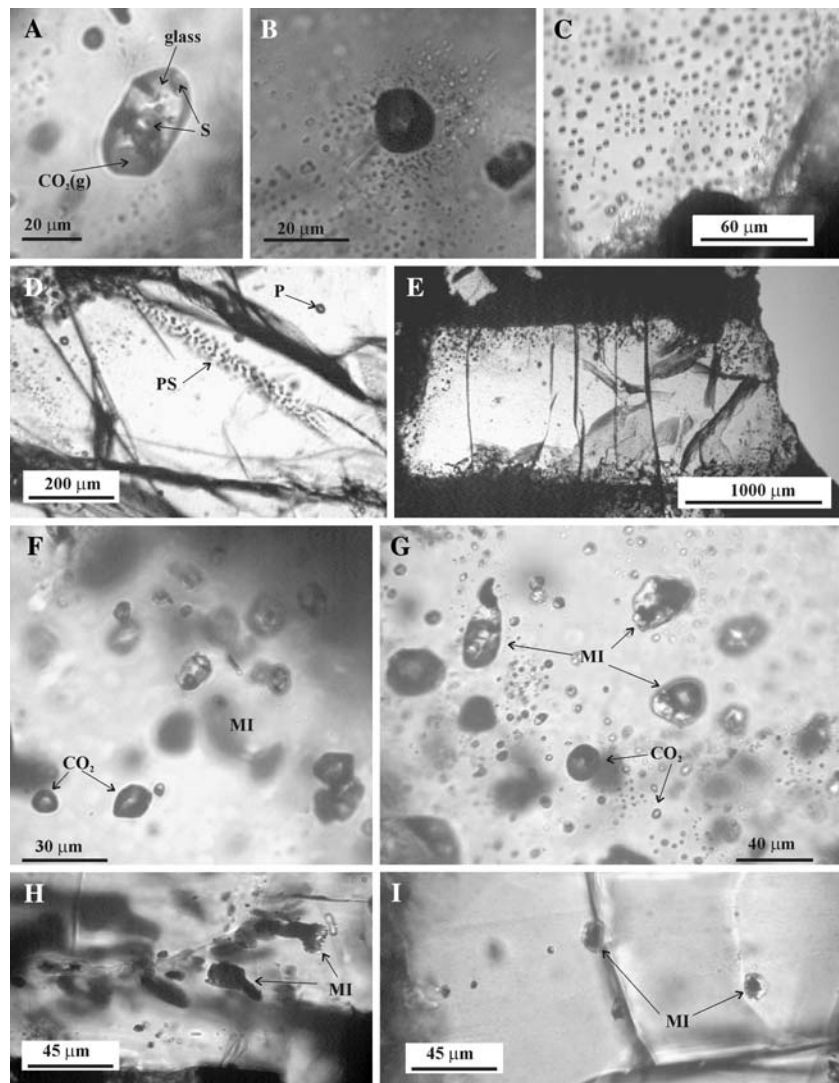
Results

Primary and pseudosecondary melt and fluid inclusions are common in the studied olivine, clinopyroxene, and

plagioclase phenocrysts. Primary inclusions are formed during the mineral growth and are represented by randomly scattered inclusions, either isolated or in clusters. Pseudosecondary inclusions (like primary) are formed during the growth of the crystal, and their appearance is connected with the healing of fractures in growing crystals. They are developed as trails or planes of inclusions not intersecting the grain boundaries. Secondary inclusions are those whose form is essentially completed by any process after crystallization of the host mineral (Roedder 1984). They are developed as trails or planes of inclusions on healed fractures crosscutting grain boundaries. Because all studied samples contain separate phenocrysts isolated in the rock matrix, it is impossible to observe the trails crosscutting phenocryst grain boundaries and the existence of secondary inclusions is moot. The distribution of melt inclusions in the studied samples differs: in some cases a single inclusion is confined to the core of the host mineral, in other cases these are groups of inclusions defining the growth zone in the host mineral (primary inclusions). Some inclusions are in planar orientation suggesting their formation involved fracture healing (pseudosecondary inclusions). The shape of inclusions is oval, rounded or irregular. The sizes vary from 1–10 up to 100 μm .

As a rule melt inclusions are numerous in olivine, clinopyroxene and plagioclase phenocrysts. Melt inclusions are usually composed of a combination of daughter crystals with glass and fluid phase (Figs. 3, 4). Where melt inclusions occur separately from fluid inclusions, the volume of the gas phase in the inclusion is between 10 and 30%. In some cases melt and fluid inclusions occur simultaneously in the same inclusion populations. In such cases the volume of gas in the melt inclusion may differ by about 10% and up to near-total gaseous inclusion with minor glass and/or crystalline phases (Fig. 3f, g). The gaseous phase in melt inclusions is composed of low-density CO_2 that was determined by melting at about -58.0°C . Because of very low CO_2 density, the homogenization into the gas phase was impossible to record. Considering the optical characteristics which were then supported by direct electron probe analysis, the major mineral phase in melt inclusions is clinopyroxene. Sulfides, spinel, rhönite, ilmenite and amphibole occur as minor phases in melt inclusions hosted by phenocrysts in tephrites and basanites (Fig. 4). In addition nepheline and apatite were also determined in melt inclusions in phenocrysts hosted by nephelinite and melilite-olivine nephelinite. Glassy inclusions (+ fluid phase + tiny daughter phases) were also observed in some phenocrysts.

Fig. 3 Melt and fluid inclusions in phenocrysts of alkaline suite of Makhtesh Ramon. **A** Typical ratios of gaseous (CO_2), glass and crystalline (s) phases in primary melt inclusion in olivine phenocryst. Sample T7/6. **B** Primary gaseous CO_2 -rich inclusions surrounded by halo of tiny inclusions. Olivine phenocryst, sample T7/6. **C** Numerous pseudosecondary gaseous CO_2 -rich inclusions. Olivine phenocryst, sample 32. **D** Primary (*P*) and pseudosecondary (*PS*) CO_2 inclusions. Clinopyroxene phenocryst. Sample 32. **E** Numerous inclusions in the border zone of olivine phenocryst. Sample T7/6. **F, G** Enlarged parts of **e**. Primary melt inclusions (*MI*) with different phase ratios coexist with CO_2 inclusions. **H** Pseudosecondary melt inclusions in plagioclase phenocryst. Sample 41/3. **I** Primary melt inclusions in clinopyroxene phenocryst. Sample 41/3



During the heating of melt inclusions it was possible to observe the initial and complete melting of solid phases. The initial melting usually corresponds to the solidus, whereas the homogenization temperature approximates the volatile-saturated liquidus temperature of the trapped melt at the internal pressure (e.g. Schiano 2003). The detailed investigation of melting behavior of melt inclusions in olivine phenocrysts in basanite sample (MR 15/3) revealed the beginning of glass melting at a temperature between 1,020 and 1,075°C. The melting continued with that of ilmenite (at a temperature of 1,130°C), clinopyroxene (between 1,140 and 1,180°C), and rhönite (between 1,180 and 1,230°C). Complete melting of the solid phases with the dissolution of spinel was obtained between 1,310 and 1,350°C. Then, the inclusions that commonly consist of homogeneous melt and gas bubble were quenched. The electron probe data on daughter phases

in melt inclusions (Fig. 4) hosted by olivine phenocrysts are shown in Table 4.

The melting behavior is rather similar for melt inclusions hosted by olivine phenocrysts in all studied samples. The daughter crystals of melt inclusions usually melt between 1,180 and 1,250°C. At these temperatures the melt inclusion is composed of abundant liquid phase (melt), a gas bubble and, in some cases a few small refractory phases (spinel). Much higher temperatures, about 1,320 to 1,350°C were necessary for the dissolution of spinel. Several inclusions hosted by olivine phenocrysts in olivine nephelinites and melilite-olivine nephelinite of Mt. Tabaat show lower liquidus temperature between 1,100 and 1,180°C. The melting of daughter phases in melt inclusions hosted by clinopyroxene phenocrysts was observed between 1,130 and 1,170°C. The liquidus temperatures of melt inclusions hosted by plagioclase phenocrysts were ob-

Fig. 4 Multiphase melt inclusions in olivine phenocrysts, sample MR15/3. **a–e** Unheated melt inclusions, **a** and **b** in transmitted and **c, d** in reflected light. **f** Melt inclusion heated up to 1,075°C: numerous solid phases are still present in the inclusion, transmitted light. Several electron probe analyses of glasses and mineral phases in melt inclusions are presented in Table 4. The following mineral phases are shown: *Cpx* clinopyroxene, *Rho* rhönite, *Cr-Sp* chrome spinel, *Sulf* sulfide, *Ilm* ilmenite

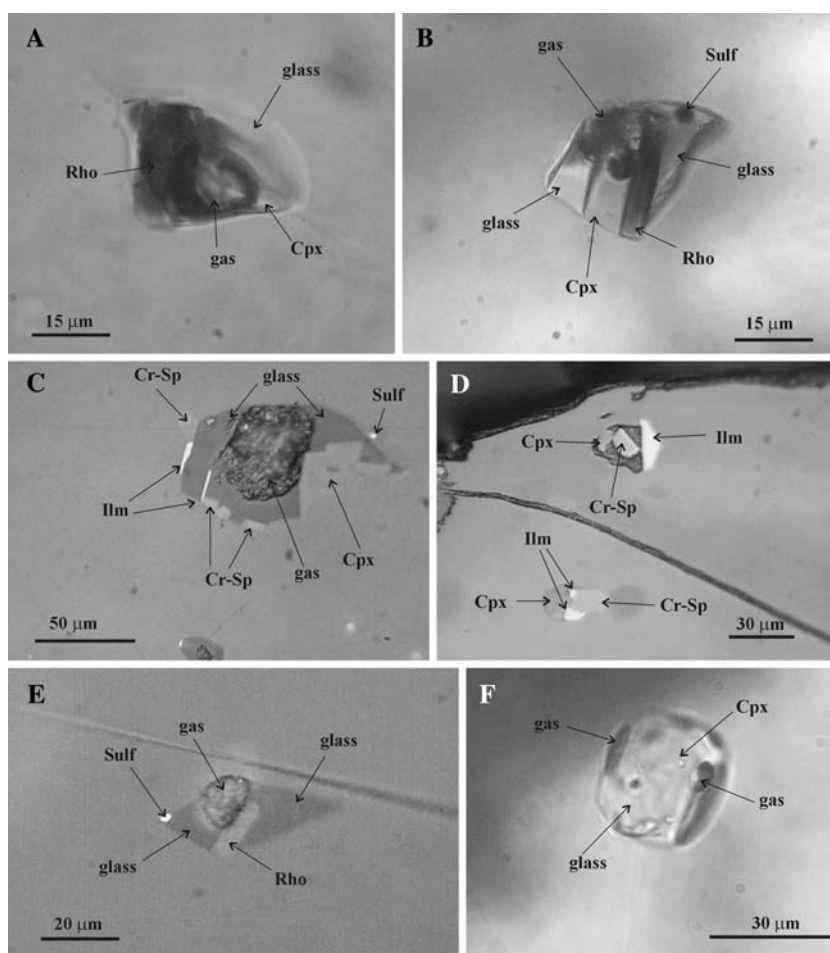


Table 4 Electron microprobe data on glass and daughter phases in melt inclusions hosted by olivine phenocrysts, sample MR15/3

Phase inclusion	Glass B	Rho B	Cpx B	Glass C	Cpx(c) C	Cpx(r) C	Cr-Sp D	Cpx D	Ilm D	Glass E	Rho E
SiO ₂	61.30	27.38	43.60	60.37	39.55	40.76	0.09	43.14	0.13	60.73	23.84
TiO ₂	0.26	10.72	4.40	0.20	5.24	3.76	3.86	5.80	55.76	0.22	11.53
Cr ₂ O ₃	0.00	0.49	0.02	0.00	0.02	0.00	17.16	0.41	0.77	0.02	1.70
Al ₂ O ₃	24.54	17.59	10.60	23.69	13.65	11.17	39.97	10.69	0.03	23.38	19.80
FeO	0.80	14.51	5.85	1.10	5.15	5.63	21.83	4.91	30.95	1.67	12.60
MnO	0.02	0.11	0.06	0.05	0.06	0.07	0.16	0.09	0.35	0.05	0.11
MgO	0.21	14.73	11.97	0.63	12.29	15.09	15.98	12.66	11.87	1.56	17.42
CaO	0.57	12.45	21.93	0.74	22.27	21.27	0.00	21.46	0.00	0.43	9.79
Na ₂ O	5.13	1.21	0.75	6.60	0.66	0.63	0.00	0.94	0.00	6.14	2.30
K ₂ O	5.70	0.00	0.00	5.76	0.00	0.03	0.00	0.00	0.00	4.93	0.00
P ₂ O ₅	0.32	0.00	0.61	0.41	1.27	0.99	0.00	0.00	0.00	0.36	0.00
BaO	—	—	—	0.04	—	—	—	—	—	0.02	0.00
SrO	0.12	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	—	—	—	0.41	—	—	—	—	—	0.28	0.02
Total	98.85	99.19	99.79	100.10	100.16	99.40	99.05	100.10	99.86	99.79	99.11

Rho rhönite, *Cpx(c)* clinopyroxene core, *Cpx(r)* clinopyroxene rim, *Cr-Sp* chrome-spinel, *Ilm* – ilmenite

tained in the temperature range of 1,130–1,180°C. For inclusions from the same sample the data suggest that olivine was the first phase to crystallize and was followed by clinopyroxene and plagioclase phenocrysts.

Based on the data on the liquidus temperature of melt inclusions (Th_1 °C) we were able to evaluate the mean temperature of phenocryst formation as shown in Table 5.

Table 5 Microthermometric data and trapping conditions of melt and fluid inclusions in phenocrysts

Sample	Rock	Host mineral	Inclusion	Th _s (°C)	Th _l (°C)	ThCO ₂	P (kbar)	Range of T (°C)
32	Tephrite	Ol	FI			–2.0	6.8–7.0	1,200–1,250
		Cpx	FI			–10.5	7.5–7.7	1,150–1,200
		Pl	FI			5.5	5.9–6.1	1,100–1,150
T19/2	Tephrite	Ol	MI	1,120	1,260			
		Cpx	MI	1,115	1,170			
		Cpx	MI	1,110	1,170			
		Ol	MI		1,270			
41/3	Tephrite	Ol	MI& FI		1,180	–3.5	6.9–7.1	1,200–1,250
		Ol	MI		1,260			
		Cpx	FI			3.0	6.3–6.5	1,150–1,200
		Pl	MI	1,100	1,140			
		Pl	MI	1,100	1,130			
T15/3	Basanite	Cpx	FI			–20.0	8.2–8.4	1,150–1,200
41/5	Basanite	Ol	MI& FI		1,200	0.0	6.6–6.8	1,200–1,250
		Ol	MI		1,220			
		Cpx	MI		1,160			
		Cpx	MI		1,130			
		Cpx	MI	1,150				
MR15/3	Basanite	Ol	MI& FI		1,310	–5.0	7.0–7.2	1,200–1,250
41/4	Basanite	Ol	MI		1,250			
		Ol	MI		1,250			
17/9	Basanitic nephelinite	Ol	MI& FI	1,210	1,250	–4.5	7.0–7.2	1,200–1,250
		Ol	MI	1,260	1,350			
		Cpx	MI	1,040	1,160			
		Cpx	MI	1,050	1,160			
17/8	Basanitic nephelinite	Ol	FI			–3.0	6.9–7.1	1,200–1,250
15l/2	Basanitic nephelinite	Ol	FI			–22.0	8.5–8.7	1,200–1,250
		Cpx	FI			–11.5	7.5–7.7	1,150–1,200
12b/2	Basanitic nephelinite	Ol	FI			–22.0	8.5–8.7	1,200–1,250
		Cpx	FI			–29.0	9.0–9.2	1,150–1,200
15f/1	Basanitic nephelinite	Cpx	FI			–18.0	8.0–8.2	1,150–1,200
12a	Basanitic nephelinite	Ol	FI			–27.0	8.9–9.1	1,200–1,250
12/1	Basanitic nephelinite	Ol	FI			–12.5	7.8–8.0	1,200–1,250
4-1	Basanitic nephelinite	Cpx	FI			–11.0	7.5–7.7	1,150–1,200
8-1	Basanitic nephelinite	Ol	FI			–15.5	7.9–8.1	1,200–1,250
		Cpx	FI			–15.5	7.8–8.1	1,150–1,200
N2	Anl-Ol nephelinite	Cpx	FI			–21.5	8.4–8.6	1,150–1,200
		Ol	MI		1,210			
		Ol	MI		1,260			
		Ol	MI		1,270			
		Ol	MI		1,320			
N5	Anl-Ol nephelinite	Cpx	FI			–16.5	8.0–8.2	1,150–1,200
		Ol	MI		1,290			
		Ol	MI		1,260			
		Ol	MI		1,290			
NR23/9	Ol nephelinite	Ol	MI& FI		1,240	–11.0	7.6–7.8	1,200–1,250
Mt. Tabaat samples								
T5/4	Nephelinite	Ol	MI& FI	1,030	1,180	11.5	5.6–5.8	1,200–1,250
		Ol	MI	1,065				
		Ol	MI	1,030	1,150			
T14/1	Ol nephelinite	Ol	MI& FI	1,090	1,160	–5.0	6.8–7.0	1,150–1,200
		Ol	MI	1,150	1,180			
		Ol	MI	1,000				
T16/1	Mel-Ol nephelinite	Ol	MI& FI		1,270	7.0	6.1–6.3	1,200–1,250
T10/9	Mel-Ol nephelinite	Ol	FI			22.0	4.4–4.5	1,150–1,200
MR8/1	Mel-Ol nephelinite	Ol	MI& FI		1,130	13.5	5.3–5.4	1,150–1,200
		Ol	MI	940	1,110			
		Ol	MI	960				
T7/6	Mel-Ol nephelinite	Ol	MI& FI	1,000	1,140	25.0	4.0–4.2	1,150–1,200
		Ol	MI	1,130	1,170			
371	Mel-Ol nephelinite	Ol	MI& FI	1,060	1,170	22.5	4.4–4.5	1,150–1,200
		Ol	MI	960	1,160			

Table 5 Continued

Sample	Rock	Host mineral	Inclusion	Th _s (°C)	Th _l (°C)	ThCO ₂	P (kbar)	Range of T (°C)
480/1	Mel-Ol nephelinite	Ol	MI		1,190			
		Ol	MI	1,050	1,180			
360	Mel-Ol nephelinite	Ol	MI& FI	1,010	1,210	27.0	3.8–4.0	1,150–1,200
		Ol	MI	940	1,160			
		Ol	MI	1,080	1,190			

MI and FI are melt and fluid inclusion, respectively; Th_s °C and Th_l °C are solidus and liquidus temperature, respectively, recorded during heating experiments with melt inclusions; ThCO₂ is the temperature of homogenization of CO₂-inclusions into the liquid phase; Range of T °C is a mean range of melt inclusion homogenization; P, kbar is the calculated pressure of CO₂ inclusion trapping (after Belonoshko and Saxena 1991) by host olivine (Ol), pyroxene (Cpx) or plagioclase (Pl) phenocryst

Fluid inclusion populations are usually distributed in one or two phenocrysts only and are not found in the remaining phenocrysts of the sample. In several samples most inclusions are of very low density, in some cases big gaseous inclusions are surrounded by a characteristic halo of tiny inclusions (Fig. 3b). The inclusions are CO₂-rich and show T_m at about −57.0 to −58.0°C, in some of them the melting point was down to −59.0°C. Several CO₂-rich inclusions were checked for their content by Raman spectroscopy. The peaks corresponding to CO₂ phase were received without any additional signal corresponding to other gases. Commonly a few CO₂ inclusions show the lowest ThCO₂ (highest density inclusions), whereas most inclusions

have higher Th. The typical distribution of ThCO₂ is shown in Fig. 5.

No aqueous inclusions were found in the phenocrysts. Several single-phase inclusions were observed in one calcite-filled miarolitic cavity (the sample T41/3). The inclusions show the melting at about 0°C indicating their low salinity.

Electron microprobe data on compositions of heated melt inclusions, and several unheated glassy inclusions (Table 6) were compared with compositions of whole-rock samples (Table 2) and natural groundmass glasses (Table 7). In general the composition of melt inclusions with lowest silica content is similar to the composition of the whole-rock sample which hosts them (Fig. 6a–d). For example, the lowest SiO₂ content in melt inclusions was recorded for olivine nephelinite and melilite-olivine nephelinite samples (Fig. 6c, d). Commonly, considering most major components, heated melt inclusions form a continuous trend from inclusions with lower SiO₂ content which are similar to whole-rock compositions, to inclusions with higher SiO₂ content which are similar to groundmass glasses. Thus, crystallization proceeds with decreasing FeO, MgO and CaO contents and increasing Al₂O₃ content. The total content of alkalis also usually increases with increasing SiO₂ content of melt inclusions. The groundmass glasses commonly show highest alkali contents apart from tephrite groundmass glasses that have lower alkali contents relative to compositions of melt inclusions (Fig. 6a). Highest P and Cl contents were recorded for olivine nephelinite and melilite-olivine nephelinite (Table 6). Ba is a major component in several melt inclusions hosted by melilite-olivine nephelinite (Fig. 6d). The glasses of unheated glassy melt inclusions are conspicuous for their highest SiO₂ and alkali contents.

Spider graphs of REE normalized with respect to chondritic abundances (Taylor and McLennan 1985) are shown in Fig. 7. The REE diagrams combine the data obtained on whole-rock samples (Table 2), SIMS data on groundmass glasses (Table 7) and on melt

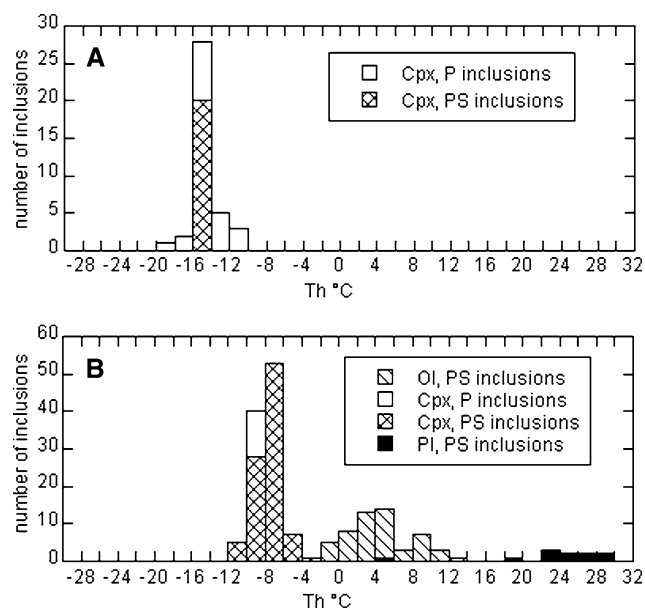


Fig. 5 Homogenization temperature of CO₂ inclusions. **A** Primary (P) and pseudosecondary (PS) inclusions in clinopyroxene (Cpx) phenocrysts. Sample T15/3. **B** Pseudosecondary inclusions in olivine (Ol) phenocrysts, primary and pseudosecondary inclusions in clinopyroxene (Cpx) phenocrysts, and pseudosecondary inclusions in plagioclase (Pl) phenocrysts. Sample 32

Table 6 Electron microprobe and SIMS data on glasses of melt inclusions

Sample Rock	T19/2 T19/2 Tephrite	41/5 Basanite		T14/1 Ol nephelinite	T14/1	T7/6	T7/6 Mel-Ol nephelinite	T7/6	480/1
Phenocryst Size of MI, μm Quenching T , $^{\circ}\text{C}$	Cpx 50 1,170	Cpx 30 1,170	Cpx 35 1,170	Ol 40 1,200	Ol 42 1,200	Ol 25 1,170	Ol 45 1,160	Ol 40 1,160	Ol 50 Unheated
SiO ₂ (wt%)	49.34	48.75	47.52	44.10	46.89	45.03	44.61	45.97	50.52
TiO ₂	3.00	3.03	2.25	1.57	2.03	3.27	2.45	1.51	0.51
Cr ₂ O ₃	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.02	0.00
Al ₂ O ₃	15.13	16.80	14.82	18.59	19.98	17.49	17.31	17.18	25.92
FeO	9.87	8.25	10.53	8.67	5.81	7.07	8.60	8.48	1.59
MnO	0.19	0.17	0.13	0.11	0.12	0.11	0.16	0.14	0.01
MgO	5.47	4.75	7.24	5.15	4.66	5.18	4.49	4.74	0.92
CaO	10.03	9.70	11.90	8.53	7.74	7.21	7.55	7.07	0.28
BaO	0.04	0.06	0.01	0.15	0.11	0.48	0.52	0.47	0.04
Na ₂ O	3.96	5.00	2.84	6.01	6.53	6.59	6.68	7.19	13.14
K ₂ O	1.78	1.56	1.25	2.35	2.97	4.36	4.29	4.18	5.52
P ₂ O ₅	1.14	1.26	1.18	2.16	1.43	1.83	1.37	1.75	0.49
Cl	0.07	0.09	0.07	0.01	0.26	0.59	0.57	0.47	0.53
Total	100.02	99.49	99.75	97.67	98.70	99.35	98.83	99.34	99.47
Mineral host									
Fo				0.80	0.80	0.81	0.81	0.81	0.82
K _D				0.27	0.36	0.31	0.31	0.37	0.22
En	0.39	0.39	0.43						
Fs	0.15	0.15	0.11						
Wo	0.46	0.46	0.46						
H ₂ O (wt%)	0.06		0.03	1.17	0.28	0.05	0.05	0.08	0.02
F (wt%)	0.13		0.06	0.58	0.26	0.38	0.09	0.31	0.04
Cr (ppm)	179	555	224	356	173	111	137	124	283
V	298	410	326	62	144	135	96	87	47
Rb	32	15.1	27.4	56	75	180	173	153	248
Ba	484	145	375	627	1697	5107	4456	4151	969
Sr	783	367	659	1470	2398	2449	2198	2203	573
Zr	200	160	215	155	350	724	581	596	425
Hf	4.7	4.9	5.2	3.4	6.3	12.7	9.7	10.0	4.8
Nb	67	34	74	143	227	647	507	460	146
Ta	2.6	2.0	3.3	4.9	7.7	21.0	15.7	13.0	5.4
Th	4.2	1.3	6.3	15.9	18.1	56	41	42	35
U	1.2	0.34	1.7	3.7	4.7	14.3	10.7	9.6	12.6
Y	28.1	34	28.2	17.8	33	54	42	47	3.3
La	46	21.5	54	125	165	297	222	244	60
Ce	94	56	104	211	290	508	399	425	63
Nd	43	38	46	71	109	167	126	138	22.3
Sm	8.5	9.8	9.5	12.3	18.0	26.9	20.6	22.6	2.2
Eu	2.5	3.2	2.7	3.4	5.0	5.0	5.0	6.2	1.0
Gd	7.7	9.9	7.6	11.2	12.9	23.9	24.8	16.5	1.9
Dy	5.9	7.4	6.4	5.6	8.5	14.3	11.6	12.2	1.2
Er	3.2	3.2	3.4	2.3	3.9	7.6	5.8	6.2	0.41
Yb	2.6	3.2	3.0	0.39	1.9	3.5	1.6	3.0	0.17
B	1.5		5.4	4.8	6.6	8.6	2.7	12.0	9.9
Li	12.9		11.4	11.4	7.5	56	34	19.8	32
Be	0.75		1.3	3.7	3.0	4.1	1.0	3.4	1.8

$$K_D = (X_{\text{Fe}}^{\text{Ol}} X_{\text{Mg}}^{\text{liq}}) / (X_{\text{Mg}}^{\text{Ol}} X_{\text{Fe}}^{\text{liq}})$$

inclusions (Table 6). The regular overall negative slope of REE spider graphs, in many cases with small positive Eu anomaly is common for entire rock sequences. The concentration of REE increases in the tephrite-

basanite-nephelinite suite. Most melt inclusions show the enrichment in REE compared to whole-rock samples. The single evident exception is the lowest REE content in an unheated glassy inclusion hosted by an

Table 7 Electron microprobe and SIMS data on groundmass glasses

Sample	P6c	N14	N14	N14	N15/2	MR23/8b		
Rock	Tephrite	Anl-Ol nephelinite				Ol nephelinite		
SiO ₂ (wt%)	55.37	52.66	52.15	52.57	49.46	51.98	49.10	52.71
TiO ₂	2.23	1.42	1.20	1.52	0.62	0.60	0.38	0.84
Al ₂ O ₃	19.22	21.23	21.06	21.31	23.40	21.23	21.79	23.21
FeO	5.69	4.32	4.36	4.53	2.70	4.56	3.02	4.33
MnO	0.08	0.08	0.07	0.13	0.06	0.08	0.08	0.17
MgO	0.74	1.27	1.19	1.14	1.58	1.17	0.90	0.49
CaO	1.05	2.64	2.48	2.72	3.00	3.95	4.44	1.33
Na ₂ O	1.51	5.21	5.25	4.44	8.90	5.05	3.63	5.02
K ₂ O	2.15	3.80	3.35	4.21	0.34	4.64	3.43	4.90
P ₂ O ₅	0.45	0.40	0.37	0.34	0.35	0.26	0.43	0.48
Cl	0.21	0.44	0.42	0.40	0.06	0.30	0.47	0.67
Total	88.70	93.52	92.00	93.37	90.47	94.10	88.24	94.53
H ₂ O (wt%)	6.32	6.09	5.51	5.88	6.81	4.39	3.90	5.36
F (wt%)	0.05	0.30	0.32	0.25	0.39	0.17	0.21	0.11
Cr (ppm)	9.0	7.5	7.4	17.3	10.4	16.9	137	6.8
V	20.2	57	59	69	33	34	131	29.8
Rb	32	93	100	80	23	89	57	154
Ba	241	3371	3447	3424	1017	6269	5155	5960
Sr	157	2132	2177	2078	269	2676	4376	3247
Zr	519	269	266	251	218	479	479	385
Hf	9.4	3.3	3.8	3.6	2.5	5.9	8.3	5.3
Nb	162	383	389	378	292	730	473	538
Ta	6.1	11.8	11.9	11.3	7.5	20.1	14.1	17.6
Th	7.6	18.7	20.1	16.9	17.7	55	35	43
U	3.0	6.9	7.6	6.1	5.9	14.4	10.4	13.6
Y	30	18.9	18.1	16.5	9.3	32	49	32
La	44	73	71	62	40	167	157	139
Ce	79	104	106	88	65	243	254	200
Nd	30	29.8	29.7	26.1	16.0	57	89	54
Sm	5.4	4.4	4.5	4.0	2.6	8.1	15.2	7.5
Eu	1.4	1.2	2.2	1.3	1.1	2.3	5.3	2.0
Gd	4.6	2.6	3.6	3.0	1.9	6.9	12.9	7.2
Dy	5.7	3.3	3.5	3.2	1.9	5.9	10.6	6.3
Er	3.4	2.2	2.2	2.1	1.2	4.5	5.8	4.4
Yb	3.2	1.8	1.6	1.4	1.1	3.5	3.9	3.2
B	7.8	13.9	13.4	19.5	18.2	24.9	17.0	18.5
Li	2.5	6.0	6.4	9.4	7.3	8.4	6.2	2.4
Be	4.9	4.8	5.0	4.6	5.8	8.5	5.9	7.5

olivine phenocryst in a melilite-olivine nephelinite sample (Fig. 7d). Groundmass glasses commonly show the lowest range of REE.

The spider-graphs of trace elements in successive rock sequence normalized to the composition of the primitive mantle (McDonough et al. 1992) are shown in Fig. 8. The REE are plotted from left to right in order of increasing compatibility in a small fraction melt of the mantle. The spider graphs of the different rocks show the similar distribution pattern of elements with the increasing trace element concentrations from tephrite to melilite-olivine nephelinite. The whole-rock samples show minima of Rb and K, and weak positive anomalies of Nb and Ta. Melt inclusions hosted in

olivine phenocrysts have the highest contents of mainly incompatible elements whereas spider graphs of trace elements in melt inclusions hosted by clinopyroxene phenocrysts are similar or depleted compared to whole-rock contents. The groundmass glasses are mainly enriched in incompatible and depleted in compatible elements.

The following SIMS data on water and fluorine content were obtained on melt inclusions (Table 6) and groundmass glasses (Table 7). The range of water content in heated glasses of melt inclusions (data on 10 inclusions) is between 0.02 and 0.28 wt%, whereas the fluorine content is between 0.06 and 0.38 wt%. In one inclusion only, hosted by an olivine phenocryst in

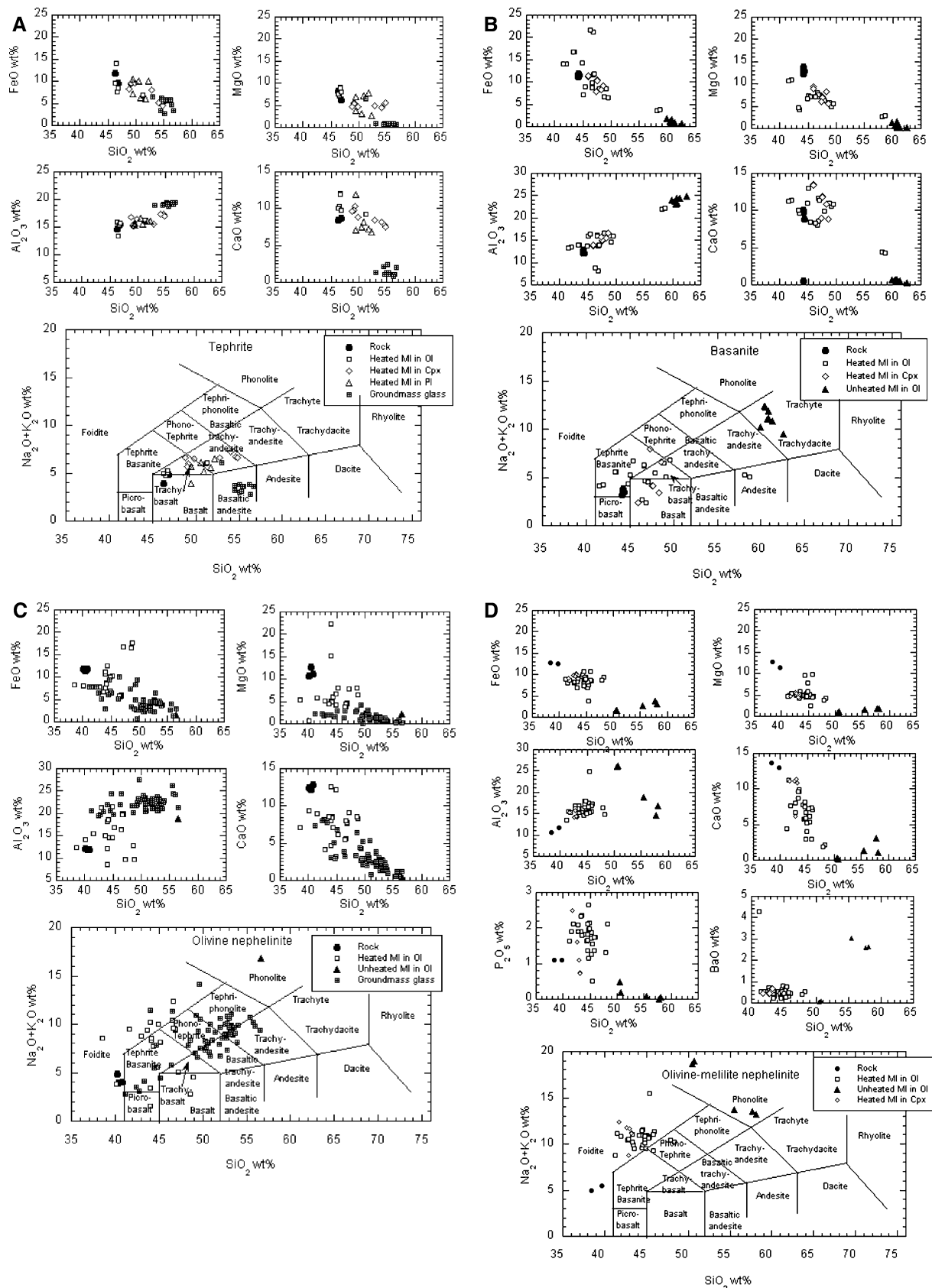
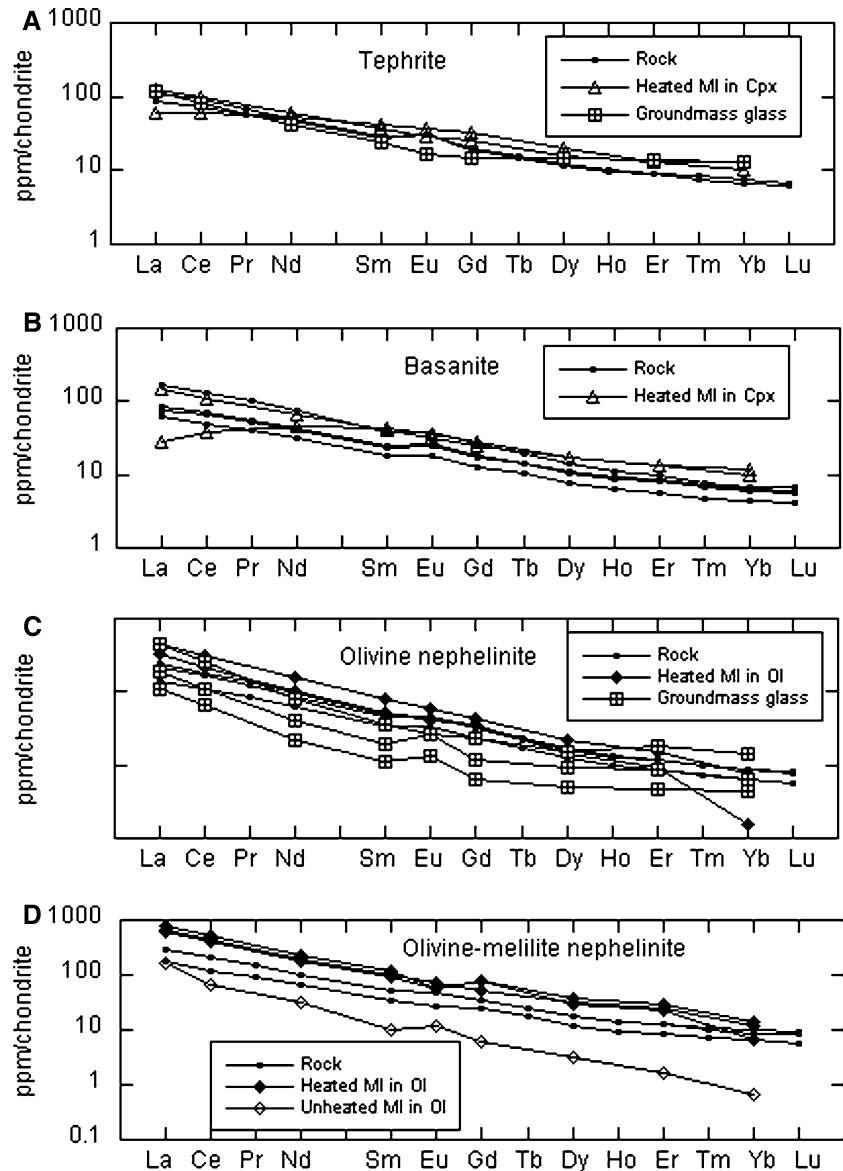


Fig. 6 SiO₂ versus other major oxides in host rock, groundmass glass, and heated and unheated melt inclusions in olivine, clinopyroxene and plagioclase phenocrysts. **a** Tephrite, **b** basanite, **c** olivine nephelinite, **d** olivine-melilitite nephelinite

Fig. 7 REE in host rock, groundmass glass, and heated and unheated melt inclusions in olivine and clinopyroxene phenocrysts normalized to chondritic meteorite values after Taylor and McLennan (1985). **a** Tephrite, **b** basanite, **c** olivine nephelinite, **d** olivine-melilite nephelinite



olivine nephelinite (sample T14/1 heated up to 1200°C), higher content of water (1.17 wt%) and fluorine (0.58 wt%) were recorded. In an unheated melt inclusion (olivine phenocryst, melilite-olivine nephelinite 480/1) the lowest concentrations of water and fluorine 0.02 and 0.04 wt%, respectively, were obtained.

Much higher content of water, which between 3.90 and 6.81 wt% (Table 7) is characteristic for groundmass glasses (data on eight glasses): the fluorine content is between 0.05 and 0.39 wt%.

According to electron probe data, melt inclusions in tephrite and basanite contain about 0.1–0.4 wt% of chlorine, whereas the chlorine content in inclusions in olivine nephelinite and melilite-olivine nephelinite is about 0.4–1.0 wt%. The common chlorine content of

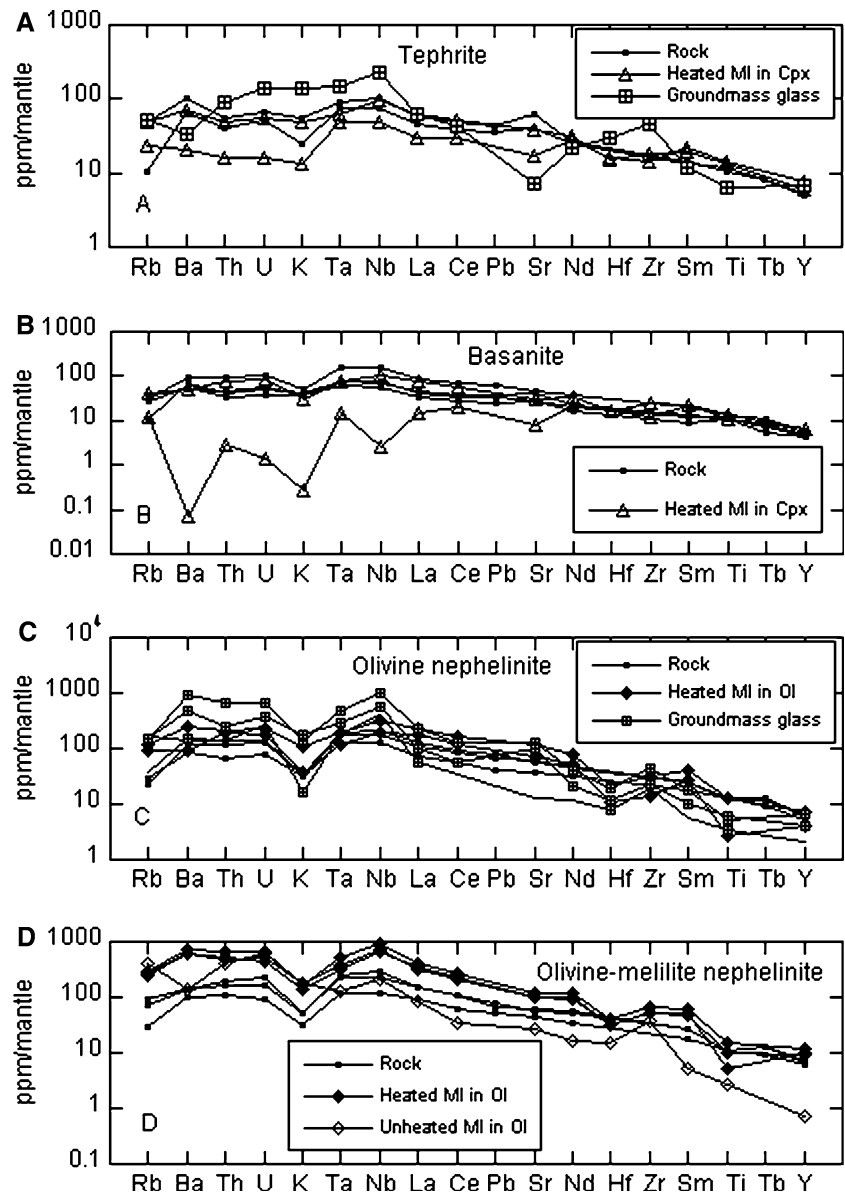
groundmass glasses is up to 0.7 wt%. P_2O_5 content in melt inclusions in tephrite and basanite is between 0.2 and 1.6 wt%, whereas inclusions in olivine nephelinite and melilite-olivine nephelinite contain between 0.4 and 3.4 wt% P_2O_5 . The P_2O_5 content in groundmass glasses is between 0.02 and 1.7 wt%.

Discussion

P–T conditions of rock generation

The common occurrence of fluid and melt inclusions in the same inclusion population indicates that fluid and melt phases coexisted during the growth of phenocrysts. Notably variable volume ratios of daughter

Fig. 8 Trace element concentrations in host rock, groundmass glass, and heated and unheated melt inclusions in olivine and clinopyroxene phenocrysts normalized to the composition of the primordial mantle (McDonough et al. 1992) and plotted from left to right in order of increasing compatibility in a small fraction melt of the mantle. **a** Tephrite, **b** basanite, **c** olivine nephelinite, **d** olivine-melilite nephelinite



crystals to vapor bubble in the same inclusion population suggest that there was magma-vapor immiscibility during the growth of phenocrysts and magma crystallization (Frezzotti 1992; Kamenetsky 2005).

The coexistence of fluid and melt inclusions allows one to use inclusion characteristics for evaluation of the P - T conditions of trapping. CO_2 inclusions usually show a rather wide range of densities. Their morphological features, such as halo of tiny inclusions surrounding bigger ones and the abundance of low-density inclusions clearly suggest the inclusion explosion within the phenocrysts during their travel within the magma to the surface (e.g. Vapnik 2005). In such a case, only a minor part of the inclusions, likely the

densest ones will preserve the primordial characteristics of inclusion trapping. Thus, the mean temperature range of melt inclusion homogenization and densest CO_2 inclusions were used for the pressure calculations (Table 5). The conditions of inclusion trapping and rock formations were evaluated as follows: tephrite: $P = 6.3\text{--}7.7$ kbar and $T = 1,150\text{--}1,250^\circ\text{C}$; basanite $P = 6.6\text{--}9.2$ kbar and $T = 1,150\text{--}1,250^\circ\text{C}$; olivine and analcime-olivine nephelinite: $P = 5.6\text{--}8.2$ kbar and $T = 1,150\text{--}1,250^\circ\text{C}$; melilite-olivine nephelinite: $P = 4.0\text{--}5.4$ kbar mainly between 1,150 and 1,200°C. Thus, the evolution of the rock suite occurred mainly at temperatures between 1,150–1,250°C and pressures from 4.0 to 9.0 kbar.

Geochemical data on whole rocks, glassy samples and melt inclusions

Electron microprobe data on heated melt inclusions show that the compositions of most silica-depleted inclusions are comparable to whole-rock compositions. This finding clearly proves that minerals containing inclusions are genuine phenocrysts. If large crystals were of xenocryst origin, the composition of inclusions would be the same in the entire rock suite. Thus, studied phenocrysts are primary daughter products of the igneous matter in which they occur.

The equilibrium coefficient of olivine phenocryst–melt inclusion is in the range of 0.27–0.37 (Table 6) indicating that commonly melt inclusion compositions are in equilibrium with host olivine phenocrysts (Ford et al. 1983). It seems that K_D range may reflect the somewhat different P – T conditions of melt inclusion trapping. Thus, the general trends of melt inclusion compositions reflect the crystallizing sequence of minerals. Melt inclusions show the accumulation of SiO_2 in the residual magma and this accumulation was accompanied by the decrease of FeO , MgO , and CaO and by the increase of Al_2O_3 and total alkali contents. Similar trends were also observed in other studies (Golovin et al. 2000; Kóthay et al. 2001; Naumov et al. 2003). Such behavior suggests the progressive crystallization of olivine and clinopyroxene that results in residual magma which is gradually enriched in leucocratic components. The groundmass glasses are formed at the final stages of this evolution. Their content is commonly more silica and alkali rich. It seems that the lower content of alkalis in tephrite glasses relatively to melt inclusions (Fig. 6a) may indicate that the crystallization of the lava flow was accompanied not only by the partial loss of volatiles but also of alkalis, specifically in the case of tephrite.

Most unheated glassy inclusions (which were composed of a large glass phase, tiny solid phases and in some cases a gas bubble) in olivines show extremely high silica and in many cases alkali contents too, whereas contents of FeO and MgO are the lowest relative to heated inclusions. The obtained glass compositions in glassy inclusions are comparable to glass compositions in unheated inclusions (Table 4) bearing numerous solid phases which occupy at least 20–40% of inclusion volume (Fig. 4b, c). Similar data on glasses of multiphase unheated inclusions were reported by Golovin et al. (2000) and Kóthay et al. (2001). It is clear that small amount of mineral phases (spinel) in glassy inclusions cannot contribute significantly to total inclusion composition. One may assume that during natural quenching of inclusions most of the olivine

which was dissolved in the melt was precipitated on the walls of cavities, and because these inclusions were not subjected to homogenization experiments they show the mentioned particular compositions. This suggestion was checked by simple calculation assuming olivine contribution into the content of inclusion glass. It was suggested that the maximal possible amount of olivine may be determined by maximal content of MgO in the heated inclusions which is about 8–9 wt%. The calculation shows that this MgO content may be achieved by the addition of about 15 wt% of olivine. The addition of 15 wt% of olivine decreases the content of silica only by about 2 wt% and thus, inclusions remained still anomalous. Such glassy inclusions were found in olivines of the highest $\text{Mg\#}$, Fo_{90-82} , whereas heterogeneous inclusions were found in Fo_{85-73} . So, glassy inclusions show distinct, usually trachyte-phonolite compositions, evidently they formed from the melt with higher viscosity which determined their glassy appearance. Furthermore, the trace element spider graph of one such inclusion completely differs from spider graphs of rocks, heated melt inclusions, and groundmass glasses (Fig. 8d). It is possible that glassy melt inclusions do not belong to the studied rock suite and reflect one of the earlier magmatic phases. Compositionally similar rocks, associated with some earlier magmatic event were reported in the area of Mt. Hermon, North Israel (Wilson et al. 2000).

The analysis of REE graphs shows a similar pattern of element distribution for the entire rock sequence. The negative Eu anomaly on REE graphs of olivine nephelinites and melilite-olivine nephelinites is absent (Fig. 7) indicating that these magmas did not evolve by fractionation of plagioclase. The tenfold enrichment in LREE is characteristic for olivine nephelinites and melilite-olivine nephelinites relative to tephrite and basanite samples. Inclusions both in olivine and clinopyroxene phenocrysts show some enrichment in REE relatively to REE content in rock samples. Such behavior suggests that phenocryst crystallization and trapping of melt inclusions occurred from magma enriched in REE which was likely to have occurred at the onset of magma crystallization. In contrast the groundmass glasses show the lowest REE pattern, which clearly indicates their quenching at the latest stage when most REE had already been incorporated in apatite.

The spider graphs of incompatible elements normalized to primordial mantle show similar features for the entire rock sequence (Fig. 8a–d). Mantle source material was enriched in incompatible elements with depletion of Rb and K, and some enrichment in Nb and Ta. Melilite-olivine nephelinites are slightly de-

pleted in Ti, which is related to their lower content of clinopyroxene. The enrichment in incompatible elements in the series tephrite-basanite-nephelinite suite is evident. Such behavior of incompatible elements may reflect the decreasing rate of partial melting at the mantle source or accumulation of trace elements in the final portions of magma during its fractionation. Considering the remarkable smooth pattern of Eu on REE graphs magma fractionation was minor and the main reason for magma diversity was likely determined by a different degree of batch partial melting.

The accumulation of mainly incompatible elements in the last products of magma crystallization is clear from the highest contents of these elements in groundmass glasses (Fig. 8a, c, d), whereas, as compatibility of elements increased, their content in groundmass glasses became similar to their content in rock samples. High content of incompatible elements is also observed in heated melt inclusions hosted by olivine phenocrysts. The exception was observed for glassy unheated melt inclusion (sample 480/1), which shows the lowest concentrations of trace elements. Inclusions in clinopyroxenes have comparable or depleted contents of trace elements relatively to rock samples. It is likely that these inclusions were trapped contemporaneously with apatite crystallization which determined their depletion in trace elements compatible with apatite.

Both REE and spider graphs (Figs. 7, 8) show similar patterns of element distribution, which implies magma generation from the same source and indicates that the rock suite constitutes a single rock series subjected to magmatic differentiation.

Magma volatile content

The composition and concentration of volatiles in the magma is one of the most important factors determining the melting processes. Analcime is an important rock-forming mineral in some subvolcanic bodies; also, biotite and amphibole were found in the matrix of several samples. These water-bearing minerals indicate the presence of water during the magma crystallization. But no water-rich inclusions were found in phenocrysts. Nevertheless, the presence of water at late magmatic and post magmatic stages is indicated by the abundance of zeolite-filled amygdules, common serpentinization of olivine and zeolitization of foid minerals. The question remains about the origin of this water. The obtained results are rather problematic. The microthermometric data on water-rich inclusions in a calcite-filled amygdule (only one amygdule was suitable for the study) indicate a meteoric source of the

water (low-salinity, high density). The dryness of the melt at the magmatic stage is supported by high liquidus temperature of melt inclusions, by the gas bubble in melt inclusions filled by CO₂ fluid, complete absence of water phase in CO₂ inclusions which are contemporaneous with melt inclusions, and also by direct analyses of volatile content in melt inclusions by SIMS. The water content in melt inclusions is commonly between 0.02 and 0.28 wt%, and only in one inclusion in olivine-nephelinite is it as high as 1.17 wt% (Table 6). The low water content in melt inclusions may be partially related to water loss during diffusion of hydrogen from melt inclusions subjected to heating (Sobolev and Danyushevsky 1994; Massare et al. 2002; Danyushevsky et al. 2002). But to minimize the water loss the inclusions were kept at highest temperature for as short a time as possible in order to achieve homogenization. Hence, water loss considered to have been minor and this is supported by the minor water contents recorded in unheated inclusion (Table 6). Nevertheless, much higher water content between 3.9 and 6.8 wt% was determined in groundmass glasses (Table 7). The late partial hydration of glasses cannot be completely excluded, but it is evident that the residual silicate liquid became enriched in H₂O and such enrichment was directly recorded in one melt inclusion hosted by olivine phenocryst in olivine-nephelinite matrix (Table 6). The same process likely describes the presence of rhönite in early anhydrous melt and then the stability of amphibole in later trapped hydrous melt inclusions. Summing up, both meteoric and exsolved water from magma were likely responsible for late rock alteration.

The database on volatile content of mafic magmas is rapidly growing. We restricted the comparison of our data on volatile content with the comprehensive study of melt inclusions in Hawaiian samples (Hauri 2002) and trachybasalt samples from southern Baikal region (Naumov et al. 2003). The last mentioned melt inclusions and our samples were studied in the same SIMS laboratory. Water contents between 0.03 and 0.81 wt% and between 0.41 and 0.68 wt% were determined for melt inclusions in Hawaiian tholeiites and alkali basalts, respectively. The SIMS data on a few inclusions in olivine phenocrysts in trachybasalt from southern Baikal region indicate water content of about 0.46 wt%. Thus, water content in Makhtesh Ramon inclusions is several times lower than in Hawaiian (Hauri 2002) and southern Baikal samples (Naumov et al. 2003).

It is impossible to evaluate directly the CO₂ content in melt inclusions because of the non-determined density of CO₂ phase. One can estimate CO₂ as a

remainder after subtracting total major element composition of melt inclusions plus trace element, water and fluorine contents. The resulting CO₂ content in melt inclusions is thousands or more likely hundreds of ppm. Several hundred ppm of CO₂ are also common in Hawaiian samples (Hauri 2002).

The fluorine content in melt inclusions is between 400 and 5,800 ppm (Table 6). A similar range of fluorine content was observed in the groundmass glasses (Table 7). For Hawaiian samples the fluorine content in melt inclusions is in the range of 300–1,000 ppm (Hauri 2002); for southern Baikal samples the fluorine content is between 600 and 700 ppm (Naumov et al. 2003).

The P₂O₅ content in melt inclusions is commonly about 1 wt% in basanite and tephrite. In olivine nephelinite and melilite-olivine nephelinite samples P₂O₅ content is up to 2.5 wt% (Fig. 6d). Chlorine in melt inclusions shows similar behavior; in basanite and tephrite common content of Cl is between 0.1 and 0.4 wt% whereas in nephelinite and melilite-olivine nephelinite it is between 0.4 and 1.0 wt%. Much lower P₂O₅ and chlorine contents in the range of 200–700 and 10–560 ppm, respectively, were determined in Hawaiian samples (Hauri 2002). P₂O₅ content between 0.77 and 0.84 wt% was obtained for southern Baikal trachybasalt, whereas chlorine content was between 300 and 600 ppm (Naumov et al. 2003). There is no indication of increased chlorine content in the groundmass glasses, whereas P₂O₅ content in glasses is strongly reduced compared with its content in melt inclusions. Such behavior of phosphorous, chlorine, and likely fluorine indicate that when crystallization of groundmass glass occurred most of these elements were already taken up by apatite.

The constraints on the genesis of alkaline rock suite in western Makhtesh Ramon

The geological observations suggest the earlier generation of tephrite and basanite magmas, followed by the intrusion of nephelinite magma. It seems that the location of the melilite-olivine nephelinite zone in the central part of Mt. Tabaat subvolcanic nephelinitic body and its gradual transition to melilite-free outer rim composed of olivine nephelinite may indicate the pattern of differentiation of the parent nephelinitic magma. The rapid crystallization of nephelinitic magma led to formation of olivine nephelinite with calcite amygdules, whereas slower crystallization with the degassing of CO₂ led to an increased surplus of Ca and crystallization of melilite. The likely similar rapid volatile degassing has been observed in several

other cases when the glassy varieties of rocks were formed in the sub-apical parts of subvolcanic bodies such as Western Hills, Nephelinitic Hill, and Analcimitic Hills.

It seems that the fixed range of *P*–*T* conditions was not critical for the formation of rock varieties in western Makhtesh Ramon. For example, olivine nephelinite of Nephelinitic Hill started to crystallize at *T* between 1,200 and 1,300°C, and pressures 8.0–8.5 kbar, olivine nephelinite at Western Hills at a temperature of about 1,250°C and pressure of about 7 kbar, olivine nephelinite at Mt. Tabaat at a temperature between 1,150 and 1,200°C and pressures between 5.5 and 7.0 kbar (Table 5). The highest pressures up to 9.0 kbar were recorded for basanitic nephelinite. This finding is in contradiction to the experimental results (Kushiro 1968) that predict the generation of most SiO₂ undersaturated magmas at rising pressures (Schiano and Bourdon 1999).

Conclusions

Early Cretaceous magmatism has been identified at several localities within the Middle East and is one of the phases of Mesozoic volcanism associated with a major extension-related volcanic event which occurred along a passive continental margin in the course of the opening of the Neotethys ocean (Abdel-Rahman 2002). In the Middle East the Early Cretaceous magmatic phase is known in Israel, Jordan, Lebanon, and Syria (Laws and Wilson 1997; Wilson et al. 2000; Abdel-Rahman 2002). Alkaline igneous rocks including basanite, tephrite and trachyte have been found at Mount Hermon, North Israel (Wilson et al. 2000) and in Syria (Mouty et al. 1992). In central Lebanon these are mainly alkali basalts (Abdel-Rahman 2002). In Makhtesh Ramon the rock sequence is represented by the evolved rock suite with alkali ultrabasic and basic rocks, such as melilite-olivine nephelinite, olivine nephelinite, basanitic nephelinite, basanite, and tephrite. The geochemical studies indicate that the primitive mafic magmas are similar to those of HIMU, and suggest the involvement of an enriched plume-related mantle source in the petrogenesis of the alkaline magma (Garfunkel 1991; Laws and Wilson 1997; Wilson et al. 2000; Abdel-Rahman 2002). The upwelling of the mantle plume may be supported by the presence of hotter than ambient mantle beneath lithosphere (Wilson et al. 2000). The support of this idea was provided by the fluid and melt inclusion data on mantle xenoliths which indicated very high geothermal gradient during the Early Cretaceous (Vapnik 2005).

The geochemical constraints provide some information on the type of mantle source involved in partial melting. Partial melting of a small fraction of garnet-peridotite facies mantle with relatively large melt fraction from spinel-peridotite facies mantle was suggested for magmas of Mt. Hermon, North Israel (Wilson et al. 2000). Spinel-peridotite partial melting was suggested for magmas of Syria (Mouty et al. 1992). The batch partial melting of primitive garnet lherzolite was argued for magmas of central Lebanon (Abdel-Rahman 2002). Transitional conditions of spinel-garnet peridotite have been suggested on the basis of a few thermobarometric calculations of mineral equilibria in spinel-lherzolite xenoliths in Makhtesh Ramon (Stein et al. 1993). A more representative thermobarometric data set, melt and fluid inclusion data, and complete lack of garnet in xenoliths suggest rather a spinel-peridotite facies mantle source (Vapnik 2005). The present work permits further clarification of the conditions of magma genesis in Makhtesh Ramon.

The microthermometric data on the fluid and melt inclusions indicate that the conditions of magma genesis corresponded to those of the spinel- and plagioclase-lherzolite fields (Hall 1996). The rock sequence was generated at temperatures between 1,200 and 1,300°C and pressures between 4.0 and 9.0 kbar. These data clearly indicate the shallowest depth of magma genesis in Makhtesh Ramon relatively to other occurrences of Early Cretaceous magmatism in the Middle East.

The different degree of batch partial melting of the same source rocks was likely the main process which determined the magma diversity in western Makhtesh Ramon. The minor diversity was controlled by volatiles loss during magma crystallization.

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