Bulletin of Volcanology

Origin and ascent history of unusually crystal-rich alkaline basaltic magmas from the western Pannonian Basin

--Manuscript Draft--

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Abstract:	The last eruptions of the monogenetic Bakony-Balaton Highland Volcanic Field (western Pannonian Basin, Hungary) produced unusually crystal- and xenolith-rich alkaline basalts which are unique among the alkaline basalts of the Carpathian-Pannonian Region. Similar alkaline basalts are only rarely known in other volcanic fields of the world. These special basaltic magmas fed the eruptions of two closely located volcanic centres: the Bondoró-hegy and the Füzes-tó scoria cone. Their uncommon enrichment in diverse crystals produced unique rock textures and modified original magma compositions (13.1-14.2 wt.% MgO, 459-657 ppm Cr, 455-564 ppm Ni contents). Detailed mineral-scale textural and chemical analyses revealed that the Bondoró-hegy and Füzes-tó alkaline basaltic magmas have a complex ascent history, and that most of their minerals (~30 vol.% of the rocks) represent foreign crystals derived from different levels of the underlying lithosphere. The most abundant xenocrysts, olivine, orthopyroxene, clinopyroxene and spinel, were incorporated from different regions and rock types of the subcontinental lithospheric mantle. Megacrysts of clinopyroxene and spinel could have originated from pegmatitic veins / sills which probably represent magmas crystallized near the crust-mantle boundary. Green clinopyroxene xenocrysts could have been derived from lower crustal mafic granulites. Minerals that crystallized in situ from the alkaline basaltic melts (olivine with Cr-spinel inclusions, clinopyroxene, plagioclase, Fe-Ti oxides) are only represented by microphenocrysts and overgrowths on the foreign crystals. The vast amount of peridotitic (most common) and mafic granulitic materials indicates a highly effective interaction between the ascending magmas and wall rocks at lithospheric mantle and lower crustal levels. However, fragments from the middle and upper crust are absent from the studied basalts, suggesting a change in the style (and possibly rate) of magma ascent in the crust. These xenocryst- and xenolith-rich basalts yield divers tools for estimating magma ascent rate that is important for hazard forecasting in monogenetic volcanic fields. According to the estimated ascent rates, the Bondoró-hegy and Füzes-tó alkaline basaltic magmas could have reached the surface within hours to few days, similarly to the estimates for other eruptive centres in the Pannonian Basin which were fed by "normal" (crystal- and xenolith-poor) alkaline basalts.
Response to Reviewers:	Dear Professor I.E.M. Smith,

	thank you very much for your corrections, we have approved all of your changes. Yours sincerely, M. Éva Jankovics on behalf of the authors

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J. D. L. White
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27 October 2012

Dear J. D. L. White,

please find enclosed a manuscript what we intend to publish in the Bulletin of Volcanology Thematic Issue: *Monogenetic volcanism and its relevance to the evolution of volcanic fields*:

M. Éva Jankovics, Gábor Dobosi, Antal Embey-Isztin, Balázs Kiss, Tamás Sági, Szabolcs Harangi, Theodoros Ntaflos:
Origin and ascent history of unusually crystal-rich alkaline basaltic magmas from the western Pannonian Basin

It is about the detailed mineral-scale textural and chemical analyses, revealed ascent history and estimated magma ascent rates of the unusually crystal- and xenolith-rich alkaline basalts which are the youngest volcanic products in the Bakony-Balaton Highland Volcanic Field, western Pannonian Basin (Hungary).

We suggest three appropriate reviewers:

1) Ronald V. Fodor - rfodor@ncsu.edu, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University

2) Hilary Downes - h.downes@ucl.ac.uk, Department of Earth and Planetary Sciences, Birkbeck University of London

3) Hannes B. Mattsson - hannes.mattsson@erdw.ethz.ch, Institute of Geochemistry and Petrology, Swiss Federal Institute of Technology (ETH Zürich)

Yours sincerely,

M. Éva Jankovics
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27 October 2012

Dear J. D. L. White,

we would like to submit our manuscript in the **Thematic Issue:** ***Monogenetic volcanism and its relevance to the evolution of volcanic fields***. It is about the detailed analyses, revealed ascent history and estimated magma ascent rates of the unusually crystal- and xenolith-rich alkaline basalts which are the youngest volcanic products in the Bakony-Balaton Highland Volcanic Field, western Pannonian Basin (Hungary). Our manuscript is longer than what is given for Research Articles (7000 words). This is because we applied a number of different methods to estimate magma ascent times and rates which, in our opinion, requires a detailed description about the background and applicability in the case of every method. We tried to shorten the extent of the manuscript but we were not able to, and now we think that the descriptions and interpretations compose a whole in the present form. However, if the editors and reviewers find it groundlessly long, we are of course open to cut down where needed.

Yours sincerely,

M. Éva Jankovics

Figure1
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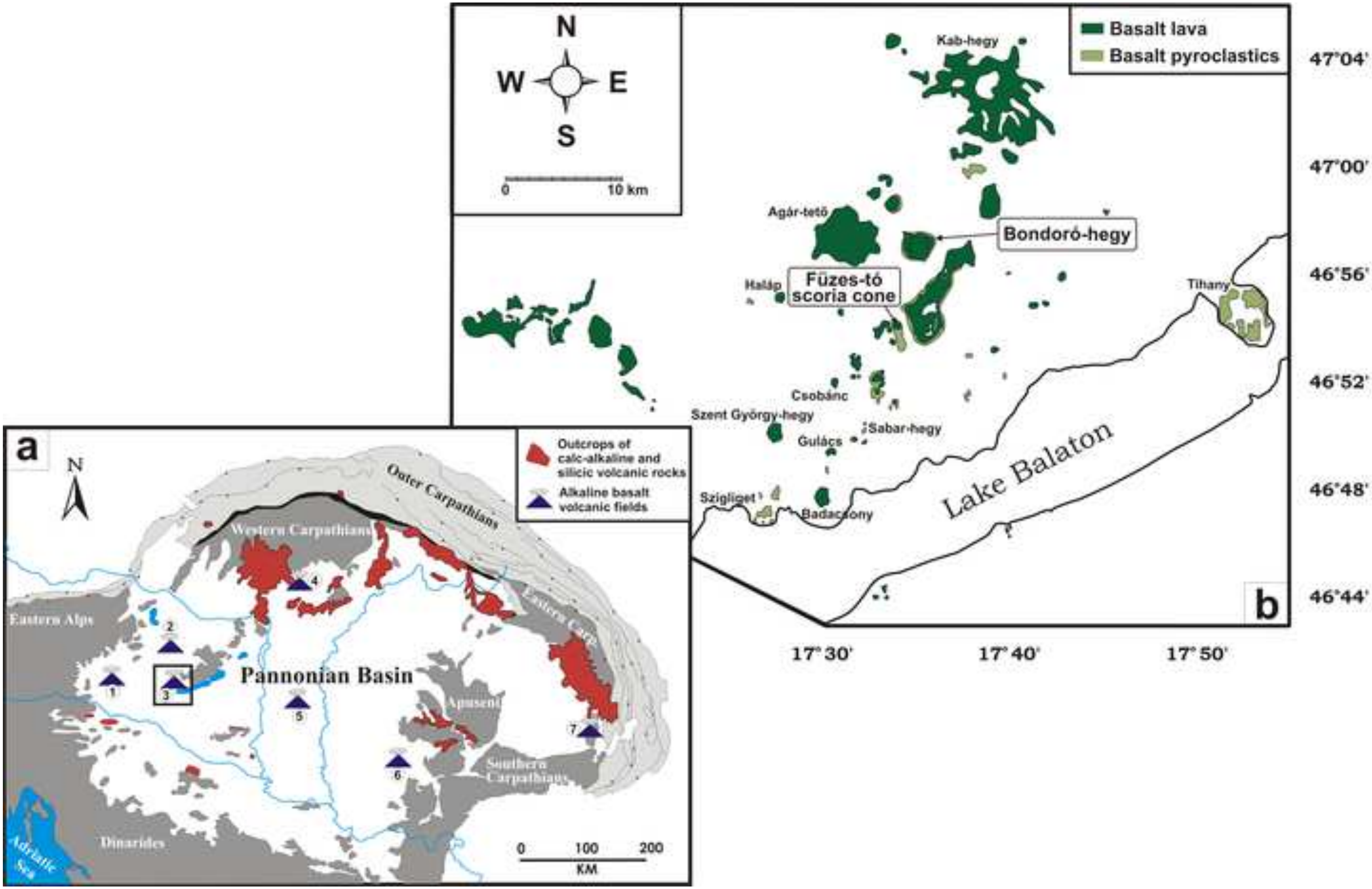

Figure3
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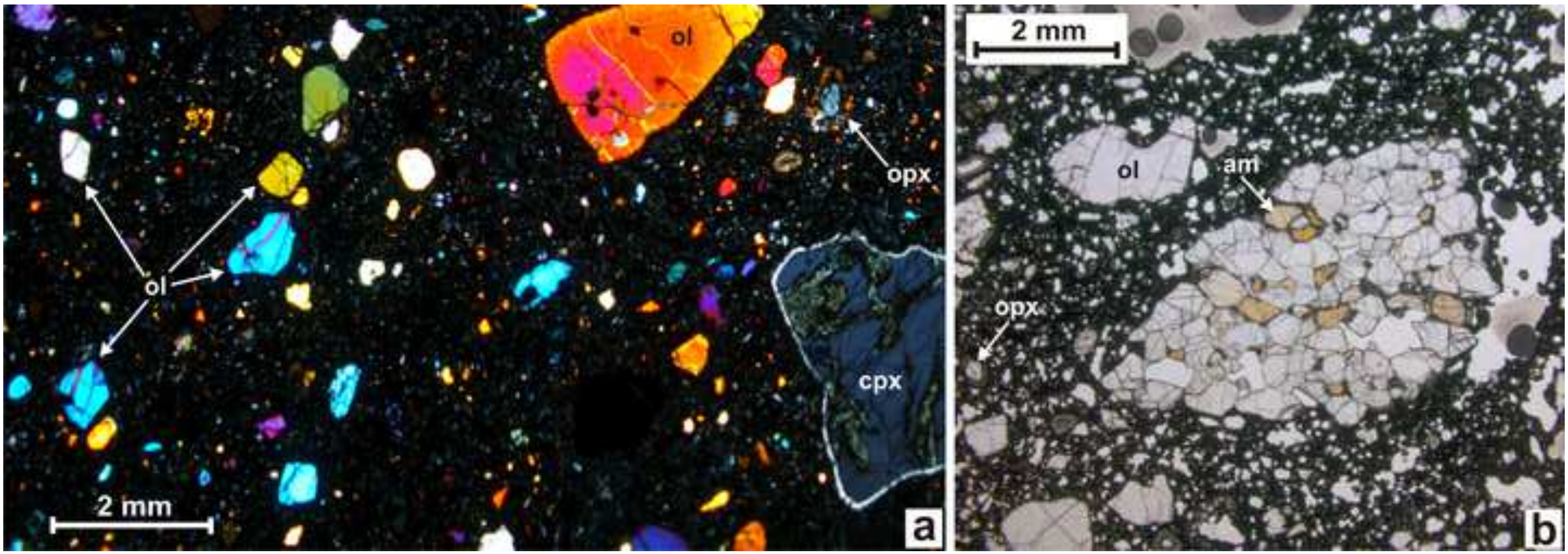

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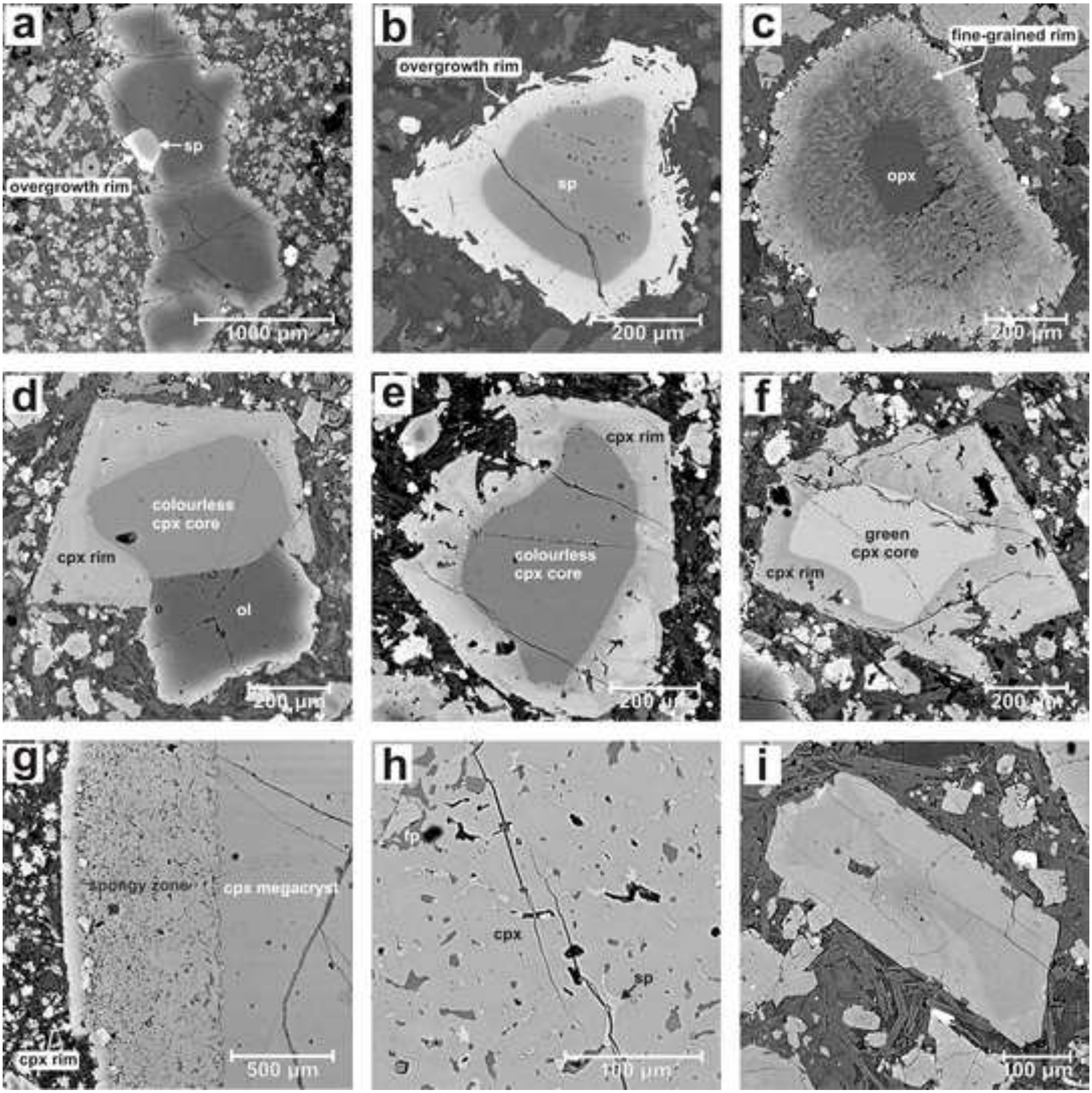

Figure5

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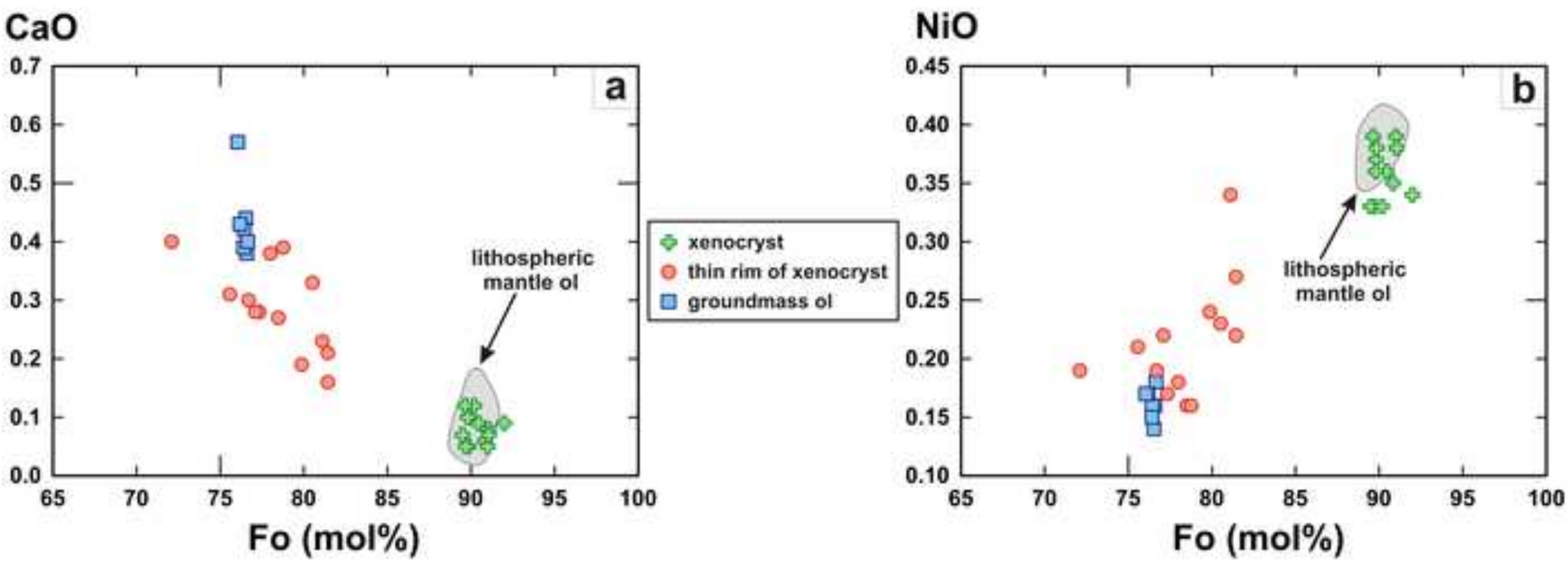

Figure6

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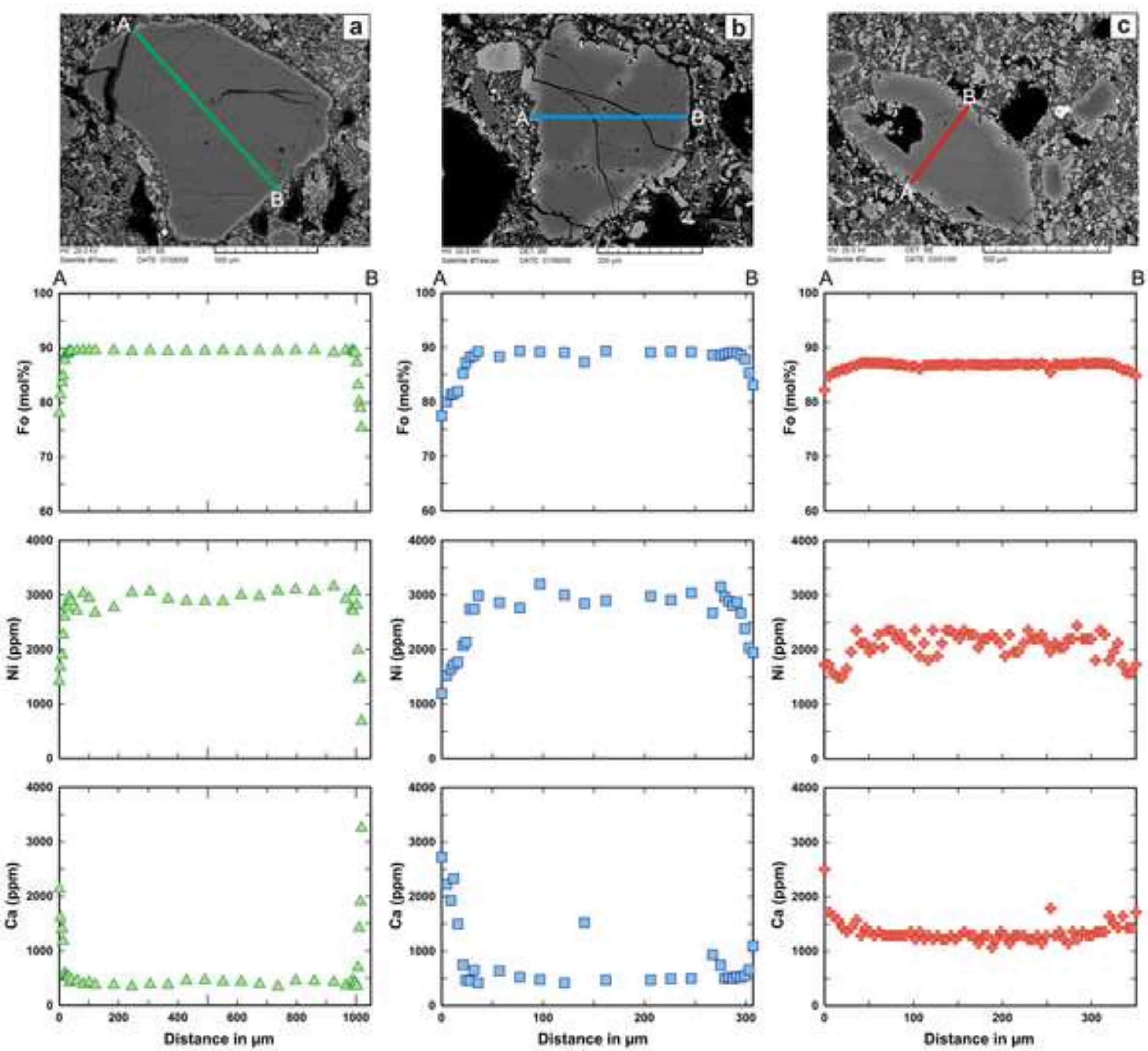

Figure7
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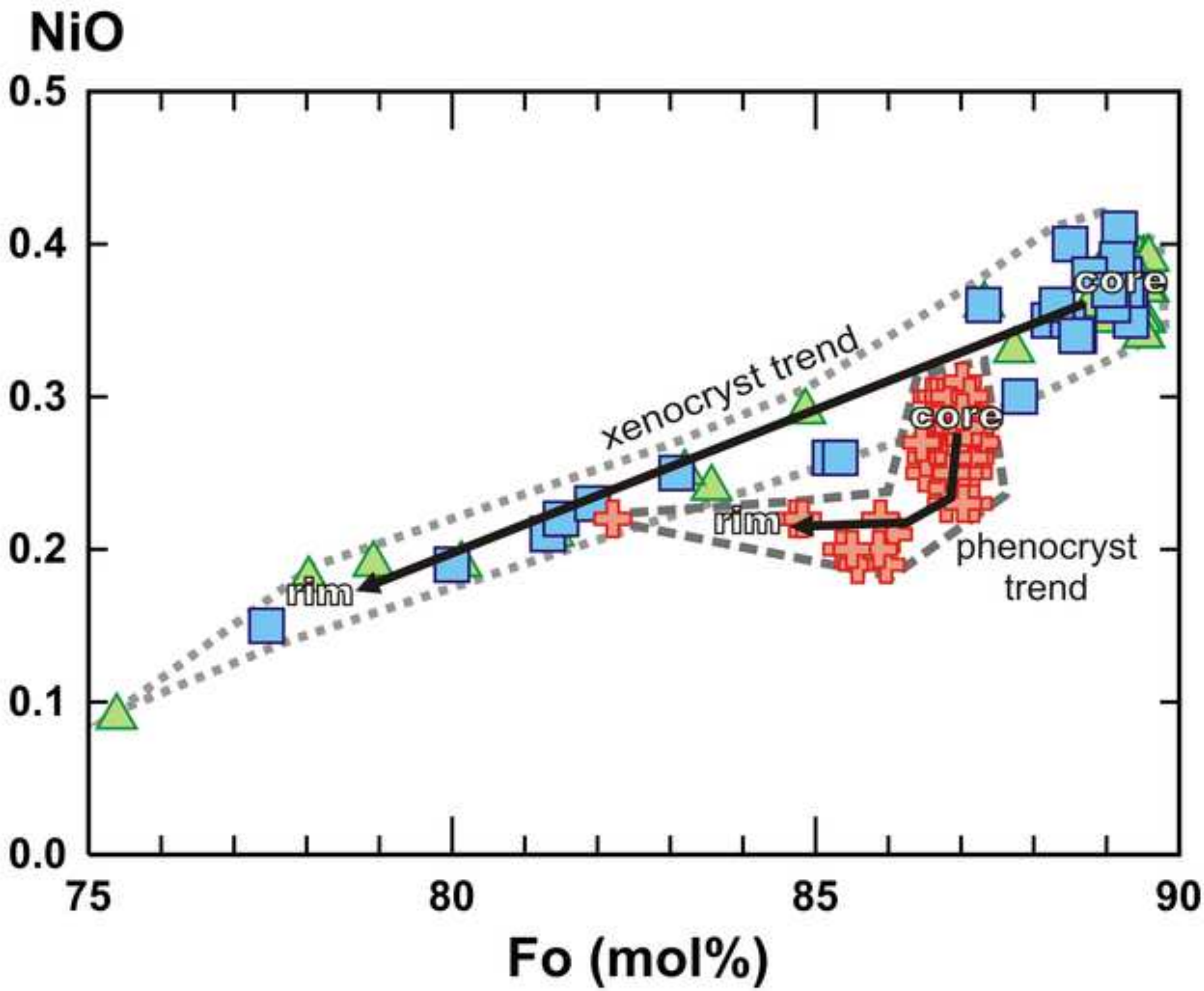

Figure8

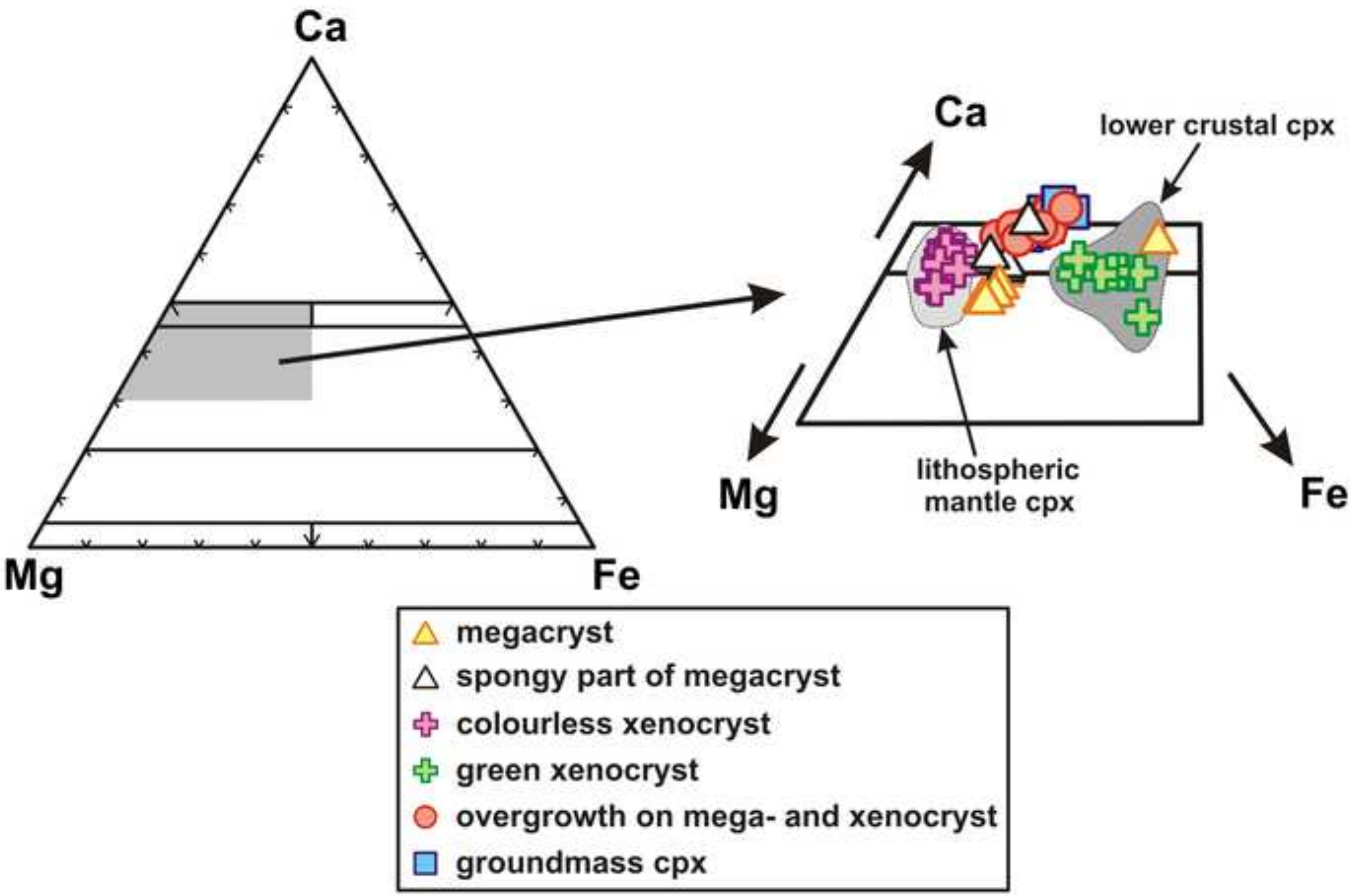
Ca
Mg
Fe
Ca
lower crustal cpx
Mg
lithospheric
mantle cpx
Fe
megacryst
spongy part of megacryst
colourless xenocryst
green xenocryst
overgrowth on mega- and xenocryst
groundmass cpx

Figure9

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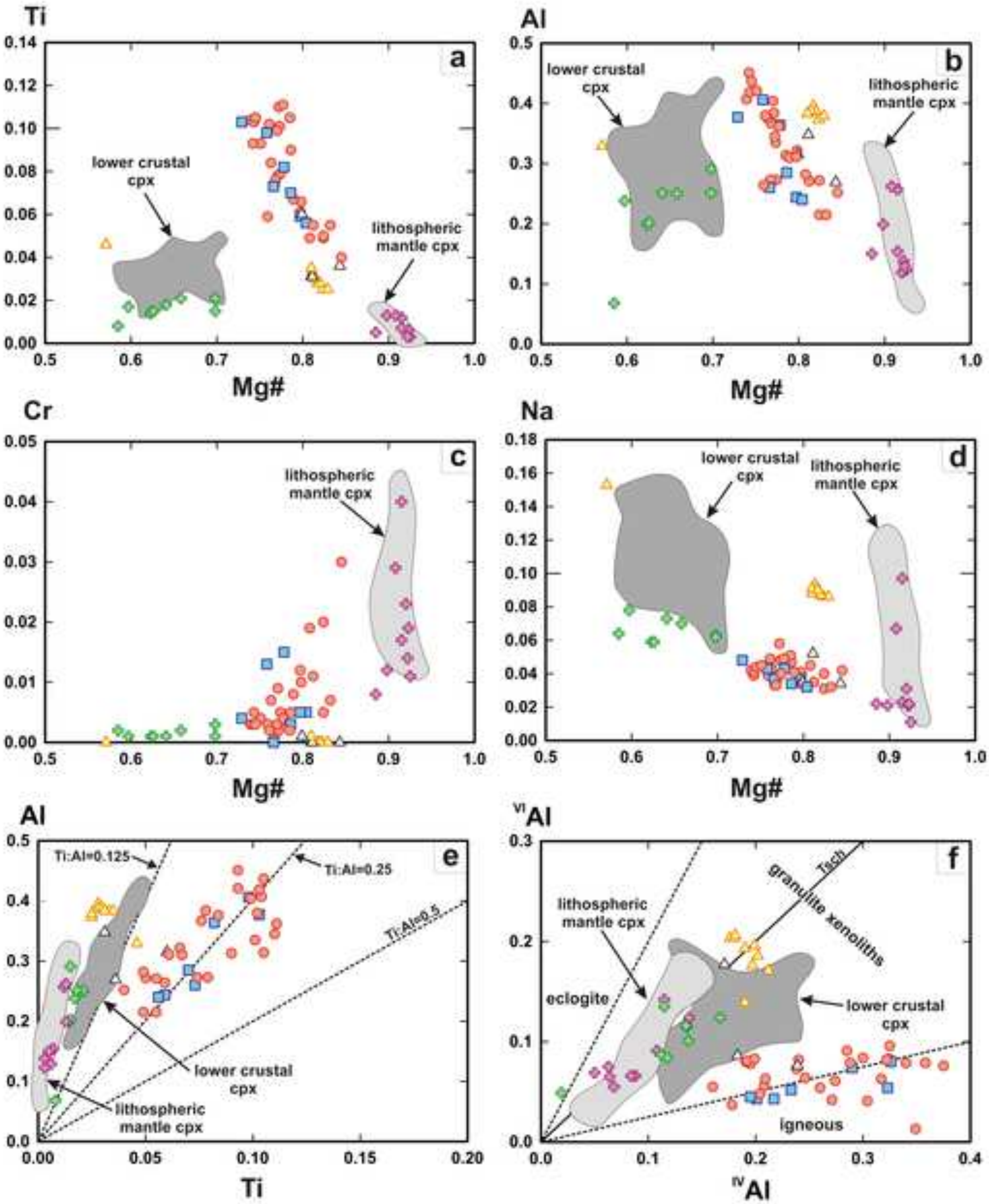

Figure10
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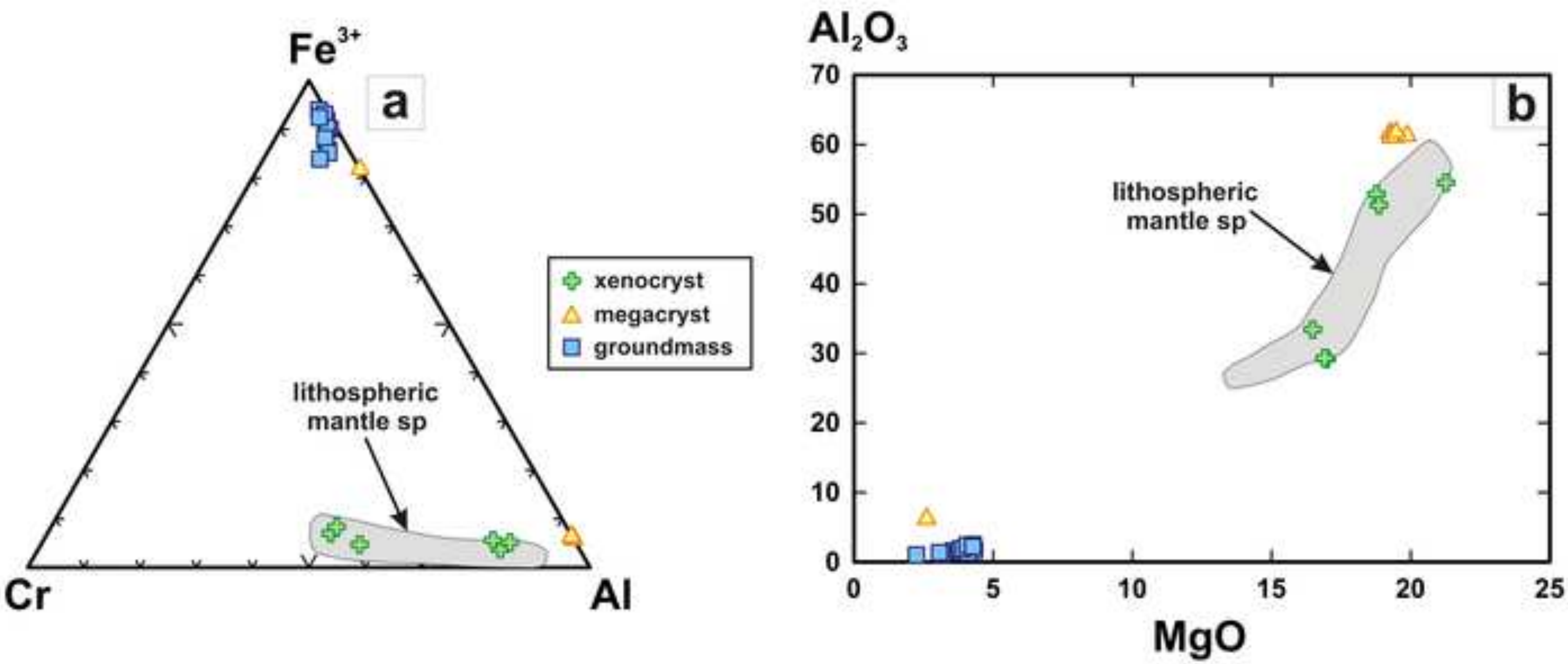

Table 1
Major and trace element analyses of the BON683 sample from Bondoró-hegy (Embey-Isztin et al., 1993

Major elements (wt%)		Trace elements (ppm)	
SiO_2	45.58	Ni	455
TiO_2	1.74	Cr	459
Al_2O_3	13.64	V	144
Fe_2O_3*	10.09	Sr	790
MnO	0.16	Rb	56
MgO	13.94	Zr	260
CaO	8.13	Nb	72
Na_2O	3.88	Ba	772
K_2O	1.97	Y	25
P_2O_5	0.75	La	47.4
Sum	99.88	Ce	91.02
LOI	0.23	Sm	6.74
SI	-16.73	Eu	2.11
ne	12.4	Yb	1.93
Mg#	76.3	Lu	0.3

total Fe is in the form of Fe_2O_3*
Mg# = 100*Mg/(Mg+Fe^{2+})

3a)

Table 2
Representative compositions of the studied olivines

	1	2	3	4	5
	Xenocryst (Fig. 2a)		Xenocryst		Groundmass
	core	rim	core	rim	ol
SiO_2	40.52	39.42	41.01	39.57	38.74
FeO^{tot}	10.08	18.03	8.78	21.09	21.24
NiO	0.39	0.23	0.38	0.19	0.16
MnO	0.19	0.50	0.12	0.49	0.49
MgO	48.96	41.82	50.03	38.94	39.01
CaO	0.12	0.33	0.08	0.30	0.38
Sum	100.26	100.33	100.39	100.58	100.02
Cations based on 4 oxygens					
Si	0.994	1.001	0.998	1.016	1.003
Fe	0.207	0.383	0.179	0.453	0.460
Ni	0.008	0.005	0.007	0.004	0.003
Mn	0.004	0.011	0.002	0.011	0.011
Mg	1.790	1.583	1.814	1.490	1.505
Ca	0.003	0.009	0.002	0.008	0.011
Fo (m%)	89.64	80.52	91.04	76.69	76.60

ol=olivine

Table 3
Representative analyses of the studied orthopyroxenes and clinopyroxenes

	1	2	3	4	5	6	7
	Opx xeno-cryst (Fig. 2b) homogeneous	Zoned cpx phenocryst (Fig. 2c) colourless		Zoned cpx phenocryst colourless		Zoned cpx phenocryst (Fig. 2e) light green	
	core	core	rim	core	rim	core	rim
SiO_2	56.07	52.47	42.92	53.25	45.43	49.95	44.61
TiO_2	0.02	0.26	3.25	0.22	2.79	0.75	3.50
Al_2O_3	2.99	3.57	10.09	3.00	8.71	5.63	9.12
Cr_2O_3	0.59	0.58	0.11	0.65	0.30	0.06	0.10
FeO^{tot}	5.67	2.79	7.05	2.55	6.42	10.54	6.33
MnO	0.13	0.10	0.14	0.07	0.12	0.14	0.13
MgO	33.70	16.89	11.38	17.05	12.13	11.39	11.87
CaO	0.78	22.58	22.66	22.72	22.67	19.66	22.57
Na_2O	0.03	0.33	0.53	0.32	0.54	0.95	0.51
Sum	99.98	99.56	98.13	99.80	99.11	99.04	98.74
Formulae for 4 cations and 6 oxygens							
Si	1.933	1.913	1.626	1.937	1.700	1.886	1.678
Al^{IV}	0.067	0.087	0.374	0.063	0.300	0.114	0.322
Al^{VI}	0.055	0.066	0.076	0.065	0.084	0.136	0.083
Ti	0.001	0.007	0.093	0.006	0.078	0.021	0.099
Cr	0.016	0.017	0.003	0.019	0.009	0.002	0.003
Fe^{3+}	0.000	0.014	0.148	0.000	0.089	0.004	0.075
Fe^{2+}	0.163	0.071	0.074	0.077	0.111	0.328	0.124
Mn	0.004	0.003	0.004	0.002	0.004	0.004	0.004
Mg	1.731	0.917	0.642	0.924	0.676	0.640	0.665
Ca	0.029	0.882	0.920	0.885	0.909	0.795	0.910
Na	0.002	0.023	0.039	0.022	0.039	0.069	0.037
Mg#	0.91	0.92	0.74	0.92	0.77	0.66	0.77

opx=orthopyroxene; cpx=clinopyroxene; Mg# = $Mg/(Mg+Fe^{tot})$

8	9	10	11	12	13	14	15
Zoned cpx phenocryst		Cpx megacryst (Fig. 2f)			Cpx megacryst		
		colourless			colourless		
light green		homogeneous	spongy	overgrowth	homogeneous	spongy	overgrowth
core	rim	core	zone	rim	core	zone	rim
49.01	47.29	49.21	49.47	44.51	49.63	49.38	44.47
0.53	2.41	1.08	1.29	3.66	1.11	1.11	3.29
6.62	7.07	9.03	6.22	9.17	8.85	7.96	9.49
0.03	0.28	0.01	0.00	0.10	0.00	0.00	0.14
9.26	6.26	5.87	5.02	7.08	5.86	5.74	6.79
0.22	0.16	0.15	0.14	0.14	0.13	0.13	0.13
12.01	13.15	14.39	15.10	11.27	13.98	13.82	11.52
20.76	22.48	18.49	21.83	22.54	18.59	20.02	22.21
0.87	0.57	1.31	0.48	0.57	1.24	0.73	0.62
99.29	99.67	99.54	99.55	99.04	99.39	98.89	98.66
1.833	1.755	1.798	1.817	1.676	1.820	1.830	1.675
0.167	0.245	0.202	0.183	0.324	0.180	0.170	0.325
0.125	0.064	0.187	0.087	0.083	0.203	0.178	0.097
0.015	0.067	0.030	0.036	0.104	0.031	0.031	0.093
0.001	0.008	0.000	0.000	0.003	0.000	0.000	0.004
0.075	0.079	0.049	0.059	0.072	0.003	0.000	0.082
0.214	0.114	0.130	0.095	0.151	0.176	0.177	0.131
0.007	0.005	0.005	0.004	0.004	0.004	0.004	0.004
0.669	0.727	0.783	0.826	0.632	0.764	0.763	0.647
0.832	0.894	0.724	0.859	0.909	0.731	0.795	0.896
0.063	0.041	0.093	0.034	0.042	0.088	0.052	0.045
0.70	0.79	0.81	0.84	0.74	0.81	0.81	0.75

16	17
Cpx megacryst green homogeneous core	Groundmass cpx
48.33	47.37
1.63	2.48
7.46	6.49
0.00	0.10
11.73	6.40
0.21	0.12
8.78	13.20
19.87	22.62
2.11	0.47
100.13	99.25
1.811	1.767
0.189	0.233
0.140	0.053
0.046	0.070
0.000	0.003
0.110	0.072
0.257	0.127
0.007	0.004
0.490	0.734
0.798	0.904
0.153	0.034
0.57	0.79

Table 4
Representative compositions of the studied spinels

	1	2	3	5	6
	Spinel megacryst	Ti-magnetite megacryst	Spinel in ol xenocryst (Fig. 2a)	Spinel in ol xenocryst	Groundmass Ti-magnetite
TiO_2	0.47	10.40	0.16	0.37	20.46
Al_2O_3	61.67	6.19	52.86	29.20	1.70
Cr_2O_3	0.00	0.01	13.46	35.07	0.51
FeO^{tot}	18.47	76.61	15.38	17.52	68.76
MnO	0.14	0.43	0.21	0.22	0.76
MgO	19.26	2.61	18.77	16.98	4.33
Sum	100.00	96.24	100.84	99.35	96.52
Formulae for 3 cations and 4 oxygens					
Ti	0.009	0.281	0.003	0.008	0.560
Al	1.859	0.262	1.638	1.007	0.073
Cr	0.000	0.000	0.280	0.811	0.015
Fe^{3+}	0.123	1.175	0.075	0.166	0.792
Fe^{2+}	0.272	1.128	0.263	0.263	1.302
Mn	0.003	0.013	0.005	0.005	0.023
Mg	0.734	0.140	0.736	0.740	0.235
Mg#	0.65	0.06	0.68	0.63	0.10
Cr#	0.00	0.07	14.59	44.62	16.75

ol=olivine; Mg# = Mg/(Mg+Fe^{tot}); Cr# = 100*Cr/(Cr+Al)

Figure2
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Figure11
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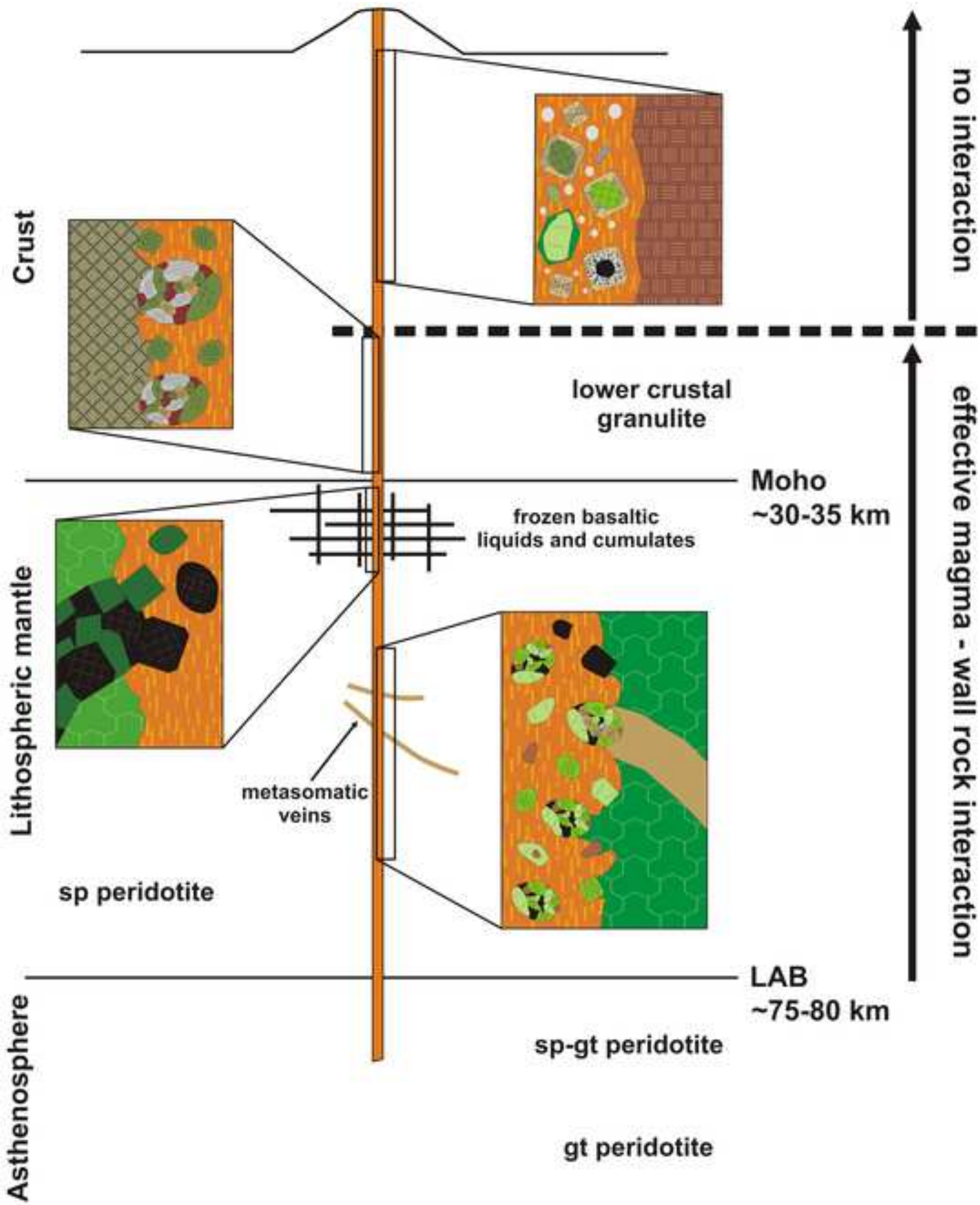

Table5

Table 5
Details of the different methods and results of the estimated magma ascent rates and times

Volcanic field	Eruptive centre	Method	details	parameters	ascent time t (h)
	alkaline basaltic magma in general	fluid filled crack propagation velocity	Eq. (8) in Sparks et al. (2006)	$\Delta\rho$=100 kg/m^3; 2w=0.5 m; η=5.5 Pa s	*1.8**
				$\Delta\rho$=300 kg/m^3; 2w=1.5 m; η=5.5 Pa s	*0.4**
BBHVF	Bondoró-hegy	fluid filled crack propagation velocity	Eq. (8) in Sparks et al. (2006)	$\Delta\rho$=100 kg/m^3; 2w=0.625-0.055 m; η=5.5 Pa s	*1.6**
				$\Delta\rho$=300 kg/m^3; 2w=0.625+0.055 m; η=5.5 Pa s	*0.8**
BBHVF	Bondoró-hegy + Füzes-tó	xenolith settling rate	Eq. (1) in Spera (1984)	R_n=0.1 m; $\Delta\rho$=400 kg/m^3;η=35 Pa s	*166***
				R_n=0.1 m; $\Delta\rho$=600 kg/m^3; η=5.5 Pa s	*40***
BBHVF	Füzes-tó	Ca profile of olivine xenocryst	$T_{1/2}=(X_{1/2})^2/2D$ in Lasaga (1998)	in Table 6	**86.4**
BBHVF	Bondoró-hegy + Füzes-tó	dissolution of orthopyroxene xenocryst	$y=ax^b$ in Shaw (1999)	max. rim width=0.48 mm; p=2 GPa	**1.4**
				max. rim width=0.48 mm; p=1 GPa	**2.2**
				max. rim width=0.48 mm, p=0.4 GPa	**7.1**
BBHVF	Szigliget + Sabar-hegy	Chemical profile of Fe-Ti oxides in granulite xenoliths	Eq. in Dégi et al. (2009)		**9**
					20
NGVF		thickness of chemical zoning bands in spinel	$t=x^2/D$		**18**
NGVF		transport and physical properties of the magmas			**37.5**
PVF	Racoş	Ca profile of olivine xenocryst	$T_{1/2}=(X_{1/2})^2/2D$ in Lasaga (1998)		**86.4**
	Bârc				**115.2**

Numbers in bold: results of the calculations. Numbers in italics: ascent rates and times computed from the given results assuming 25 km (numbers with *) and 60 km
BBHVF=Bakony-Balaton Highland Volcanic Field, NGVF=Nógrád-Gömör Volcanic field, PVF=Perşani Volcanic Field
For the details see the Electronic Appendix.

ascent rate v (m/s)	result of calculation	reference
3.9 **15.9**	v (m/s) ascent rate	this work
4.4 **9.2**	v (m/s) ascent rate	this work
0.10 **0.41**	v (m/s) settling rate	this work
*0.19***	t (h) interaction time	this work
*11.9*** *7.5*** *2.3***	t (h) interaction time	this work
*0.77** *0.35**	t (h) interaction time	Dégi et al. (2009)
*0.93***	t (h) interaction time	Szabó and Bodnar (1996)
	t (h) residence time	Szabó and Bodnar (1996)
*0.19*** *0.14***	t (h) interaction time	Harangi et al. (in press)

(numbers with **) long ascent path in the lithosphere.

Table 6
Calculated residence times of the studied olivine xenocrysts

	Rim A		Rim B		inner plateau	
Crystal	**$X_{1/2}$ A (μm)**	**$T_{1/2}$ A (days)**	**$X_{1/2}$ B (μm)**	**$T_{1/2}$ B (days)**	**$X_{1/2}$ I P (μm)**	**$T_{1/2}$ I P (days)**
xen 1 (Fig. 6a)	10	3.5	9	2.9	108	425
xen 2	12	5.2				
xen 3	8	2.3	12	5.2		
xen 4	10	3.6				
xen 5_p1	12	5.2	8	2.3		
xen 5_p2	8	2.3				
Average	***10***	***3.7***	***9.7***	***3.5***	***108***	***425***

$T_{1/2}=(X_{1/2})^2/2D$, where $T_{1/2}$ is the time necessary to reach the half of the equilibration concentration of Ca in olivine; $X_{1/2}$ is the distance from crystal rim to this point; D=diffusion coefficient for Ca in olivine.

Appendix

Figure A1
Click here to download Supplementary Material: FigA1.tif

Figure A2

Dear Professor I.E.M. Smith and Professor R.V. Fodor,

we are thankful for your valuable suggestions and comments which were very helpful in the revision.

Please find below our answers / comments (text with blue colour) to your suggestions.

Yours sincerely,
M. Éva Jankovics
on behalf of the authors

Comments of Professor I.E.M. Smith:

This manuscript has been reviewed and the recommendation is that you be given the opportunity to revise. My additional comment is that in you revision you should try to shorten the manuscript. I have no specific suggestions as to how best to do this but if you can shorten to a length more typical of Bulletin of Volcanology - approximately 7000 words you will have a achieved a more focussed manuscript on this very interesting topic.

We extensively shortened the former version of the manuscript. On one hand, we deleted a lot of unnecessary sentences and repetitions with the help of Professor R.V. Fodor`s suggestions. On the other hand, we took out the detailed descriptions and hypothetical background of the magma ascent rate estimations from the main article text, and took them into an appendix (after numerous corrections, changes and shortening as well). In the main body text, we made a separate heading (before the Discussion heading) for the magma ascent rate estimates and wrote there only shortly our results given by the different methods. We tried to focus the discussion as far as possible.

Comments of Professor R.V. Fodor:

1) My comments and edits are in the attached **Word document**. Please note that I converted the PDF into Word for easier and clearer editing, especially for line-editing – namely, correcting and improving the written English by cross-outs and insertions. Also important to

note is that the PDF to Word conversion put the line numbers into the text, and it distorted or omitted some symbols. Even though there are these distortions in the Word doc, the editing process, while long for me, was much faster compared to creating edit 'flags' in a PDF.

I put my corrected English in red font, and where I questioned or commented on something, I wrote in *red italics*. The authors will see that I removed many unnecessary words to help shorten the text, and to make the reading more clear and concise.

Also note this: there are many places where a comma is needed in the sentence. To call attention to those places, I purposely left an extra space before the comma (and I did not make the comman red). So, this will require carefully looking at each line in the Word doc

Thank you for all of the English corrections and questions / comments. We corrected the text carefully and based on your comments / questions we made a lot of changes.

2) My general comments are that this manuscript is certainly appropriate for Bulletin of Volcanology. It is a detailed, well thought-out presentation of the characteristics and dynamics of some basalts and their eruptions that will make a contribution in its many ways for which ascent rates are evaluated. One concern I have, however (and it's mentioned in the edited Word doc), is that the descriptions for these various calculations (for ascent) are too long. My editing includes some suggestions for shortening, but the authors can better address this concern about shortening such a lengthy section within the Discussion. I think that there is a chance the authors will lose the reader if they don't make the ascent rate presentation more concise.

You are right concerning the length of these descriptions. We took them out from the main article text, and moved them into an appendix (after numerous corrections, shortening and changes as well). In the main body text, we made a separate heading (before the Discussion heading) for the magma ascent rate estimates and wrote there only shortly our results given by the different methods.

Maybe more important to address here is the presentation on style of eruption (in the Discussion). It adds little to the paper. This is because there are too many unknowns (and the authors acknowledge this in some words) (e.g., channelway diameters; availability of crustal rocks to ascending magma, ...is the crustal rock easily fragmented; wider channelways may lessen the chances of entraining, and more....). I don't think that you can make judgments about a style because something is missing from the magma (such as crustal fragments). Most alkalic basalt do not have xenoliths of any type. The main contribution of the paper seems to be ascent rate calculations, and placing weight on whether or not certain kinds of xenoliths are present or absent distracts from the calculations by making speculations about 'style'.

We think that because of the length and inadequate construction of the former version of the manuscript, it was difficult to understand what the main points are. We tried to change the construction a lot and to focus on the essentials. We omitted the highly uncertain parts from the text (concerning mainly the ascent style) and tried to write clearly the suggested ascent history of these basaltic magmas.

We think that based on the absence of something, some suggestions can be made (it is a similar case as when somebody write in a paper that "based on the absence of garnets in the peridotite xenoliths, they can derive from shallower depths, i.e., from the spinel peridotite region"). Here, we just would like to draw attention to the fact, that the magmas incorporated a huge amount of fragments and crystals from the lithosphere at mantle depths as well as a number of fragments from the lower crust, but at shallower depths (middle-upper crust) no additional wall rock fragments were entrained. We tried to think about what could be the reason for this, but because there are many unknown parameters, we did not go into the details in the revised version how to interpret this fact. We only made the suggestion that the absence of any middle-upper crustal materials in the magmas, together with the fact that from greater depths the magmas incorporated a vast amount of fragments, can suggest some changes in the ascent style (an effective magma-wall rock interaction can be reasonable at greater depths, but no interaction can be inferred between magma and wall rock at shallower depths).

3) Some other suggestions:

a) when reporting the wt.% in the text, use on 00.0 and not 00.00. The detail of the hundredths decimal place is for the Tables....and it only burdens readers of the text with largely insignificant numbers. You only have to present the general composition in the text (e.g. 50.2 wt.%, and not 50.17), as leaving only tenths place makes for a cleaner text. One exception is for numbers <1.0%. Using two decimal places is justified there (e.g., 0.78 wt.%).

Thank you, we corrected every numbers in the text, as suggested.

b) about the word ‘alkaline’ when used with basalt. The US Geological Survey guidelines for authors reports that ‘alkalic’ is the proper adjective for basalts, and not ‘alkaline’. I have scanned and included below the USGS recommendations for such geologic adjectives.

I know that this is a European authorship, but I think that alkalic is used world-wide. I understand, too, that the authors may have a history of using ‘alkaline’ and will want to keep it that way – but I wanted to give my opinion and the recommendations for US government publications (and also, the Hawaiian terminology has long used ‘alkalic’).

We accept the comment on the usage of the alkalic versus alkaline adjective for basalts. So far, we have used consistently the alkaline adjective as we could read and hear it in many publications and conferences. We do not know whether there is a difference in the American and British English usage for this term. If both adjectives are acceptable we would like to keep the alkaline term.

c) line 166: ‘Petrography and whole-rock compositions’ may be a better heading. It’s not really presenting petrochemistry as the headline presently read.

All right, we corrected.

line 288: Remove heading ‘olivine profiles’ -- what following line 288 can be part of the olivine presentation before line 288. (also, as noted in my edits: much of that profile information is for Figure caption that goes with the profiles).

All right, we changed.

line 422 ‘Crystal diversity’ doesn’t say much. I thing ‘Mineral Sources’, or ‘Sources for the diverse mineral assemblage’ is more what this section presents.

All right, we corrected for ‘Sources for the diverse mineral assemblage’.

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Origin and ascent history of unusually crystal-rich alkaline basaltic magmas from the western Pannonian Basin

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Abstract

The last eruptions of the monogenetic Bakony-Balaton Highland Volcanic Field (western Pannonian Basin, Hungary) produced unusually crystal- and xenolith-rich alkaline basalts which are unique among the alkaline basalts of the Carpathian-Pannonian Region. Similar alkaline basalts are only rarely known in other volcanic fields of the world. These special basaltic magmas fed the eruptions of two closely located volcanic centres: the Bondoró-hegy and the Füzes-tó scoria cone. Their uncommon enrichment in diverse crystals produced unique rock textures and modified original magma compositions (13.1-14.2 wt.% MgO, 459-657 ppm Cr, 455-564 ppm Ni contents).

Detailed mineral-scale textural and chemical analyses revealed that the Bondoró-hegy and Füzes-tó alkaline basaltic magmas have a complex ascent history, and that most of their minerals (~30 vol.% of the rocks) represent foreign crystals derived from different levels of the underlying lithosphere. The most abundant xenocrysts, olivine, orthopyroxene, clinopyroxene and spinel, were incorporated from different regions and rock types of the subcontinental lithospheric mantle. Megacrysts of clinopyroxene and spinel could have originated from pegmatitic veins / sills which probably represent magmas crystallized near the crust-mantle boundary. Green clinopyroxene xenocrysts could have been derived from lower crustal mafic granulites. Minerals that crystallized in situ from the alkaline basaltic melts (olivine with Cr-spinel inclusions, clinopyroxene, plagioclase, Fe-Ti oxides) are only represented by microphenocrysts and overgrowths on the foreign crystals. The vast amount of peridotitic (most common) and mafic granulitic materials indicates a highly effective interaction between the ascending magmas and wall rocks at lithospheric mantle and lower crustal levels. However, fragments from the middle and upper crust are absent from the studied basalts, suggesting a change in the style (and possibly rate) of magma ascent in the crust. These xenocryst- and xenolith-rich basalts yield divers tools for estimating magma ascent rate that is important for hazard forecasting in monogenetic volcanic fields. According to the estimated ascent rates, the Bondoró-hegy and Füzes-tó alkaline basaltic magmas could have reached the surface within hours to few days, similarly to the estimates for other eruptive centres in the Pannonian Basin which were fed by "normal" (crystal- and xenolith-poor) alkaline basalts.

Keywords

alkaline basalt, ascent history, crystal-rich, magma ascent rate, monogenetic volcanism, xenocryst, xenolith

Introduction

Monogenetic basaltic volcanic fields consist of small individual eruptive centres characterized by a single brief eruption (Walker, 1993) and low magma supply (e.g., Hasenaka and Carmichael, 1985; Takada, 1994). These monogenetic eruptions of basalt are generally assumed to be simple in terms of volcanology and petrology. That is, they produce small volcanic edifices during continuous activity within a relatively short time span, and are fed by a single, compositionally discrete batch of magma (e.g., Connor and Conway 2000). However, several authors suggested that individual eruptive centres can be characterized by multiple eruptions involving different magma batches with hiatuses during their activity (e.g., Reiners 2002; Martin and Németh 2005; Brenna et al. 2010, 2011; Needham et al. 2011, Shane et al. 2013) implying a complex evolution history of the magmatic system. These studies focused mainly on the compositional variations of the feeding magma batches and suggest differences in their source regions and / or degrees of partial melting. However, processes acting during the ascent of the magma batches are also important~~ to determine~~ (Brenna et al. 2010). This is essential information because the evolution of the magma in the feeding system can have a significant effect on the rate and style of magma ascent, and therefore on the nature of eruptions (e.g., Ruprecht and Bachmann 2010; McGee et al. 2012; Russell et al. 2012). Detailed textural and chemical analyses of phenocrysts in basalts can provide insights into the details of their magma evolution~~s~~ (e.g., Dobosi 1989; Dobosi et al. 1991; Roeder et al. 2001, 2003, 2006; Smith and Leeman 2005; Jankovics et al. 2009, 2012).

The monogenetic Bakony-Balaton Highland Volcanic Field, located in the western part of the Carpathian-Pannonian Region, was active for approximately 6 My. Its last active phase was closed by two eruptive centres: the Bondoró-hegy (2.3 Ma; Balogh and Pécskay 2001) and the Füzes-tó scoria cone (2.6 Ma; Wijbrans et al. 2007) each fed by alkaline basaltic magmas with special compositions and petrological appearance~~s~~ (Jankovics et al. 2009, 2012). These alkaline basalts are characterized by extremely high Mg, Ni and Cr contents and are unusually rich in diverse crystals and xenoliths (peridotite, mafic granulite). Similar magmas did not erupt in the above mentioned volcanic field and even in the other six volcanic fields in the whole Carpathian-Pannonian Region (CPR). Nevertheless, basalts of numerous eruptive centres in the region contain diverse xenoliths. In other volcanic fields of the world, magmas with characteristics similar to those of the Bondoró-hegy and Füzes-tó scoria cone are known (e.g., Ancochea et al. 1987; Mattsson 2012; Kozákov Hill in Ulrych et al. in press) but they are rare. Due to their crystal-rich feature these rocks provide unique insights into the ascent history of basaltic magmas. Following the detailed investigations and descriptions of the Füzes-tó basalt (Jankovics et al. 2009, 2012), in this study we analyse~~d~~ the ~~highly~~ similar (both in age and petrology) basalt of Bondoró-hegy ~~(both in age and petrology)~~ and reveal~~ed~~ its ascent history. It is generally assumed that such xenolith-rich magmas can reach the surface very rapidly. We estimate~~d~~ the ascent rates of these xenocryst- and xenolith-rich alkaline basalts, and compare~~d~~ the results with xenolith-poor basalts. Understanding the ascent history and estimating the magma ascent velocity is important in monogenetic volcanic fields for their volcanic hazard assessments. This study demonstrates the importance of the especially crystal-rich basaltic magmas of monogenetic volcanic fields for enabling estimating the magma ascent rate by several different methods.

Geological setting

The Pannonian Basin is a Miocene extensional back-arc basin surrounded by the Alpine, Carpathian and Dinarides orogenic belts (Fig.1a). It is characterized by thin lithosphere (50-80 km) and crust (22-30 km) coupled with high heat flow (>80 mW/m^2; Csontos et al. 1992;

Fodor et al. 1999; Tari et al. 1999; Bada and Horváth 2001; Lenkey et al. 2002). These features are due to the initial syn-rift phase (17–12 Ma; Horváth 1995) of the Pannonian Basin that was characterized by subduction roll-back, related back-arc extension and lithospheric thinning (Csontos et al. 1992; Horváth 1993; Tari et al. 1999). This was followed by the Late Miocene–Pliocene post-rift phase (e.g., Horváth 1995) which was accompanied by thermal subsidence, thickening of the lithosphere and sedimentation in the basin areas. Tectonic inversion has characterized the Pannonian Basin since the late Pliocene due to the push of the Adriatic plate from the southwest and blocking by the East European platform in the east (Horváth and Cloetingh 1996).

Post-extensional alkaline basaltic volcanism occurred from 11 to 0.13 Ma in the region, mainly on its marginal parts, which formed monogenetic volcanic fields. The tectonic background of the alkaline basaltic magmatism is still under debate. Several researchers suggested that localised mantle plume fingers (deriving from a common mantle reservoir named ”„European Asthenospheric Reservoir”; Hoernle et al. 1995) could be responsible for the alkaline basaltic volcanism in Western and Central Europe, accordingly in the Pannonian Basin as well (Granet et al. 1995; Seghedi et al. 2004). However, Harangi and Lenkey (2007) and Harangi (2009) argued against the plume-related magmatism. They suggested that the significantly stretched Pannonian Basin provided suction in the sublithospheric mantle and generated an asthenospheric mantle flow from below the thick Alpine regime which could lead to the partial melting of the heterogeneous upper mantle.

The Bakony-Balaton Highland Volcanic Field (Fig. 1b) comprises approximately 150-200 eruptive centres (Németh and Martin 1999a, 1999b) that are erosional remnants of maars, tuff rings, scoria cones and shield volcanoes (e.g., Jugovics 1968; Németh and Martin 1999a, 1999b; Martin et al. 2003). Several of these alkaline basalt occurrences contain ultramafic and mafic xenoliths, as well as discrete megacrysts which were extensively studied in the past decades (e.g., Embey-Isztin 1976; Embey-Isztin et al. 1989, 1990, 2001a, 2001b, 2003; Downes et al. 1992; Downes and Vaselli 1995; Dobosi et al. 2003; Dégi et al. 2009). These studies together with those for whole-rock geochemistry of the basalts (e.g., Embey-Isztin et al. 1993a, 1993b; Embey-Isztin and Dobosi 1995; Seghedi et al. 2004) have yielded important information on the nature of the upper mantle beneath the area and the partial melting processes. Based on several studies (e.g., Embey-Isztin et al. 1989, 1990, 2001a; Szabó et al. 2004; Hidas et al. 2007; Dégi et al. 2009) we have an extensive knowledge about the structure of the whole lithosphere as well.

Volcanological background

In this paper, we describe the volcanological background for the Bondoró-hegy eruptive centre. The features of the Füzes-tó scoria cone were reported in a previous paper (Jankovics et al. 2009). Bondoró-hegy volcano is one of the most complex eruption centres of this volcanic field ~~which~~ and consists of several discrete ~~different~~ eruptive units: basal tuff ring pyroclastics with a lava lake, reworked basaltic debris beds, lava flow units (1st and 2nd lava flow) and capping scoria cone associated with the 3rd lava flow (Kereszturi et al. 2010). The capping scoriaceous basalt (e.g., spindle and scoriaceous bombs) and the 3rd lava flow unit (representing the youngest eruptive phase) are rich in xenoliths of upper mantle and lower crustal origins (peridotite, wehrlite, clinopyroxenite, mafic granulite) and in clinopyroxene and spinel megacrysts.

In an outcrop of the capping scoria unit (in the breached side of the scoria cone remnant), Kereszturi et al (2010) described a dyke that crosscuts the scoriaceous breccia. Based on our field observations (Fig. 2), this massive dyke has an average width of 0.625±0.055 m and can be interpreted as a feeder dyke of the scoria cone.

Several K-Ar ages are available: the basalt of the lava lake is estimated at about ≤3.86±0.20 Ma and the 2nd lava unit at about 2.90±0.62 Ma (Balogh et al. 1986). A sample from the 3rd lava flow unit gave an age of 2.29±0.22 Ma (Balogh and Pécskay 2001). According to Kereszturi et al. (2010), these ages represent the best fit with the geological and stratigraphical observations. Unfortunately, Bondoró-hegy was not included in the $^{40}Ar/^{39}Ar$ dating of the Balaton Highland basaltic rocks (Wijbrans et al. 2007). Based on the preferred K-Ar ages (that indicate prolonged volcanic activity) and the discordance between the phreatomagmatic unit and the subsequent lava flows (implying a significant time gap), Bondoró-hegy can be regarded as a polycyclic monogenetic volcano (Kereszturi et al. 2010).

Petrography and whole-rock compositions

Samples of the Bondoró-hegy were collected from the 3rd lava flow unit. Samples of the Füzes-tó scoria cone were collected in the inner slope around the central depression (various basaltic bombs). In this paper, we describe only the features of the Bondoró-hegy basalt, the descriptions of the Füzes-tó basalt are in Jankovics et al. (2009, 2012). Figure 3a shows the typical petrographic appearance of the studied crystal-rich alkaline basalts.

~~In this heading, t~~The term ‘phenocryst’ is here used in a general sense, i.e., for larger, up to 5 mm, crystals in fine-grained groundmasses, regardless of their origins (i.e., phenocryst *sensu lato*). ~~After that, i~~In the ~~next headings~~following, the term ‘phenocryst’ ~~is already~~has been used in a genetic sense, i.e., for crystals that have grown in situ in the magma in which they are found now (i.e., phenocryst *sensu stricto*).

The studied lava samples have porphyritic texture characterized by non- to low-vesicularity and ~30 vol.% anhedral to euhedral phenocrysts (on a vesicle-free basis). The phenocryst assemblage consists of olivine, clinopyroxene, orthopyroxene and spinel characterized by variable forms and sizes, and ~~they~~ crystals often occur together as crystal clots (Fig. 4d). Microphenocrysts (<150 μm) are clinopyroxene, olivine, plagioclase and Fe-Ti-oxides. The fine-grained groundmass is composed of microlitic feldspars (plagioclase and alkali feldspar), clinopyroxene, olivine, Fe-Ti-oxides, apatite and some glass.

Most of the olivine phenocrysts (up to 5 mm) are characterized by rounded and embayed margins. These crystals ~~often~~commonly show undulose extinction, and have bright rims (with diffuse boundaries toward the crystal interiors) in the backscattered electron (BSE) images (e.g., Fig. 4a). They frequently contain subhedral-anhedral (often rounded), light green to brown spinel inclusions which range in size from ~50 to 300 μm. The smaller (150-900 μm) olivine grains are euhedral to subhedral and often skeletal and their outermost margin is frequently iddingsitised. They often contain black, euhedral-subhedral chromian spinel inclusions (~3-10 μm).

Orthopyroxene crystals (up to 2.4 mm) are always surrounded by fine-grained rims of various thicknesses (Fig. 4c) consisting of olivine, clinopyroxene, glass and rarely spinel. The outermost part of this corona often contains numerous Fe-Ti-oxides as well. This fine-grained rim is frequently overgrown by a pale brown, twinned and sector zoned clinopyroxene.

Clinopyroxene phenocrysts (up to 3 mm) are euhedral to subhedral in shape and usually have an anhedral, rounded core (with a sharp boundary) and a pale brown, twinned, sector zoned rim characterized by various thicknesses (rarely some sector zoned clinopyroxenes without a rounded crystal core are also found; Fig. 4i). Two types of the anhedral, variously resorbed cores can be distinguished. The first and more frequent type is colourless under the optical microscope, and darker grey than the rim in the BSE images (Fig. 4d, e). The other type is light green under the optical microscope, and lighter grey than the surrounding rim in the BSE images (Fig. 4f) which indicates reverse zoning. The green cores often have spongy or sieved texture.

Spinel crystals (up to 0.5 mm) occur as individual crystals in the matrix (Fig. 4b) and as inclusions in olivine phenocrysts (Fig. 4a). They usually have ragged, anhedral margins, are characterized by variable colours (light green to brown), and often have a bright (Ti-magnetite) overgrowth rim (with a relatively sharp boundary toward the crystal interior) in the BSE images where it is in contact with the groundmass (Fig. 4a, b).

All these disequilibrium textures (ragged, rounded, resorbed, embayed, spongy features) suggest a xenocrystic origin for the anhedral olivines, colourless and green cores of clinopyroxene phenocrysts, orthopyroxenes and spinels.

In addition to the abundant xenocrysts, the studied samples include numerous peridotite xenoliths. These are spinel peridotites which occasionally contain amphiboles (Fig. 3b). Along the contact between the peridotite and basalt the peridotitic orthopyroxene grains have the same fine-grained rims as the orthopyroxene xenocrysts in the basaltic groundmass. Therefore, these rims are interpreted as mineral-melt reaction products. Similar~~ly~~ to most of the olivine xenocrysts, the olivine grains in the peridotite xenoliths often have undulose extinction which implies deformation.

Additionally, clinopyroxene and spinel megacrysts are also common. Most of the clinopyroxene megacrysts (up to 6 cm, elongated) are colourless, they have homogeneous interiors crosscutting with ~~former~~ cracks filled with secondary fluid inclusions, and are overgrown by a pale brown, zoned clinopyroxene rim similar to that of the clinopyroxene xenocrysts. Spongy zones are present between this rim and the homogeneous part of the megacrysts (Fig. 4g). In the spongy zones, small inclusions of feldspars (plagioclase and alkali feldspar) and skeletal spinels are present (Fig. 4h). Besides the colourless megacrysts, one piece of a green clinopyroxene megacryst has also been found. The spinel megacrysts are ~1-2 cm in size, mostly dark green, but one was black, under the optical microscope.

The whole rock composition of the Bondoró-hegy basalt has been described by Jugovics (1976) and Embey-Isztin et al. (1993a, 1993b). The compositional data identify the lavas of Bondoró-hegy as undersaturated basanite (Table 1), similar to the compositions of the other basalts in the region, however, the basaltic rocks from Bondoró-hegy are extremely rich in MgO (13.1-13.9 wt.%). Similar MgO enrichment has been reported only at the Füzes-tó scoria cone from the Pannonian Basin (see Fig. 1b), which has 13.4-14.2 wt.% MgO content (Jankovics et al. 2009). This is correlated~~consistent~~ with the abundance of xenocrystic olivine and orthopyroxene. The high MgO content is accompanied by extreme enrichment in Ni and Cr contents (455-474 and 459-489 ppm, respectively; Embey-Isztin et al. 1993a, 1993b), also caused by the presence of abundant peridotitic xenocrysts. The incompatible trace element content of the Bondoró-hegy basalt is approximately the same as that of the other basalts of the region, though some incompatible trace element and radiogenic isotope ratios are different. While the lavas of the Bakony-Balaton Highland Volcanic Field tend to show higher K/Nb, Rb/Nb and lower Ce/Pb, as well as higher $^{207}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$, the opposite is true for the Bondoró-hegy basalt. This is explained by the involvement of an enriched lithospheric component in the lavas, which is missing from the Bondoró-hegy basaltic magma (Embey-Isztin et al. 1993b).

Mineral chemistry

Analyses of minerals in the Bondoró-hegy basalt were obtained on a JEOL Superprobe 733 using wavelength-dispersive spectrometers at the Institute for Geological and Geochemical Research in Budapest, Hungary. Analytical conditions were 20 kV accelerating voltage, 35 nA beam current, and all analyses were made against mineral standards. Raw data were corrected by the ZAF correction program of JEOL. Olivine profiles of the Füzes-tó basalt were determined using a CAMECA SX100 electron microprobe equipped with four WDS and one EDS at the University of Vienna, Department of Lithospheric Research (Austria). The operating conditions were as follows: 15 kV accelerating voltage, 20 nA beam current, 20 s counting time on peak position, focused beam diameter and PAP correction procedure for data reduction. The following standards were applied: albite (for Si, Al); almandine (for Fe); olivine (for Mg); wollastonite (for Ca); spessartine (for Mn) and Ni-oxide (for Ni). The mineral compositions of the Füzes-tó basalt are discussed in Jankovics et al. (2009, 2012).

Olivine

Olivine crystals display a wide range of Fo (Table 2). The xenocrysts are chemically homogeneous and typically have Fo from 89.5 to 92 mol% (Fo=100*Mg/(Mg+Fe), all Fe is assumed to be divalent). They have thin rims with lower Fo (72.1-81.4 mol%), which overlap that of the groundmass olivines (76.1-76.7 mol%).

Olivine xenocrysts have low CaO and high NiO contents (0.05-0.12 wt.% and 0.33-0.39 wt.%, respectively), while their rims are enriched in CaO (0.16-0.40 wt.%) and depleted in NiO (0.16-0.34 wt.%) (Fig. 5). CaO shows a weak negative, whereas NiO shows a weak positive correlation with Fo content (Fig. 5). The highest Ca and lowest Ni contents are in groundmass olivines (0.38-0.57 wt.% CaO and 0.14-0.18 wt.% NiO). The compositions of the studied xenocrysts resemble those of the olivines of the peridotite xenoliths in the Balaton Highland (Fig. 5).

All olivine Fo profiles are symmetric to the centre of the grain, but their shapes differ (Fig. 6). Olivine xenocrysts have well-defined inner plateaus bounded by large compositional gradients toward the rims (Fig. 6a, b). Their inner part contains less than 500 ppm Ca, ~3000 ppm Ni and ~90 mol% Fo. In the rims, Ca sharply increases to >3000 ppm, while Ni and Fo sharply decrease to <1000 ppm and to 75 mol%, respectively. In several xenocrysts, the inner plateaus show some compositional variations (maybe related to healed cracks or tiny inclusions) (Fig. 6b). The profiles of olivine phenocrysts have a shield-like shape indicating a gradual compositional variation toward the rims (Fig. 6c). The Ca and Ni profiles are less smooth than those in xenocrysts, which may be the result of skeletal growth of the phenocrysts. Compared to the xenocrysts, the Ca content of their inner part is significantly higher (~1250 ppm), while the Ni and Fo contents are lower (between ~2000-2500 ppm and ~87 mol%, respectively). Phenocrysts and xenocrysts can be distinguished in the Fo-NiO diagram (Fig. 7), which shows that olivine xenocrysts show linear trends towards the rims indicating that the formation of core-to-rim zoning was~~were~~ mainly driven by diffusion. However, phenocrystic olivine has a curved trend towards the rims that can be interpreted as mainly growth-related core-to-rim zoning considering the implications of Costa et al. (2008).

The compositions of the xenocryst rims (Fig. 5, 6a) are similar to those of the olivine xenocryst rims and olivine phenocryst rims in the Füzes-tó basalt (Jankovics et al. 2009, 2012). The formation of these Fe-rich~~, bright~~ rims ~~of olivine xenocrysts~~ can be explained by diffusion during re-equilibration of the xenocryst with the host basaltic magma (note the diffuse boundary toward the crystal interior; Fig. 4a, d) as well as some subsequent crystallization of phenocrystic olivine on the xenocrysts.

Orthopyroxene

Orthopyroxenes occur only as xenocrysts in the studied basalt. They are enstatites (Morimoto et al., 1988) with high Mg#s (0.91-0.92; Mg/(Mg+Fe^{tot})) and contain 2.9-3 wt.%

Al_2O_3 (Table 3). These compositions are characteristic for mantle orthopyroxenes similar to those of the peridotite xenoliths in the Balaton Highland (Embey-Isztin et al. 2001a).

Clinopyroxene

The clinopyroxene compositions are highly variable (Table 3, Figs. 8, 9) but basically four different types can be distinguished. They are: 1) colourless xenocrystic cores, 2) light green xenocrystic cores, 3) megacrysts, 4) phenocrysts, microphenocrysts and groundmass clinopyroxenes.

Colourless cores

Colourless cores (Table 3, analyses No. 2 and 4) are homogeneous but have variable compositions in the different crystals. They are chromian diopsides (Fig. 8) with high Mg#s (0.88-0.92; Mg/(Mg+Fe^{tot})) and SiO_2 contents (51.2-53.7 wt.%), and varying Cr_2O_3 and Al_2O_3 contents (0.28-1.4 wt.% and 2.8-6.1 wt.%, respectively). They are generally low in TiO_2 (up to 0.48 wt.%) and have low Ti/Al ratios (≤0.07) and high Al^{VI}/Al^{IV} ratios (0.81-1.3). The compositions of these colourless xenocrystic cores are similar to those of the clinopyroxenes from the peridotite xenoliths in the Balaton Highland (Figs. 8, 9).

Green cores

Representative analyses of green cores are in Table 3 (analyses No. 6 and 8). The green cores are homogeneous and enriched in iron (Fig. 8). Their Mg#s (Mg/(Mg+Fe^{tot})) varies between 0.59-0.69 which is lower than those of the overgrowth rims. Their TiO_2 and Al_2O_3

contents are relatively low (0.49-0.76 wt.% and 4.5-6.6 wt.%, respectively) and the amount of Cr_2O_3 is around (or below) the detection limit. The compositions of these xenocrystic cores resemble those of the clinopyroxenes of the lower crustal granulite xenoliths in the Balaton Highland (Figs. 8, 9). Their Ti/Al and Al^{VI}/Al^{IV} ratios are in the same range as in the colourless cores (Fig. 9e, f). One of the green cores has a different composition: it has slightly lower Mg# (0.58) and significantly lower TiO_2 (0.28 wt.%) and Al_2O_3 (1.5 wt.%) contents than the other green cores of the samples.

Megacrysts

The interiors of the megacrysts are homogeneous. The colourless megacrysts show a restricted range of composition (Figs. 8, 9; Table 3, analyses No. 10 and 13). Their Mg#s ($Mg/(Mg+Fe^{tot})$) are 0.81-0.83, the TiO_2 and Al_2O_3 contents are in the range of 0.91-1.3 wt.% and 8.7-9.2 wt.%, respectively. They are characterized by low Ti/Al (0.07-0.09) and high Al^{VI}/Al^{IV} ratios (0.90-1.2) (Fig. 9e, f). They have high Na_2O contents (1.2-1.3 wt.%) compared to the phenocrysts, and do not contain Cr_2O_3 in detectable amount. The clinopyroxene composition in the spongy part is slightly different from that of the interior of the megacryst having higher TiO_2 (1.1-2.2 wt.%), lower Al_2O_3 (6.2-8 wt.%) and Na_2O (0.48-0.73 wt.%), while the Mg# is the same.

The green megacryst ~~can be~~are characterized by lower Mg# (0.57) and Al_2O_3 (7.5 wt.%), and higher TiO_2 (1.6 wt.%) and Na_2O (2.1 wt.%) contents than the other megacrysts. It has similar Al^{VI}/Al^{IV} (0.93), but a slightly higher Ti/Al ratio (0.14) compared to the colourless megacrysts.

Phenocrysts, microphenocrysts and groundmass grains

The pale brown clinopyroxene phenocrysts (i.e., the overgrowth rims on clinopyroxene xenocrysts and megacrysts as well as on the reaction rim of orthopyroxene xenocrysts), microphenocrysts and microlites of the groundmass are titanian augites or titanaugites according to the traditional pyroxene nomenclature (Deer et al. 1978), but can be classified as diopside, aluminian diopside and titanian aluminian diopside according to the I.M.A. classification of pyroxenes (Morimoto et al. 1988). Some representative analyses of these clinopyroxenes can be seen in Table 3 (e.g., analyses No. 3, 7, 12 and 17). Their Mg#s ($Mg/(Mg+Fe^{tot})$) range from 0.73 to 0.85 and their TiO_2 and Al_2O_3 contents vary between 1.5-3.9 wt.% and 4.9-10.1 wt.%, respectively. Ti and Al show positive correlation (Fig. 9e) and both elements increase with iron enrichment (Fig. 9a, b). Their increasing Ti with decreasing Mg# reflects the normal fractionation trend (e.g., Tracy and Robinson 1977). The Cr_2O_3 contents can reach 1 wt.% but it sharply decreases with decreasing Mg# (Fig. 9c). Their Ti/Al ratios (0.16-0.34) are higher, while the Al^{VI}/Al^{IV} ratios (0.12-0.48) are lower than those of any other type of the studied clinopyroxenes (Fig. 9e, f). These ratios imply that they could have crystallized under relatively low-pressure conditions (e.g., Yagi and Onuma 1967; Wass 1979; Dobosi et al. 1991). Based on their slightly increasing Ti/Al ratios during crystallization (Fig. 9e), they could have precipitated under continuously decreasing pressure. They could have been characterized by a significantly higher crystallization rate compared to the olivine phenocrysts (as suggested by Fig. 4d).

Oxide minerals

Representative analyses of the studied oxide minerals are shown in Table 4. The xenocrysts are Mg- and Al-rich spinels showing variable compositions (Fig. 10). Their Mg#s

($Mg/(Mg+Fe^{tot})$) vary between 0.63 and 0.74 and their Cr#s (100*Cr/(Cr+Al)) range from 12.3 to 45.8 (Cr_2O_3=11.4-37 wt.%, Al_2O_3=29.2-54.5 wt.%). Additionally, they have low TiO_2 contents (0.11-0.37 wt.%). The compositions of the studied xenocrysts are very similar to those of the spinels of the peridotite xenoliths in the Balaton Highland (Fig. 10).

The dark green megacrysts are also Mg-Al-rich spinels (Fig. 10) with 0.65-0.67 Mg#s, however they are characterized by higher Al_2O_3 contents (61-61.8 wt.%) and very low Cr_2O_3 contents (≤0.15 wt.%). The black megacryst has a completely different composition: it is a titanomagnetite with 10.4 wt.% TiO_2 and 76.6 wt.% FeO^{tot} contents.

The oxides in the groundmass are mainly titanomagnetites which contain 17.3-23.5 wt.% TiO_2 and 66.8-72.5 wt.% FeO^{tot}. Matrix ilmenites are also present characterized by 49.3-51.3 wt.% TiO_2 and 38.8-43.1 wt.% FeO^{tot}.

In summary, the compositional characteristics of the phenocryst (*s.s.*) phases (olivine, clinopyroxene, Fe-Ti-oxides) in the Bondoró-hegy basalt are similar to those of the phenocrysts found in other basalts in the Balaton Highland.

Magma ascent rate estimates

The Bondoró-hegy and Füzes-tó crystal-rich basalts provide a tool for estimating the magma ascent rate by a number of methods (Table 5). The detailed descriptions and background information of the different methods are presented in the Electronic Appendix.

1) We carried out calculations to estimate the ascent velocity for alkaline basaltic magmas in general based on fluid filled crack propagation velocities. These computations yield magma ascent rates in the range of 3.9-15.9 m/s, which are (at a given dyke width and density

contrast between melt and wall rock) lower than the ascent velocities of melilitites (e.g., Mattsson 2012) and kimberlites (e.g., Sparks et al. 2006).

Based on this method, 4.4-9.2 m/s magma ascent rates would be reasonable for the observed dyke width (0.625±0.055 m; Fig. 2) in the case of the youngest eruptive phase of Bondoró-hegy (capping scoriaceous basalt and the 3rd lava flow). According to Valentine and Krogh (2006), complex sill and dyke systems can be present beneath small volume, alkaline basaltic volcanic centres with variable dyke widths of main / parent dykes (3-9 m) and dyke-parallel segments (few decimetres-1.2 m). The observed dyke width in Bondoró-hegy falls in the range of these dyke widths, and it may represent a part of a similar dyke system.

2) We calculated the settling rate of the largest (20 cm in diameter) peridotite xenoliths found at Bondoró-hegy and Füzes-tó scoria cone. These computations yield xenolith settling rates in the range of 0.10-0.41 m/s, which corresponds to minimum ascent rates.

3) We used the Ca profiles of olivine xenocrysts (from the Füzes-tó basalt) which can be appropriate for estimating magma ascent time because the profiles were measured in rapidly quenched basaltic bombs. The average of the calculated residence times for the xenocrysts (Table 6) is 3.6 days (86.4 hours) which means the time that olivine xenocrysts could have spent in the basaltic melt. Considering for example a 60 km long ascent route, this gives an ascent rate of 0.19 m/s.

4) We estimated the dissolution times of orthopyroxene xenocrysts based on the thicknesses of their reaction rims. The thickest studied reaction rim can form in 86-426 minutes (1.4-7.1 hours). This gives the interaction time between orthopyroxene and basaltic melt which denotes the minimum time that the magma must have spent in the feeding system. Using for example a 60 km long ascent route again, this means an ascent rate of 11.9 m/s.

In summary, the different methods resulted in a large ~~interval~~ range of ascent rates. The minimum ascent velocities are 0.10-0.19 m/s derived from the 2nd and 3rd methods (respectively), and the maximum ascent rates are 9.2-11.9 m/s resulted from the 1st and 4th methods (respectively). These results imply that the Bondoró-hegy and Füzes-tó crystal-rich magmas could have reached the surface from their source within hours to few days.

Discussion

Alkaline basalts of the Bakony-Balaton Highland Volcanic Field have phenocryst assemblages of olivine, and more rarely, clinopyroxene (e.g., Embey-Isztin et al. 1993a). Olivine is frequently the only phenocryst phase and clinopyroxene is restricted to the groundmass. In contrast, the basalts of the Bondoró-hegy and Füzes-tó are more complex, having large textural and compositional heterogeneity, especially among clinopyroxenes. Most of the minerals could not be in equilibrium with each other and with the host magma, and many of them must be xenocrysts entrained from various depths. Here, we discuss the origins of the diverse crystals of the Bondoró-hegy basalt, the interpretations in the case of the Füzes-tó basalt were reported in previous papers (Jankovics et al. 2009, 2012). We also provide the magma ascent history and estimates of ascent rate.

Sources for the diverse mineral assemblage

Xenocrysts

The compositional range of olivine xenocrysts (Fig. 5) is typical for mantle olivines (e.g., Boudier et al. 1991; Hirano et al. 2004; Rohrbach et al. 2005). The Fo value for average olivines in the lithospheric mantle is 90 mol% (Sato 1977). Most of the studied olivine xenocrysts contain Fo around 90 mol%, but some of them have higher Fo contents suggesting that they are derived from depleted peridotites.

Orthopyroxene xenocrysts are also Mg-rich which is characteristic for orthopyroxenes of the upper mantle (e.g., Embey-Isztin et al. 2001a). Their reaction rims are common features of mantle-derived orthopyroxenes that are incorporated by silica-undersaturated alkaline melts. This mineral-melt reaction results in the incongruent dissolution of the orthopyroxene and formation of a reaction corona (olivine + Si-rich glass + clinopyroxene ± spinel) at the expense of the orthopyroxene (e.g., Arai and Abe 1995; Shaw et al. 1998; Shaw 1999; Shaw and Dingwell 2008). Comparing the compositions of the studied enstatite xenocrysts with the orthopyroxenes from the Bondoró-hegy peridotite xenoliths (Embey-Isztin et al. 2001a), they could have derived from moderately depleted peridotite (e.g., 2.9-3 wt.% Al_2O_3, 33.4-33.9 wt.% MgO).

The compositional variation of the colourless clinopyroxene xenocrysts (Figs. 8, 9) is typical for Cr-diopsides of peridotite xenoliths (e.g., Wass 1979). The low Ti/Al ratios of the colourless xenocrystic cores suggest a relatively high-pressure origin (e.g., Yagi and Onuma 1967; Wass 1979; Dobosi et al. 1991). They are derived from the disaggregation of incorporated peridotite fragments (together with the olivine and orthopyroxene xenocrysts). Compared to the compositions of clinopyroxenes of peridotite xenoliths from the Bondoró-hegy (Embey-Isztin et al. 2001a), most of the studied Cr-diopside xenocrysts could represent moderately depleted peridotite and some of them could indicate fertile peridotite (e.g., lower Mg# and higher TiO_2).

Light green clinopyroxene xenocrysts have more Fe and less Ti than the phenocrysts. Their low Ti/Al ratios reflect their relatively high-pressure origin (e.g., Yagi and Onuma 1967; Wass 1979; Dobosi et al. 1991). Several interpretations exist for the origin of such green clinopyroxene cores, for example, they are cognate phases of high-pressure origin; or crystallized from evolved magmas; or represent locally metasomatized upper mantle wall rock (e.g., Brooks and Printzlau 1978; Wass 1979; Barton and Bergen 1981; Duda and Schmincke 1985; Dobosi and Fodor 1992). Most of our studied green cores are compositionally very similar to the green clinopyroxenes found in lower crustal mafic granulite xenoliths in the Balaton Highland (Embey-Isztin et al. 2003) (Figs. 8, 9). Therefore, these light green clinopyroxene xenocrysts may represent crystals entrained from lower crustal mafic granulite.

According to their composition (Fig. 10), the spinel xenocrysts also have a lithospheric mantle origin. Compared with the compositions of spinels found in the peridotite xenoliths from the Bondoró-hegy (Embey-Isztin et al. 2001a), half of the studied spinel xenocrysts could have originated from fertile peridotite (e.g., lower Cr# and higher Al_2O_3) and half could represent moderately depleted peridotite.

In summary, the olivine, orthopyroxene, colourless clinopyroxene and spinel xenocrysts have diverse chemistry covering the compositional variations of minerals in peridotite xenoliths and representing variably depleted regions of the subcontinental lithospheric mantle. This is supported by the former study of spinel peridotite xenoliths having various textures and different calculated equilibrium temperatures (Embey-Isztin et al. 2001a). The xenocrysts acted as nucleation sites for the crystallization of the phenocryst phases which isolated them from the basaltic melt as crystal rims.

Megacrysts

Clinopyroxene megacrysts of alkaline basalts are frequently interpreted as high-pressure near-liquidus phases that crystallized from their host magmas (e.g., Binns et al. 1970; Ellis 1976; Irving and Frey 1984) or as accidental fragments of pyroxenite veins that precipitated from melts at elevated pressures (e.g., Righter and Carmichael 1993; Shaw and Eyzaguirre

2000). The relatively high Mg-numbers, high Al^{VI}/Al^{IV} and low Ti/Al ratios (Fig. 9e, f) of most of the Bondoró-hegy megacrysts could reflect their high-pressure cognate origin. However, their rounded outlines and the presence of the spongy reaction zone suggest that megacrysts were in disequilibrium with the host magma during ascent implying their accidental origin. Isotope data for the megacrysts and the host alkaline basalts of the Transdanubian region (Embey-Isztin et al. 1993a; Dobosi et al. 2003) also suggest an accidental origin because the megacrysts have significantly less radiogenic Sr and Nd isotope ratios than their host basalts. Trace element abundances, however, are compatible with a cognate origin. In order to resolve this contradiction, clinopyroxene megacrysts are interpreted as accidental fragments of pegmatitic veins which crystallized from earlier alkaline basaltic melts resembling the host basalt. These melts had different radiogenic isotope ratios, but similar major and trace element compositions as the present host basalt of the megacrysts, and crystallized as pyroxenite veins in the upper mantle. The presence of pyroxenite/peridotite composite xenoliths in the Transdanubian region (Embey-Isztin et al. 1989, 1990) supports this hypothesis. The earlier crystallized coarse-grained pyroxenite veins were disrupted and carried to the surface as individual megacrysts by the ascending magma of Bondoró-hegy. During ascent, the megacrysts were out of equilibrium with the basaltic magma and through incipient partial melting, spongy domains developed in the megacrysts.

Some clinopyroxene megacrysts contain inclusions of spinel with similar compositions to the spinel megacrysts. This may suggest that spinel megacrysts had an origin similar to that of the clinopyroxene megacrysts.- The iron-rich green clinopyroxene megacryst and the titanomagnetite megacryst probably crystallized from a differentiated melt.

Ascent history

The ascent history of the Bondoró-hegy alkaline basaltic magma and origin of the diverse crystals are summarized in Fig. 11. The information for the Füzes-tó basaltic magma was presented by Jankovics et al. (2009, 2012). The model in Fig. 11 also gives a general view about the ascent history of both the crystal-rich alkaline basaltic magmas (Bondoró-hegy and Füzes-tó) in the CPR. After the generation of magma in the asthenosphere, it ascended through the lithospheric mantle in a destructive fashion, fracturing the wall rock and incorporating a vast amount of fragments from the lithospheric mantle now represented by the xenocrysts and peridotite xenoliths. During ascent, the basaltic magma strongly resorbed these crystals and fragments resulted in various disequilibrium textures and modification of the host magma composition. In the uppermost lithospheric mantle, near the crust-mantle boundary (CMB), a number of bodies (veins, dykes, sills) of frozen basaltic liquids and cumulates (i.e., earlier crystallized basaltic magma batches) can be present (Embey-Isztin et al. 1990). When the ascending magma reached this region, it incorporated additional crystals – having compositions different from those of the mantle xenocrysts – represented by the observed clinopyroxene and spinel megacrysts. As the magma passed through the CMB, the style of its ascent did not change as numerous fragments and green clinopyroxene crystals were entrained from lower crustal granulite. These fragments and crystals were also resorbed and could have additionally modified the magma composition. Accordingly, at mantle depths and near the CMB there was an effective interaction between the basaltic magma and the lithosphere. An explanation for this effective interaction could be some cryptic processes. In the case of kimberlitic magmas a recent discovery (Russell et al. 2012) suggests that continuous assimilation of foreign minerals (especially orthopyroxene) – that can modify the composition of the host melt toward more silicic compositions – causes changes in the volatile solubility in the host melt. The result is volatile exsolution and due to this process the magma can fracture more effectively the wall rock. However, this model requires that the parental melt of the host magma should have much lower silica content and high amount of dissolved volatiles (i.e., carbonatitic or near-carbonatitic composition). To be able to reveal similar cryptic processes in the case of the studied alkaline basaltic magmas, experimental studies would be necessary which could help to decide whether these processes can be also expanded for alkaline basalts or operate only in the case of kimberlites. Thus, the applicability of this model in our case is not obvious.

~~Oppositely~~ In contrast to the effective magma-wall rock interaction at lithospheric mantle and lower crustal depths, the ascending magma did not incorporate additional crustal material in the middle and upper part of the crust. This suggests a change in the style (and possibly in the rate) of the magma ascent. The main driving force of magma ascent is the process of magma-filled crack propagation (e.g., Spera 1984; Russell et al. 2012). Change in the style and rate of ascent can be caused by the variations in volatile solubility in the melt, by the change in the physical state of magma and wall rocks along the ascent path, and by varying dyke widths. Szabó and Bodnar (1996) suggested a change during the ascent of alkaline basaltic magmas in the Nógrád-Gömör Volcanic Field (Fig. 1a): the magmas accelerated near the MOHO. The observed recent activity of El Hierro (2011-2012) may also support their model, as the seismic signals suggested that the erupted magma passed rapidly through the crust (e.g., Carracedo et al. 2011). This process may be a possible interpretation for the lack of middle and upper crustal wall rock fragments in our case.

Thermobarometric studies of basaltic magmas from ocean islands indicate melt accumulation near the CMB during the ascent of the magma batches (e.g., Klügel et al. 2005; Hildner et al. 2012). The calculated ascent rates / times in the case of the Bondoró-hegy and Füzes-tó magmas, however, do not indicate a longer time of stagnation anywhere in the lithosphere. In addition, there ~~are~~ is no petrologic evidence~~s~~ for magma accumulation /

storage (e.g., common cognate crystal cumulates), and the large amount of dense materials also needs a continuous ascent.

Magma ascent rates in the monogenetic volcanic fields of the Pannonian Basin

In monogenetic volcanic fields where eruptions of basaltic magmas give scarce precursory signs, estimating magma ascent rates is essential ~~due~~ to hazard forecasting. As there are scarce direct observations about the activity of these eruptive centres, it is important to evaluate the ascent rate (as well as the ascent history) of basaltic magmas represented by diverse eruption products in various geodynamic settings.

In the case of other basalts in the Pannonian Basin, magma ascent time was determined by Dégi et al. (2009) for two eruptive centres in the Bakony-Balaton Highland Volcanic Field, by Szabó and Bodnar (1996) for several volcanic centres at the Nógrád-Gömör Volcanic Field and by Harangi et al. (in press) for two centres in the Perşani Volcanic Field. It is notable that these basalts contain a much smaller amount of lithospheric mantle-derived xenoliths and xenocrysts compared to the basalts of Bondoró-hegy and Füzes-tó. Dégi et al. (2009) studied the Fe-Ti-oxides in lower crustal mafic granulite xenoliths and modeled their diffusion-controlled chemical alteration. On the basis of diffusion profiles they estimated the duration of granulite xenolith–host basaltic melt interaction to be at least 9-20 h. This time interval gives a minimum ascent time and can be applied only in the crust, but the ascent time concerning the deeper parts of the lithosphere is not known. In the Nógrád-Gömör Volcanic Field, Szabó and Bodnar (1996) published ~37.5 hours for the residence time of upper mantle xenoliths in the host magmas and 18 hours for the residence time of a spinel xenocryst based on the thickness of its rim. Harangi et al. (in press) found that the residence time of mantle-derived olivine xenocrysts in the host alkaline basaltic magma was 3.6-4.8 days. This is very similar to our results calculated by the same method, which is notable. These three mentioned estimations are close to our results but in the case of the first, the ascent time can be much longer.

So, although the studied basalts are extremely rich in xenoliths and xenocrysts, a significant difference in their magma ascent rates compared to the other alkaline basalts in the Pannonian Basin cannot be inferred. This is not in accordance with the common view that ultramafic xenolith-rich basaltic magmas reach the surface more rapidly than xenolith-poor ones.

Conclusions

The last eruptions of the Bakony-Balaton Highland Volcanic Field are represented by especially crystal- and xenolith-rich alkaline basaltic magmas ~~including~~ forming two monogenetic eruptive centres: Bondoró-hegy and Füzes-tó scoria cone. Similar magmas did not erupt in the above mentioned volcanic field and even in the other volcanic fields in the whole Carpathian-Pannonian Region, nevertheless basalts of numerous eruptive centres contain diverse xenoliths.

Detailed textural and chemical analyses of the rock-forming minerals ~~highlighted~~ showed that almost the whole set of phenocrysts *s.l.* represents a mineral assemblage originating from different levels of the lithosphere. The foreign crystals have diverse compositions and are divided into three larger groups. The most abundant group originates from different regions of the subcontinental lithospheric mantle. Megacrysts can derive from pegmatitic veins / sills that probably represent crystallized magmas which froze near the crust-mantle boundary. Green clinopyroxenes show similar compositions compared to the clinopyroxenes in mafic granulites indicating lower crustal origin for these xenocryts. Minerals that crystallized from the basaltic melt are only represented by microphenocrysts and overgrowths on the foreign crystals. Consequently, the different whole-rock compositions of the studied basalts compared to those of the other basalts of the volcanic field are not caused by magma generation from a dissimilar mantle source or by differing degree of partial melting, but are the result of their different (more complex) evolution histories, i.e., incorporation of a vast amount of xenoliths and xenocrysts from the lithosphere at mantle and lower crustal depths.

A sudden change in the style of magma ascent is suggested by the fact that abundant crystals and xenoliths were entrained from the lithospheric mantle and lower crust but fragments from the middle-upper crust are absent from the studied basalts.

The xenocrysts show variable disequilibrium textures allowing us to calculate differing mineral-melt reaction times which can be used for magma ascent rate estimations. Based on our results calculated with different methods, we can conclude that despite the special feature of the Bondoró-hegy and Füzes-tó alkaline basalts, significant differences in their magma ascent velocities cannot be inferred compared to other alkaline basaltic magmas in the Pannonian Basin. The calculations indicate that these crystal-rich alkaline basaltic magmas could have reached the surface within hours to few days.

Based on our studies, these unique basalts enable ~~to document in detail~~ the detailed documentation of the ascent history of basaltic magmas feeding monogenetic eruptions. Furthermore, they bear valuable implications for the rock types in the underlying lithosphere.

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Figure captions

Fig. 1

a) Geological sketch map of the Carpathian-Pannonian Region. Alkaline basaltic volcanic fields are assigned with numbers: 1=Styrian Basin, 2=Little Hungarian Plain, 3=Bakony-Balaton Highland, 4=Stiavnica-Nógrád-Gömör, 5=Kecel, 6=Banat, 7= Perşani; b) Simplified geological map of the Bakony-Balaton Highland Volcanic Field (after Jugovics 1968;

Harangi 2001) with the locality of the Bondoró-hegy and the Füzes-tó scoria cone (and the names of some other volcanic centres).

Fig. 2

Outcrop photo of the scoria cone remnant, first shown by Kereszturi et al. (2010). The scoriaceous breccia of the cone is cross-cut by a massive basalt dyke (the boundaries of the dyke are marked by the white dashed lines), that we interpret as a feeder dyke based on field observations. The white arrow indicates the direction of the dyke injection. The hammer (shown by the black arrow) is 30 cm in length.

Fig. 3

a) Typical petrographic appearance of the studied crystal-rich alkaline basalts (photomicrograph, XN, sample: Ft3). Note that almost all of the phenocrysts *s.l.* are foreign minerals; b) Amphibole-bearing spinel peridotite xenolith occasionally occur in the studied alkaline basalts (photomicrograph, 1N, sample: Fuz3). Ol – olivine, opx – orthopyroxene, cpx – clinopyroxene, am – amphibole.

Fig. 4

a) Anhedral, embayed olivine which has a bright rim and contains a light green spinel that has a bright overgrowth rim adjacent to the groundmass; b) Rounded spinel crystal with a bright overgrowth rim; c) Orthopyroxene and its fine-grained rim consisting of olivine, clinopyroxene and glass; d) Crystal clot that consists of an anhedral olivine and a clinopyroxene with a rounded colourless core; e) Clinopyroxene crystal having an anhedral colourless core and a sector zoned rim; f) Clinopyroxene crystal with a resorbed light green core and a sector zoned rim; g) Homogeneous, colourless clinopyroxene megacryst that has a thick spongy zone and a zoned clinopyroxene overgrowth on it; h) Enlargement of the spongy zone of the clinopyroxene megacryst (g) containing feldspar and spinel inclusions; i) Sector zoned clinopyroxene phenocryst. SEM backscattered electron images. Ol – olivine, sp – spinel, opx – orthopyroxene, cpx – clinopyroxene, fp – feldspar.

Fig. 5

a) Relationship between the Fo (mol%) and CaO (wt.%) content of the studied olivine crystals; b) Plot of Fo (mol%) and NiO (wt.%) contents of the studied olivines. Light grey dashed line fields indicate the compositions of olivines in upper mantle peridotite xenoliths from the Balaton Highland (Embey-Isztin et al. 2001a).

Fig. 6

Fo (mol%), Ni and Ca (ppm) profiles of olivine xenocrysts (a, b) and an olivine phenocryst *s.s.* (c). The lines of measured points are indicated by the A-B lines in each picture (SEM backscattered electron images). In the case of the xenocrysts, at the crystal margins (in a 50-100 μm thick band) points were measured with ~5 μm gaps between each other, while in the central part of the olivine the gaps were increased to 20-50 μm. In the case of olivine phenocrysts, the whole profile was prepared with 5 μm gaps (5 μm distances between measuring points were necessary because of the effect of the e^- beam on the crystal surface).

Fig. 7

Fo (mol%) vs. NiO (wt.%) relationship of representative olivine xenocrysts (Fig. 6a, b) and normal zoned phenocryst (Fig. 6c). The different core-to-rim trends are indicative for diffusion- or growth-related development of the zoning (for details see text).

Fig. 8

Compositions of the studied clinopyroxenes plotted in the atomic Mg-Fe-Ca ternary diagram (boundaries after Morimoto et al. 1988). The light grey dashed line field indicates the compositions of clinopyroxenes in upper mantle peridotite xenoliths from the Balaton Highland (Embey-Isztin et al. 2001a), the dark grey dashed line field indicates the compositions of clinopyroxenes in lower crustal mafic granulite xenoliths from the Balaton Highland (Embey-Isztin et al. 2003).

Fig. 9

Variation of Mg# (Mg/(Mg+Fe^{tot})) vs. Ti (a), Al (b), Cr (c) and Na (d) (cations per formula unit based on 6 O); e) Plot of Ti vs. Al (cations per formula unit based on 6 O); f) ^{IV}Al vs. ^{VI}Al diagram (Aoki and Kushiro 1968). Symbols as in Fig. 8. Light and dark grey dashed line fields indicate the same clinopyroxene compositions as in Fig. 8 (the Cr content of granulitic clinopyroxenes were not analysed in Embey-Isztin et al. 2003).

Fig. 10

a) Cr-Al-Fe^{3+} ternary plot of the studied spinels; b) Variation of MgO (wt.%) vs. Al_2O_3 (wt.%) contents in the studied spinel grains. Light grey dashed line fields indicate the compositions of spinels in upper mantle peridotite xenoliths from the Balaton Highland (Embey-Isztin et al. 2001a).

Fig. 11

Schematic cartoon of the proposed model for the ascent history of the Bondoró-hegy and Füzes-tó alkaline basaltic magmas. Enlargements of the ascent path show the dominant processes (see the text for details). The figure is to scale. LAB – lithosphere–asthenosphere boundary, gt – garnet, sp – spinel. The source for the crustal and lithospheric thicknesses is: http://geophysics.elte.hu/atlas/geodin_atlas.htm.

Table captions

Table 1

Major and trace element analyses of the BON683 sample from Bondoró-hegy (Embey-Isztin et al. 1993a)

Table 2

Representative compositions of the studied olivines

Table 3

Representative analyses of the studied orthopyroxenes and clinopyroxenes

Table 4

Representative compositions of the studied spinels

Table 5

Details of the different methods and results of the estimated magma ascent rates and times

Table 6

Calculated residence times of the studied olivine xenocrysts

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Origin and ascent history of unusually crystal-rich alkaline basaltic magmas from the western Pannonian Basin

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Abstract

The last eruptions of the monogenetic Bakony-Balaton Highland Volcanic Field (western Pannonian Basin, Hungary) produced unusually crystal- and xenolith-rich alkaline basalts

which are unique among the alkaline basalts of the Carpathian-Pannonian Region. Similar alkaline basalts are only rarely known in other volcanic fields of the world. These special basaltic magmas fed the eruptions of two closely located volcanic centres: the Bondoró-hegy and the Füzes-tó scoria cone. Their uncommon enrichment in diverse crystals produced unique rock textures and modified original magma compositions (13.1-14.2 wt.% MgO, 459-657 ppm Cr, 455-564 ppm Ni contents).

Detailed mineral-scale textural and chemical analyses revealed that the Bondoró-hegy and Füzes-tó alkaline basaltic magmas have a complex ascent history, and that most of their minerals (~30 vol.% of the rocks) represent foreign crystals derived from different levels of the underlying lithosphere. The most abundant xenocrysts, olivine, orthopyroxene, clinopyroxene and spinel, were incorporated from different regions and rock types of the subcontinental lithospheric mantle. Megacrysts of clinopyroxene and spinel could have originated from pegmatitic veins / sills which probably represent magmas crystallized near the crust-mantle boundary. Green clinopyroxene xenocrysts could have been derived from lower crustal mafic granulites. Minerals that crystallized in situ from the alkaline basaltic melts (olivine with Cr-spinel inclusions, clinopyroxene, plagioclase, Fe-Ti oxides) are only represented by microphenocrysts and overgrowths on the foreign crystals. The vast amount of peridotitic (most common) and mafic granulitic materials indicates a highly effective interaction between the ascending magmas and wall rocks at lithospheric mantle and lower crustal levels. However, fragments from the middle and upper crust are absent from the studied basalts, suggesting a change in the style (and possibly rate) of magma ascent in the crust. These xenocryst- and xenolith-rich basalts yield divers tools for estimating magma ascent rate that is important for hazard forecasting in monogenetic volcanic fields. According to the estimated ascent rates, the Bondoró-hegy and Füzes-tó alkaline basaltic magmas could have reached the surface within hours to few days, similarly to the estimates for other eruptive centres in the Pannonian Basin which were fed by "normal" (crystal- and xenolith-poor) alkaline basalts.

Keywords

alkaline basalt, ascent history, crystal-rich, magma ascent rate, monogenetic volcanism, xenocryst, xenolith

Introduction

Monogenetic basaltic volcanic fields consist of small individual eruptive centres characterized by a single brief eruption (Walker, 1993) and low magma supply (e.g., Hasenaka and Carmichael, 1985; Takada, 1994). These monogenetic eruptions of basalt are generally assumed to be simple in terms of volcanology and petrology. That is, they produce small volcanic edifices during continuous activity within a relatively short time span, and are fed by a single, compositionally discrete batch of magma (e.g., Connor and Conway 2000). However, several authors suggested that individual eruptive centres can be characterized by multiple eruptions involving different magma batches with hiatuses during their activity (e.g., Reiners 2002; Martin and Németh 2005; Brenna et al. 2010, 2011; Needham et al. 2011, Shane et al. 2013) implying a complex evolution history of the magmatic system. These studies focused mainly on the compositional variations of the feeding magma batches and suggest differences in their source regions and / or degrees of partial melting. However, processes acting during the ascent of the magma batches are also important (Brenna et al. 2010). This is essential information because the evolution of the magma in the feeding system can have a significant effect on the rate and style of magma ascent, and therefore on the nature of eruptions (e.g., Ruprecht and Bachmann 2010; McGee et al. 2012; Russell et al. 2012). Detailed textural and chemical analyses of phenocrysts in basalts can provide insights into the details of their magma evolution (e.g., Dobosi 1989; Dobosi et al. 1991; Roeder et al. 2001, 2003, 2006; Smith and Leeman 2005; Jankovics et al. 2009, 2012).

The monogenetic Bakony-Balaton Highland Volcanic Field, located in the western part of the Carpathian-Pannonian Region, was active for approximately 6 My. Its last active phase was closed by two eruptive centres: the Bondoró-hegy (2.3 Ma; Balogh and Pécskay 2001) and the Füzes-tó scoria cone (2.6 Ma; Wijbrans et al. 2007) each fed by alkaline basaltic magmas with special compositions and petrological appearance (Jankovics et al. 2009, 2012). These alkaline basalts are characterized by extremely high Mg, Ni and Cr contents and are unusually rich in diverse crystals and xenoliths (peridotite, mafic granulite). Similar magmas did not erupt in the above mentioned volcanic field and even in the other six volcanic fields in the whole Carpathian-Pannonian Region (CPR). Nevertheless, basalts of numerous eruptive centres in the region contain diverse xenoliths. In other volcanic fields of the world, magmas with characteristics similar to those of the Bondoró-hegy and Füzes-tó scoria cone are known (e.g., Ancochea et al. 1987; Mattsson 2012; Kozákov Hill in Ulrych et al. in press) but they are rare. Due to their crystal-rich feature these rocks provide unique insights into the ascent history of basaltic magmas. Following the detailed investigations and descriptions of the Füzes-tó basalt (Jankovics et al. 2009, 2012), in this study we analyse the similar (both in age and petrology) basalt of Bondoró-hegy and reveal its ascent history. It is generally assumed that such xenolith-rich magmas can reach the surface very rapidly. We estimate the ascent rates of these xenocryst- and xenolith-rich alkaline basalts, and compare the results with xenolith-poor basalts. Understanding the ascent history and estimating the magma ascent velocity is important in monogenetic volcanic fields for their volcanic hazard assessments. This study demonstrates the importance of the especially crystal-rich basaltic magmas of monogenetic volcanic fields for enabling estimating the magma ascent rate by several different methods.

Geological setting

The Pannonian Basin is a Miocene extensional back-arc basin surrounded by the Alpine, Carpathian and Dinarides orogenic belts (Fig.1a). It is characterized by thin lithosphere (50-80 km) and crust (22-30 km) coupled with high heat flow (>80 mW/m^2; Csontos et al. 1992;

Fodor et al. 1999; Tari et al. 1999; Bada and Horváth 2001; Lenkey et al. 2002). These features are due to the initial syn-rift phase (17–12 Ma; Horváth 1995) of the Pannonian Basin that was characterized by subduction roll-back, related back-arc extension and lithospheric thinning (Csontos et al. 1992; Horváth 1993; Tari et al. 1999). This was followed by the Late Miocene–Pliocene post-rift phase (e.g., Horváth 1995) which was accompanied by thermal subsidence, thickening of the lithosphere and sedimentation in the basin areas. Tectonic inversion has characterized the Pannonian Basin since the late Pliocene due to the push of the Adriatic plate from the southwest and blocking by the East European platform in the east (Horváth and Cloetingh 1996).

Post-extensional alkaline basaltic volcanism occurred from 11 to 0.13 Ma in the region, mainly on its marginal parts, which formed monogenetic volcanic fields. The tectonic background of the alkaline basaltic magmatism is still under debate. Several researchers suggested that localised mantle plume fingers (deriving from a common mantle reservoir named ”European Asthenospheric Reservoir”; Hoernle et al. 1995) could be responsible for the alkaline basaltic volcanism in Western and Central Europe, accordingly in the Pannonian Basin as well (Granet et al. 1995; Seghedi et al. 2004). However, Harangi and Lenkey (2007) and Harangi (2009) argued against the plume-related magmatism. They suggested that the significantly stretched Pannonian Basin provided suction in the sublithospheric mantle and generated an asthenospheric mantle flow from below the thick Alpine regime which could lead to the partial melting of the heterogeneous upper mantle.

The Bakony-Balaton Highland Volcanic Field (Fig. 1b) comprises approximately 150-200 eruptive centres (Németh and Martin 1999a, 1999b) that are erosional remnants of maars, tuff rings, scoria cones and shield volcanoes (e.g., Jugovics 1968; Németh and Martin 1999a, 1999b; Martin et al. 2003). Several of these alkaline basalt occurrences contain ultramafic and mafic xenoliths, as well as discrete megacrysts which were extensively studied in the past decades (e.g., Embey-Isztin 1976; Embey-Isztin et al. 1989, 1990, 2001a, 2001b, 2003; Downes et al. 1992; Downes and Vaselli 1995; Dobosi et al. 2003; Dégi et al. 2009). These studies together with those for whole-rock geochemistry of the basalts (e.g., Embey-Isztin et al. 1993a, 1993b; Embey-Isztin and Dobosi 1995; Seghedi et al. 2004) have yielded important information on the nature of the upper mantle beneath the area and the partial melting processes. Based on several studies (e.g., Embey-Isztin et al. 1989, 1990, 2001a; Szabó et al. 2004; Hidas et al. 2007; Dégi et al. 2009) we have an extensive knowledge about the structure of the whole lithosphere as well.

Volcanological background

In this paper, we describe the volcanological background for the Bondoró-hegy eruptive centre. The features of the Füzes-tó scoria cone were reported in a previous paper (Jankovics et al. 2009). Bondoró-hegy volcano is one of the most complex eruption centres of this volcanic field and consists of several discrete eruptive units: basal tuff ring pyroclastics with a lava lake, reworked basaltic debris beds, lava flow units (1st and 2nd lava flow) and capping scoria cone associated with the 3rd lava flow (Kereszturi et al. 2010). The capping scoriaceous basalt (e.g., spindle and scoriaceous bombs) and the 3rd lava flow unit (representing the youngest eruptive phase) are rich in xenoliths of upper mantle and lower crustal origins (peridotite, wehrlite, clinopyroxenite, mafic granulite) and in clinopyroxene and spinel megacrysts.

In an outcrop of the capping scoria unit (in the breached side of the scoria cone remnant), Kereszturi et al (2010) described a dyke that crosscuts the scoriaceous breccia. Based on our field observations (Fig. 2), this massive dyke has an average width of 0.625±0.055 m and can be interpreted as a feeder dyke of the scoria cone.

Several K-Ar ages are available: the basalt of the lava lake is estimated at about ≤3.86±0.20 Ma and the 2nd lava unit at about 2.90±0.62 Ma (Balogh et al. 1986). A sample from the 3rd lava flow unit gave an age of 2.29±0.22 Ma (Balogh and Pécskay 2001). According to Kereszturi et al. (2010), these ages represent the best fit with the geological and stratigraphical observations. Unfortunately, Bondoró-hegy was not included in the $^{40}Ar/^{39}Ar$ dating of the Balaton Highland basaltic rocks (Wijbrans et al. 2007). Based on the preferred K-Ar ages (that indicate prolonged volcanic activity) and the discordance between the phreatomagmatic unit and the subsequent lava flows (implying a significant time gap), Bondoró-hegy can be regarded as a polycyclic monogenetic volcano (Kereszturi et al. 2010).

Petrography and whole-rock compositions

Samples of the Bondoró-hegy were collected from the 3rd lava flow unit. Samples of the Füzes-tó scoria cone were collected in the inner slope around the central depression (various basaltic bombs). In this paper, we describe only the features of the Bondoró-hegy basalt, the descriptions of the Füzes-tó basalt are in Jankovics et al. (2009, 2012). Figure 3a shows the typical petrographic appearance of the studied crystal-rich alkaline basalts.

The term 'phenocryst' is here used in a general sense, i.e., for larger, up to 5 mm, crystals in fine-grained groundmasses, regardless of their origins (i.e., phenocryst *sensu lato*). In the following, the term 'phenocryst' has been used in a genetic sense, i.e., for crystals that have grown in situ in the magma in which they are found now (i.e., phenocryst *sensu stricto*).

The studied lava samples have porphyritic texture characterized by non- to low-vesicularity and ~30 vol.% anhedral to euhedral phenocrysts (on a vesicle-free basis). The phenocryst assemblage consists of olivine, clinopyroxene, orthopyroxene and spinel characterized by variable forms and sizes, and crystals often occur together as crystal clots

(Fig. 4d). Microphenocrysts (<150 μm) are clinopyroxene, olivine, plagioclase and Fe-Ti-oxides. The fine-grained groundmass is composed of microlitic feldspars (plagioclase and alkali feldspar), clinopyroxene, olivine, Fe-Ti-oxides, apatite and some glass.

Most of the olivine phenocrysts (up to 5 mm) are characterized by rounded and embayed margins. These crystals commonly show undulose extinction, and have bright rims (with diffuse boundaries toward the crystal interiors) in the backscattered electron (BSE) images (e.g., Fig. 4a). They frequently contain subhedral-anhedral (often rounded), light green to brown spinel inclusions which range in size from ~50 to 300 μm. The smaller (150-900 μm) olivine grains are euhedral to subhedral and often skeletal and their outermost margin is frequently iddingsitised. They often contain black, euhedral-subhedral chromian spinel inclusions (~3-10 μm).

Orthopyroxene crystals (up to 2.4 mm) are always surrounded by fine-grained rims of various thicknesses (Fig. 4c) consisting of olivine, clinopyroxene, glass and rarely spinel. The outermost part of this corona often contains numerous Fe-Ti-oxides as well. This fine-grained rim is frequently overgrown by a pale brown, twinned and sector zoned clinopyroxene.

Clinopyroxene phenocrysts (up to 3 mm) are euhedral to subhedral in shape and usually have an anhedral, rounded core (with a sharp boundary) and a pale brown, twinned, sector zoned rim characterized by various thicknesses (rarely some sector zoned clinopyroxenes without a rounded crystal core are also found; Fig. 4i). Two types of the anhedral, variously resorbed cores can be distinguished. The first and more frequent type is colourless under the optical microscope, and darker grey than the rim in the BSE images (Fig. 4d, e). The other type is light green under the optical microscope, and lighter grey than the surrounding rim in the BSE images (Fig. 4f) which indicates reverse zoning. The green cores often have spongy or sieved texture.

Spinel crystals (up to 0.5 mm) occur as individual crystals in the matrix (Fig. 4b) and as inclusions in olivine phenocrysts (Fig. 4a). They usually have ragged, anhedral margins, are characterized by variable colours (light green to brown), and often have a bright (Ti-magnetite) overgrowth rim (with a relatively sharp boundary toward the crystal interior) in the BSE images where it is in contact with the groundmass (Fig. 4a, b).

All these disequilibrium textures (ragged, rounded, resorbed, embayed, spongy features) suggest a xenocrystic origin for the anhedral olivines, colourless and green cores of clinopyroxene phenocrysts, orthopyroxenes and spinels.

In addition to the abundant xenocrysts, the studied samples include numerous peridotite xenoliths. These are spinel peridotites which occasionally contain amphiboles (Fig. 3b). Along the contact between the peridotite and basalt the peridotitic orthopyroxene grains have the same fine-grained rims as the orthopyroxene xenocrysts in the basaltic groundmass. Therefore, these rims are interpreted as mineral-melt reaction products. Similar to most of the olivine xenocrysts, the olivine grains in the peridotite xenoliths often have undulose extinction which implies deformation.

Additionally, clinopyroxene and spinel megacrysts are also common. Most of the clinopyroxene megacrysts (up to 6 cm, elongated) are colourless, they have homogeneous interiors crosscutting with cracks filled with secondary fluid inclusions, and are overgrown by a pale brown, zoned clinopyroxene rim similar to that of the clinopyroxene xenocrysts. Spongy zones are present between this rim and the homogeneous part of the megacrysts (Fig. 4g). In the spongy zones, small inclusions of feldspars (plagioclase and alkali feldspar) and skeletal spinels are present (Fig. 4h). Besides the colourless megacrysts, one piece of a green clinopyroxene megacryst has also been found. The spinel megacrysts are ~1-2 cm in size, mostly dark green, but one was black, under the optical microscope.

The whole rock composition of the Bondoró-hegy basalt has been described by Jugovics (1976) and Embey-Isztin et al. (1993a, 1993b). The compositional data identify the lavas of Bondoró-hegy as undersaturated basanite (Table 1), similar to the compositions of the other basalts in the region, however, the basaltic rocks from Bondoró-hegy are extremely rich in MgO (13.1-13.9 wt.%). Similar MgO enrichment has been reported only at the Füzes-tó scoria cone from the Pannonian Basin (see Fig. 1b), which has 13.4-14.2 wt.% MgO content (Jankovics et al. 2009). This is correlated with the abundance of xenocrystic olivine and orthopyroxene. The high MgO content is accompanied by extreme enrichment in Ni and Cr contents (455-474 and 459-489 ppm, respectively; Embey-Isztin et al. 1993a, 1993b), also caused by the presence of abundant peridotitic xenocrysts. The incompatible trace element content of the Bondoró-hegy basalt is approximately the same as that of the other basalts of the region, though some incompatible trace element and radiogenic isotope ratios are different. While the lavas of the Bakony-Balaton Highland Volcanic Field tend to show higher K/Nb, Rb/Nb and lower Ce/Pb, as well as higher $^{207}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$, the opposite is true for the Bondoró-hegy basalt. This is explained by the involvement of an enriched lithospheric component in the lavas, which is missing from the Bondoró-hegy basaltic magma (Embey-Isztin et al. 1993b).

Mineral chemistry

Analyses of minerals in the Bondoró-hegy basalt were obtained on a JEOL Superprobe 733 using wavelength-dispersive spectrometers at the Institute for Geological and Geochemical Research in Budapest, Hungary. Analytical conditions were 20 kV accelerating voltage, 35 nA beam current, and all analyses were made against mineral standards. Raw data were corrected by the ZAF correction program of JEOL. Olivine profiles of the Füzes-tó basalt were determined using a CAMECA SX100 electron microprobe equipped with four WDS and one EDS at the University of Vienna, Department of Lithospheric Research (Austria). The operating conditions were as follows: 15 kV accelerating voltage, 20 nA beam current, 20 s counting time on peak position, focused beam diameter and PAP correction procedure for data reduction. The following standards were applied: albite (for Si, Al); almandine (for Fe); olivine (for Mg); wollastonite (for Ca); spessartine (for Mn) and Ni-oxide (for Ni). The mineral compositions of the Füzes-tó basalt are discussed in Jankovics et al. (2009, 2012).

Olivine

Olivine crystals display a wide range of Fo (Table 2). The xenocrysts are chemically homogeneous and typically have Fo from 89.5 to 92 mol% (Fo=100*Mg/(Mg+Fe), all Fe is assumed to be divalent). They have thin rims with lower Fo (72.1-81.4 mol%), which overlap that of the groundmass olivines (76.1-76.7 mol%).

Olivine xenocrysts have low CaO and high NiO contents (0.05-0.12 wt.% and 0.33-0.39 wt.%, respectively), while their rims are enriched in CaO (0.16-0.40 wt.%) and depleted in NiO (0.16-0.34 wt.%) (Fig. 5). CaO shows a weak negative, whereas NiO shows a weak positive correlation with Fo content (Fig. 5). The highest Ca and lowest Ni contents are in groundmass olivines (0.38-0.57 wt.% CaO and 0.14-0.18 wt.% NiO). The compositions of the studied xenocrysts resemble those of the olivines of the peridotite xenoliths in the Balaton Highland (Fig. 5).

All olivine Fo profiles are symmetric to the centre of the grain, but their shapes differ (Fig. 6). Olivine xenocrysts have well-defined inner plateaus bounded by large compositional gradients toward the rims (Fig. 6a, b). Their inner part contains less than 500 ppm Ca, ~3000 ppm Ni and ~90 mol% Fo. In the rims, Ca sharply increases to >3000 ppm, while Ni and Fo sharply decrease to <1000 ppm and to 75 mol%, respectively. In several xenocrysts, the inner plateaus show some compositional variations (maybe related to healed cracks or tiny inclusions) (Fig. 6b). The profiles of olivine phenocrysts have a shield-like shape indicating a gradual compositional variation toward the rims (Fig. 6c). The Ca and Ni profiles are less smooth than those in xenocrysts, which may be the result of skeletal growth of the phenocrysts. Compared to the xenocrysts, the Ca content of their inner part is significantly higher (~1250 ppm), while the Ni and Fo contents are lower (between ~2000-2500 ppm and ~87 mol%, respectively). Phenocrysts and xenocrysts can be distinguished in the Fo-NiO diagram (Fig. 7), which shows that olivine xenocrysts show linear trends towards the rims indicating that the formation of core-to-rim zoning was mainly driven by diffusion. However, phenocrystic olivine has a curved trend towards the rims that can be interpreted as mainly growth-related core-to-rim zoning considering the implications of Costa et al. (2008).

The compositions of the xenocryst rims (Fig. 5, 6a) are similar to those of the olivine xenocryst rims and olivine phenocryst rims in the Füzes-tó basalt (Jankovics et al. 2009, 2012). The formation of these Fe-rich rims can be explained by diffusion during re-equilibration of the xenocryst with the host basaltic magma (note the diffuse boundary toward the crystal interior; Fig. 4a, d) as well as some subsequent crystallization of phenocrystic olivine on the xenocrysts.

Orthopyroxene

Orthopyroxenes occur only as xenocrysts in the studied basalt. They are enstatites (Morimoto et al., 1988) with high Mg#s (0.91-0.92; Mg/(Mg+Fe^{tot})) and contain 2.9-3 wt.%

Al_2O_3 (Table 3). These compositions are characteristic for mantle orthopyroxenes similar to those of the peridotite xenoliths in the Balaton Highland (Embey-Isztin et al. 2001a).

Clinopyroxene

The clinopyroxene compositions are highly variable (Table 3, Figs. 8, 9) but basically four different types can be distinguished. They are: 1) colourless xenocrystic cores, 2) light green xenocrystic cores, 3) megacrysts, 4) phenocrysts, microphenocrysts and groundmass clinopyroxenes.

Colourless cores

Colourless cores (Table 3, analyses No. 2 and 4) are homogeneous but have variable compositions in the different crystals. They are chromian diopsides (Fig. 8) with high Mg#s (0.88-0.92; $Mg/(Mg+Fe^{tot})$) and SiO_2 contents (51.2-53.7 wt.%), and varying Cr_2O_3 and Al_2O_3 contents (0.28-1.4 wt.% and 2.8-6.1 wt.%, respectively). They are generally low in TiO_2 (up to 0.48 wt.%) and have low Ti/Al ratios (≤0.07) and high Al^{VI}/Al^{IV} ratios (0.81-1.3). The compositions of these colourless xenocrystic cores are similar to those of the clinopyroxenes from the peridotite xenoliths in the Balaton Highland (Figs. 8, 9).

Green cores

Representative analyses of green cores are in Table 3 (analyses No. 6 and 8). The green cores are homogeneous and enriched in iron (Fig. 8). Their Mg#s ($Mg/(Mg+Fe^{tot})$) varies between 0.59-0.69 which is lower than those of the overgrowth rims. Their TiO_2 and Al_2O_3

contents are relatively low (0.49-0.76 wt.% and 4.5-6.6 wt.%, respectively) and the amount of Cr_2O_3 is around (or below) the detection limit. The compositions of these xenocrystic cores resemble those of the clinopyroxenes of the lower crustal granulite xenoliths in the Balaton Highland (Figs. 8, 9). Their Ti/Al and Al^{VI}/Al^{IV} ratios are in the same range as in the colourless cores (Fig. 9e, f). One of the green cores has a different composition: it has slightly lower Mg# (0.58) and significantly lower TiO_2 (0.28 wt.%) and Al_2O_3 (1.5 wt.%) contents than the other green cores of the samples.

Megacrysts

The interiors of the megacrysts are homogeneous. The colourless megacrysts show a restricted range of composition (Figs. 8, 9; Table 3, analyses No. 10 and 13). Their Mg#s ($Mg/(Mg+Fe^{tot})$) are 0.81-0.83, the TiO_2 and Al_2O_3 contents are in the range of 0.91-1.3 wt.% and 8.7-9.2 wt.%, respectively. They are characterized by low Ti/Al (0.07-0.09) and high Al^{VI}/Al^{IV} ratios (0.90-1.2) (Fig. 9e, f). They have high Na_2O contents (1.2-1.3 wt.%) compared to the phenocrysts, and do not contain Cr_2O_3 in detectable amount. The clinopyroxene composition in the spongy part is slightly different from that of the interior of the megacryst having higher TiO_2 (1.1-2.2 wt.%), lower Al_2O_3 (6.2-8 wt.%) and Na_2O (0.48-0.73 wt.%), while the Mg# is the same.

The green megacryst are characterized by lower Mg# (0.57) and Al_2O_3 (7.5 wt.%), and higher TiO_2 (1.6 wt.%) and Na_2O (2.1 wt.%) contents than the other megacrysts. It has similar Al^{VI}/Al^{IV} (0.93), but a slightly higher Ti/Al ratio (0.14) compared to the colourless megacrysts.

Phenocrysts, microphenocrysts and groundmass grains

The pale brown clinopyroxene phenocrysts (i.e., the overgrowth rims on clinopyroxene xenocrysts and megacrysts as well as on the reaction rim of orthopyroxene xenocrysts), microphenocrysts and microlites of the groundmass are titanian augites or titanaugites according to the traditional pyroxene nomenclature (Deer et al. 1978), but can be classified as diopside, aluminian diopside and titanian aluminian diopside according to the I.M.A. classification of pyroxenes (Morimoto et al. 1988). Some representative analyses of these clinopyroxenes can be seen in Table 3 (e.g., analyses No. 3, 7, 12 and 17). Their Mg#s ($Mg/(Mg+Fe^{tot})$) range from 0.73 to 0.85 and their TiO_2 and Al_2O_3 contents vary between 1.5-3.9 wt.% and 4.9-10.1 wt.%, respectively. Ti and Al show positive correlation (Fig. 9e) and both elements increase with iron enrichment (Fig. 9a, b). Their increasing Ti with decreasing Mg# reflects the normal fractionation trend (e.g., Tracy and Robinson 1977). The Cr_2O_3 contents can reach 1 wt.% but it sharply decreases with decreasing Mg# (Fig. 9c). Their Ti/Al ratios (0.16-0.34) are higher, while the Al^{VI}/Al^{IV} ratios (0.12-0.48) are lower than those of any other type of the studied clinopyroxenes (Fig. 9e, f). These ratios imply that they could have crystallized under relatively low-pressure conditions (e.g., Yagi and Onuma 1967; Wass 1979; Dobosi et al. 1991). Based on their slightly increasing Ti/Al ratios during crystallization (Fig. 9e), they could have precipitated under continuously decreasing pressure. They could have been characterized by a significantly higher crystallization rate compared to the olivine phenocrysts (as suggested by Fig. 4d).

Oxide minerals

Representative analyses of the studied oxide minerals are shown in Table 4. The xenocrysts are Mg- and Al-rich spinels showing variable compositions (Fig. 10). Their Mg#s

(Mg/(Mg+Fe^{tot})) vary between 0.63 and 0.74 and their Cr#s (100*Cr/(Cr+Al)) range from 12.3 to 45.8 (Cr_2O_3=11.4-37 wt.%, Al_2O_3=29.2-54.5 wt.%). Additionally, they have low TiO_2 contents (0.11-0.37 wt.%). The compositions of the studied xenocrysts are very similar to those of the spinels of the peridotite xenoliths in the Balaton Highland (Fig. 10).

The dark green megacrysts are also Mg-Al-rich spinels (Fig. 10) with 0.65-0.67 Mg#s, however they are characterized by higher Al_2O_3 contents (61-61.8 wt.%) and very low Cr_2O_3 contents (≤0.15 wt.%). The black megacryst has a completely different composition: it is a titanomagnetite with 10.4 wt.% TiO_2 and 76.6 wt.% FeO^{tot} contents.

The oxides in the groundmass are mainly titanomagnetites which contain 17.3-23.5 wt.% TiO_2 and 66.8-72.5 wt.% FeO^{tot}. Matrix ilmenites are also present characterized by 49.3-51.3 wt.% TiO_2 and 38.8-43.1 wt.% FeO^{tot}.

In summary, the compositional characteristics of the phenocryst (*s.s.*) phases (olivine, clinopyroxene, Fe-Ti-oxides) in the Bondoró-hegy basalt are similar to those of the phenocrysts found in other basalts in the Balaton Highland.

Magma ascent rate estimates

The Bondoró-hegy and Füzes-tó crystal-rich basalts provide a tool for estimating the magma ascent rate by a number of methods (Table 5). The detailed descriptions and background information of the different methods are presented in the Electronic Appendix.

1) We carried out calculations to estimate the ascent velocity for alkaline basaltic magmas in general based on fluid filled crack propagation velocities. These computations yield magma ascent rates in the range of 3.9-15.9 m/s, which are (at a given dyke width and density

contrast between melt and wall rock) lower than the ascent velocities of melilitites (e.g., Mattsson 2012) and kimberlites (e.g., Sparks et al. 2006).

Based on this method, 4.4-9.2 m/s magma ascent rates would be reasonable for the observed dyke width (0.625±0.055 m; Fig. 2) in the case of the youngest eruptive phase of Bondoró-hegy (capping scoriaceous basalt and the 3rd lava flow). According to Valentine and Krogh (2006), complex sill and dyke systems can be present beneath small volume, alkaline basaltic volcanic centres with variable dyke widths of main / parent dykes (3-9 m) and dyke-parallel segments (few decimetres-1.2 m). The observed dyke width in Bondoró-hegy falls in the range of these dyke widths, and it may represent a part of a similar dyke system.

2) We calculated the settling rate of the largest (20 cm in diameter) peridotite xenoliths found at Bondoró-hegy and Füzes-tó scoria cone. These computations yield xenolith settling rates in the range of 0.10-0.41 m/s, which corresponds to minimum ascent rates.

3) We used the Ca profiles of olivine xenocrysts (from the Füzes-tó basalt) which can be appropriate for estimating magma ascent time because the profiles were measured in rapidly quenched basaltic bombs. The average of the calculated residence times for the xenocrysts (Table 6) is 3.6 days (86.4 hours) which means the time that olivine xenocrysts could have spent in the basaltic melt. Considering for example a 60 km long ascent route, this gives an ascent rate of 0.19 m/s.

4) We estimated the dissolution times of orthopyroxene xenocrysts based on the thicknesses of their reaction rims. The thickest studied reaction rim can form in 86-426 minutes (1.4-7.1 hours). This gives the interaction time between orthopyroxene and basaltic melt which denotes the minimum time that the magma must have spent in the feeding system. Using for example a 60 km long ascent route again, this means an ascent rate of 11.9 m/s.

In summary, the different methods resulted in a large range of ascent rates. The minimum ascent velocities are 0.10-0.19 m/s derived from the 2nd and 3rd methods (respectively), and the maximum ascent rates are 9.2-11.9 m/s resulted from the 1st and 4th methods (respectively). These results imply that the Bondoró-hegy and Füzes-tó crystal-rich magmas could have reached the surface from their source within hours to few days.

Discussion

Alkaline basalts of the Bakony-Balaton Highland Volcanic Field have phenocryst assemblages of olivine, and more rarely, clinopyroxene (e.g., Embey-Isztin et al. 1993a). Olivine is frequently the only phenocryst phase and clinopyroxene is restricted to the groundmass. In contrast, the basalts of the Bondoró-hegy and Füzes-tó are more complex, having large textural and compositional heterogeneity, especially among clinopyroxenes. Most of the minerals could not be in equilibrium with each other and with the host magma, and many of them must be xenocrysts entrained from various depths. Here, we discuss the origins of the diverse crystals of the Bondoró-hegy basalt, the interpretations in the case of the Füzes-tó basalt were reported in previous papers (Jankovics et al. 2009, 2012). We also provide the magma ascent history and estimates of ascent rate.

Sources for the diverse mineral assemblage

Xenocrysts

The compositional range of olivine xenocrysts (Fig. 5) is typical for mantle olivines (e.g., Boudier et al. 1991; Hirano et al. 2004; Rohrbach et al. 2005). The Fo value for average olivines in the lithospheric mantle is 90 mol% (Sato 1977). Most of the studied olivine xenocrysts contain Fo around 90 mol%, but some of them have higher Fo contents suggesting that they are derived from depleted peridotites.

Orthopyroxene xenocrysts are also Mg-rich which is characteristic for orthopyroxenes of the upper mantle (e.g., Embey-Isztin et al. 2001a). Their reaction rims are common features of mantle-derived orthopyroxenes that are incorporated by silica-undersaturated alkaline melts. This mineral-melt reaction results in the incongruent dissolution of the orthopyroxene and formation of a reaction corona (olivine + Si-rich glass + clinopyroxene ± spinel) at the expense of the orthopyroxene (e.g., Arai and Abe 1995; Shaw et al. 1998; Shaw 1999; Shaw and Dingwell 2008). Comparing the compositions of the studied enstatite xenocrysts with the orthopyroxenes from the Bondoró-hegy peridotite xenoliths (Embey-Isztin et al. 2001a), they could have derived from moderately depleted peridotite (e.g., 2.9-3 wt.% Al_2O_3, 33.4-33.9 wt.% MgO).

The compositional variation of the colourless clinopyroxene xenocrysts (Figs. 8, 9) is typical for Cr-diopsides of peridotite xenoliths (e.g., Wass 1979). The low Ti/Al ratios of the colourless xenocrystic cores suggest a relatively high-pressure origin (e.g., Yagi and Onuma 1967; Wass 1979; Dobosi et al. 1991). They are derived from the disaggregation of incorporated peridotite fragments (together with the olivine and orthopyroxene xenocrysts). Compared to the compositions of clinopyroxenes of peridotite xenoliths from the Bondoró-hegy (Embey-Isztin et al. 2001a), most of the studied Cr-diopside xenocrysts could represent moderately depleted peridotite and some of them could indicate fertile peridotite (e.g., lower Mg# and higher TiO_2).

Light green clinopyroxene xenocrysts have more Fe and less Ti than the phenocrysts. Their low Ti/Al ratios reflect their relatively high-pressure origin (e.g., Yagi and Onuma 1967; Wass 1979; Dobosi et al. 1991). Several interpretations exist for the origin of such green clinopyroxene cores, for example, they are cognate phases of high-pressure origin; or crystallized from evolved magmas; or represent locally metasomatized upper mantle wall rock (e.g., Brooks and Printzlau 1978; Wass 1979; Barton and Bergen 1981; Duda and Schmincke 1985; Dobosi and Fodor 1992). Most of our studied green cores are compositionally very similar to the green clinopyroxenes found in lower crustal mafic granulite xenoliths in the Balaton Highland (Embey-Isztin et al. 2003) (Figs. 8, 9). Therefore, these light green clinopyroxene xenocrysts may represent crystals entrained from lower crustal mafic granulite.

According to their composition (Fig. 10), the spinel xenocrysts also have a lithospheric mantle origin. Compared with the compositions of spinels found in the peridotite xenoliths from the Bondoró-hegy (Embey-Isztin et al. 2001a), half of the studied spinel xenocrysts could have originated from fertile peridotite (e.g., lower Cr# and higher Al_2O_3) and half could represent moderately depleted peridotite.

In summary, the olivine, orthopyroxene, colourless clinopyroxene and spinel xenocrysts have diverse chemistry covering the compositional variations of minerals in peridotite xenoliths and representing variably depleted regions of the subcontinental lithospheric mantle. This is supported by the former study of spinel peridotite xenoliths having various textures and different calculated equilibrium temperatures (Embey-Isztin et al. 2001a). The xenocrysts acted as nucleation sites for the crystallization of the phenocryst phases which isolated them from the basaltic melt as crystal rims.

Megacrysts

Clinopyroxene megacrysts of alkaline basalts are frequently interpreted as high-pressure near-liquidus phases that crystallized from their host magmas (e.g., Binns et al. 1970; Ellis 1976; Irving and Frey 1984) or as accidental fragments of pyroxenite veins that precipitated from melts at elevated pressures (e.g., Righter and Carmichael 1993; Shaw and Eyzaguirre

2000). The relatively high Mg-numbers, high Al^{VI}/Al^{IV} and low Ti/Al ratios (Fig. 9e, f) of most of the Bondoró-hegy megacrysts could reflect their high-pressure cognate origin. However, their rounded outlines and the presence of the spongy reaction zone suggest that megacrysts were in disequilibrium with the host magma during ascent implying their accidental origin. Isotope data for the megacrysts and the host alkaline basalts of the Transdanubian region (Embey-Isztin et al. 1993a; Dobosi et al. 2003) also suggest an accidental origin because the megacrysts have significantly less radiogenic Sr and Nd isotope ratios than their host basalts. Trace element abundances, however, are compatible with a cognate origin. In order to resolve this contradiction, clinopyroxene megacrysts are interpreted as accidental fragments of pegmatitic veins which crystallized from earlier alkaline basaltic melts resembling the host basalt. These melts had different radiogenic isotope ratios, but similar major and trace element compositions as the present host basalt of the megacrysts, and crystallized as pyroxenite veins in the upper mantle. The presence of pyroxenite/peridotite composite xenoliths in the Transdanubian region (Embey-Isztin et al. 1989, 1990) supports this hypothesis. The earlier crystallized coarse-grained pyroxenite veins were disrupted and carried to the surface as individual megacrysts by the ascending magma of Bondoró-hegy. During ascent, the megacrysts were out of equilibrium with the basaltic magma and through incipient partial melting, spongy domains developed in the megacrysts.

Some clinopyroxene megacrysts contain inclusions of spinel with similar compositions to the spinel megacrysts. This may suggest that spinel megacrysts had an origin similar to that of the clinopyroxene megacrysts.- The iron-rich green clinopyroxene megacryst and the titanomagnetite megacryst probably crystallized from a differentiated melt.

Ascent history

The ascent history of the Bondoró-hegy alkaline basaltic magma and origin of the diverse crystals are summarized in Fig. 11. The information for the Füzes-tó basaltic magma was presented by Jankovics et al. (2009, 2012). The model in Fig. 11 also gives a general view about the ascent history of both the crystal-rich alkaline basaltic magmas (Bondoró-hegy and Füzes-tó) in the CPR. After the generation of magma in the asthenosphere, it ascended through the lithospheric mantle in a destructive fashion, fracturing the wall rock and incorporating a vast amount of fragments from the lithospheric mantle now represented by the xenocrysts and peridotite xenoliths. During ascent, the basaltic magma strongly resorbed these crystals and fragments resulted in various disequilibrium textures and modification of the host magma composition. In the uppermost lithospheric mantle, near the crust-mantle boundary (CMB), a number of bodies (veins, dykes, sills) of frozen basaltic liquids and cumulates (i.e., earlier crystallized basaltic magma batches) can be present (Embey-Isztin et al. 1990). When the ascending magma reached this region, it incorporated additional crystals – having compositions different from those of the mantle xenocrysts – represented by the observed clinopyroxene and spinel megacrysts. As the magma passed through the CMB, the style of its ascent did not change as numerous fragments and green clinopyroxene crystals were entrained from lower crustal granulite. These fragments and crystals were also resorbed and could have additionally modified the magma composition. Accordingly, at mantle depths and near the CMB there was an effective interaction between the basaltic magma and the lithosphere. An explanation for this effective interaction could be some cryptic processes. In the case of kimberlitic magmas a recent discovery (Russell et al. 2012) suggests that continuous assimilation of foreign minerals (especially orthopyroxene) – that can modify the composition of the host melt toward more silicic compositions – causes changes in the volatile solubility in the host melt. The result is volatile exsolution and due to this process the magma can fracture more effectively the wall rock. However, this model requires that the parental melt of the host magma should have much lower silica content and high amount of dissolved volatiles (i.e., carbonatitic or near-carbonatitic composition). To be able to reveal similar cryptic processes in the case of the studied alkaline basaltic magmas, experimental studies would be necessary which could help to decide whether these processes can be also expanded for alkaline basalts or operate only in the case of kimberlites. Thus, the applicability of this model in our case is not obvious.

In contrast to the effective magma-wall rock interaction at lithospheric mantle and lower crustal depths, the ascending magma did not incorporate additional crustal material in the middle and upper part of the crust. This suggests a change in the style (and possibly in the rate) of the magma ascent. The main driving force of magma ascent is the process of magma-filled crack propagation (e.g., Spera 1984; Russell et al. 2012). Change in the style and rate of ascent can be caused by the variations in volatile solubility in the melt, by the change in the physical state of magma and wall rocks along the ascent path, and by varying dyke widths. Szabó and Bodnar (1996) suggested a change during the ascent of alkaline basaltic magmas in the Nógrád-Gömör Volcanic Field (Fig. 1a): the magmas accelerated near the MOHO. The observed recent activity of El Hierro (2011-2012) may also support their model, as the seismic signals suggested that the erupted magma passed rapidly through the crust (e.g., Carracedo et al. 2011). This process may be a possible interpretation for the lack of middle and upper crustal wall rock fragments in our case.

Thermobarometric studies of basaltic magmas from ocean islands indicate melt accumulation near the CMB during the ascent of the magma batches (e.g., Klügel et al. 2005; Hildner et al. 2012). The calculated ascent rates / times in the case of the Bondoró-hegy and Füzes-tó magmas, however, do not indicate a longer time of stagnation anywhere in the lithosphere. In addition, there is no petrologic evidence for magma accumulation / storage (e.g., common cognate crystal cumulates), and the large amount of dense materials also needs a continuous ascent.

Magma ascent rates in the monogenetic volcanic fields of the Pannonian Basin

In monogenetic volcanic fields where eruptions of basaltic magmas give scarce precursory signs, estimating magma ascent rates is essential to hazard forecasting. As there are scarce direct observations about the activity of these eruptive centres, it is important to evaluate the ascent rate (as well as the ascent history) of basaltic magmas represented by diverse eruption products in various geodynamic settings.

In the case of other basalts in the Pannonian Basin, magma ascent time was determined by Dégi et al. (2009) for two eruptive centres in the Bakony-Balaton Highland Volcanic Field, by Szabó and Bodnar (1996) for several volcanic centres at the Nógrád-Gömör Volcanic Field and by Harangi et al. (in press) for two centres in the Perşani Volcanic Field. It is notable that these basalts contain a much smaller amount of lithospheric mantle-derived xenoliths and xenocrysts compared to the basalts of Bondoró-hegy and Füzes-tó. Dégi et al. (2009) studied the Fe-Ti-oxides in lower crustal mafic granulite xenoliths and modeled their diffusion-controlled chemical alteration. On the basis of diffusion profiles they estimated the duration of granulite xenolith–host basaltic melt interaction to be at least 9-20 h. This time interval gives a minimum ascent time and can be applied only in the crust, but the ascent time concerning the deeper parts of the lithosphere is not known. In the Nógrád-Gömör Volcanic Field, Szabó and Bodnar (1996) published ~37.5 hours for the residence time of upper mantle xenoliths in the host magmas and 18 hours for the residence time of a spinel xenocryst based on the thickness of its rim. Harangi et al. (in press) found that the residence time of mantle-derived olivine xenocrysts in the host alkaline basaltic magma was 3.6-4.8 days. This is very similar to our results calculated by the same method, which is notable. These three mentioned estimations are close to our results but in the case of the first, the ascent time can be much longer.

So, although the studied basalts are extremely rich in xenoliths and xenocrysts, a significant difference in their magma ascent rates compared to the other alkaline basalts in the Pannonian Basin cannot be inferred. This is not in accordance with the common view that ultramafic xenolith-rich basaltic magmas reach the surface more rapidly than xenolith-poor ones.

Conclusions

The last eruptions of the Bakony-Balaton Highland Volcanic Field are represented by especially crystal- and xenolith-rich alkaline basaltic magmas forming two monogenetic eruptive centres: Bondoró-hegy and Füzes-tó scoria cone. Similar magmas did not erupt in the above mentioned volcanic field and even in the other volcanic fields in the whole Carpathian-Pannonian Region, nevertheless basalts of numerous eruptive centres contain diverse xenoliths.

Detailed textural and chemical analyses of the rock-forming minerals showed that almost the whole set of phenocrysts *s.l.* represents a mineral assemblage originating from different levels of the lithosphere. The foreign crystals have diverse compositions and are divided into three larger groups. The most abundant group originates from different regions of the subcontinental lithospheric mantle. Megacrysts can derive from pegmatitic veins / sills that probably represent crystallized magmas which froze near the crust-mantle boundary. Green clinopyroxenes show similar compositions compared to the clinopyroxenes in mafic granulites indicating lower crustal origin for these xenocryts. Minerals that crystallized from the basaltic melt are only represented by microphenocrysts and overgrowths on the foreign crystals. Consequently, the different whole-rock compositions of the studied basalts compared to those of the other basalts of the volcanic field are not caused by magma generation from a dissimilar mantle source or by differing degree of partial melting, but are the result of their different (more complex) evolution histories, i.e., incorporation of a vast amount of xenoliths and xenocrysts from the lithosphere at mantle and lower crustal depths.

A sudden change in the style of magma ascent is suggested by the fact that abundant crystals and xenoliths were entrained from the lithospheric mantle and lower crust but fragments from the middle-upper crust are absent from the studied basalts.

The xenocrysts show variable disequilibrium textures allowing us to calculate differing mineral-melt reaction times which can be used for magma ascent rate estimations. Based on our results calculated with different methods, we can conclude that despite the special feature of the Bondoró-hegy and Füzes-tó alkaline basalts, significant differences in their magma ascent velocities cannot be inferred compared to other alkaline basaltic magmas in the Pannonian Basin. The calculations indicate that these crystal-rich alkaline basaltic magmas could have reached the surface within hours to few days.

Based on our studies, these unique basalts enable the detailed documentation of the ascent history of basaltic magmas feeding monogenetic eruptions. Furthermore, they bear valuable implications for the rock types in the underlying lithosphere.

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Figure captions

Fig. 1

a) Geological sketch map of the Carpathian-Pannonian Region. Alkaline basaltic volcanic fields are assigned with numbers: 1=Styrian Basin, 2=Little Hungarian Plain, 3=Bakony-Balaton Highland, 4=Stiavnica-Nógrád-Gömör, 5=Kecel, 6=Banat, 7= Perşani; b) Simplified geological map of the Bakony-Balaton Highland Volcanic Field (after Jugovics 1968;

Harangi 2001) with the locality of the Bondoró-hegy and the Füzes-tó scoria cone (and the names of some other volcanic centres).

Fig. 2

Outcrop photo of the scoria cone remnant, first shown by Kereszturi et al. (2010). The scoriaceous breccia of the cone is cross-cut by a massive basalt dyke (the boundaries of the dyke are marked by the white dashed lines), that we interpret as a feeder dyke based on field observations. The white arrow indicates the direction of the dyke injection. The hammer (shown by the black arrow) is 30 cm in length.

Fig. 3

a) Typical petrographic appearance of the studied crystal-rich alkaline basalts (photomicrograph, XN, sample: Ft3). Note that almost all of the phenocrysts *s.l.* are foreign minerals; b) Amphibole-bearing spinel peridotite xenolith occasionally occur in the studied alkaline basalts (photomicrograph, 1N, sample: Fuz3). Ol – olivine, opx – orthopyroxene, cpx – clinopyroxene, am – amphibole.

Fig. 4

a) Anhedral, embayed olivine which has a bright rim and contains a light green spinel that has a bright overgrowth rim adjacent to the groundmass; b) Rounded spinel crystal with a bright overgrowth rim; c) Orthopyroxene and its fine-grained rim consisting of olivine, clinopyroxene and glass; d) Crystal clot that consists of an anhedral olivine and a clinopyroxene with a rounded colourless core; e) Clinopyroxene crystal having an anhedral colourless core and a sector zoned rim; f) Clinopyroxene crystal with a resorbed light green core and a sector zoned rim; g) Homogeneous, colourless clinopyroxene megacryst that has a thick spongy zone and a zoned clinopyroxene overgrowth on it; h) Enlargement of the spongy zone of the clinopyroxene megacryst (g) containing feldspar and spinel inclusions; i) Sector zoned clinopyroxene phenocryst. SEM backscattered electron images. Ol – olivine, sp – spinel, opx – orthopyroxene, cpx – clinopyroxene, fp – feldspar.

Fig. 5

a) Relationship between the Fo (mol%) and CaO (wt.%) content of the studied olivine crystals; b) Plot of Fo (mol%) and NiO (wt.%) contents of the studied olivines. Light grey dashed line fields indicate the compositions of olivines in upper mantle peridotite xenoliths from the Balaton Highland (Embey-Isztin et al. 2001a).

Fig. 6

Fo (mol%), Ni and Ca (ppm) profiles of olivine xenocrysts (a, b) and an olivine phenocryst *s.s.* (c). The lines of measured points are indicated by the A-B lines in each picture (SEM backscattered electron images). In the case of the xenocrysts, at the crystal margins (in a 50-100 µm thick band) points were measured with ~5 µm gaps between each other, while in the central part of the olivine the gaps were increased to 20-50 µm. In the case of olivine phenocrysts, the whole profile was prepared with 5 µm gaps (5 µm distances between measuring points were necessary because of the effect of the e^- beam on the crystal surface).

Fig. 7

Fo (mol%) vs. NiO (wt.%) relationship of representative olivine xenocrysts (Fig. 6a, b) and normal zoned phenocryst (Fig. 6c). The different core-to-rim trends are indicative for diffusion- or growth-related development of the zoning (for details see text).

Fig. 8

Compositions of the studied clinopyroxenes plotted in the atomic Mg-Fe-Ca ternary diagram (boundaries after Morimoto et al. 1988). The light grey dashed line field indicates the compositions of clinopyroxenes in upper mantle peridotite xenoliths from the Balaton Highland (Embey-Isztin et al. 2001a), the dark grey dashed line field indicates the compositions of clinopyroxenes in lower crustal mafic granulite xenoliths from the Balaton Highland (Embey-Isztin et al. 2003).

Fig. 9

Variation of Mg# ($Mg/(Mg+Fe^{tot})$) vs. Ti (a), Al (b), Cr (c) and Na (d) (cations per formula unit based on 6 O); e) Plot of Ti vs. Al (cations per formula unit based on 6 O); f) ^{IV}Al vs. ^{VI}Al diagram (Aoki and Kushiro 1968). Symbols as in Fig. 8. Light and dark grey dashed line fields indicate the same clinopyroxene compositions as in Fig. 8 (the Cr content of granulitic clinopyroxenes were not analysed in Embey-Isztin et al. 2003).

Fig. 10

a) Cr-Al-Fe^{3+} ternary plot of the studied spinels; b) Variation of MgO (wt.%) vs. Al_2O_3 (wt.%) contents in the studied spinel grains. Light grey dashed line fields indicate the compositions of spinels in upper mantle peridotite xenoliths from the Balaton Highland (Embey-Isztin et al. 2001a).

Fig. 11

Schematic cartoon of the proposed model for the ascent history of the Bondoró-hegy and Füzes-tó alkaline basaltic magmas. Enlargements of the ascent path show the dominant processes (see the text for details). The figure is to scale. LAB – lithosphere–asthenosphere boundary, gt – garnet, sp – spinel. The source for the crustal and lithospheric thicknesses is: http://geophysics.elte.hu/atlas/geodin_atlas.htm.

Table captions

Table 1

Major and trace element analyses of the BON683 sample from Bondoró-hegy (Embey-Isztin et al. 1993a)

Table 2

Representative compositions of the studied olivines

Table 3

Representative analyses of the studied orthopyroxenes and clinopyroxenes

Table 4

Representative compositions of the studied spinels

Table 5

Details of the different methods and results of the estimated magma ascent rates and times

Table 6

Calculated residence times of the studied olivine xenocrysts