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PRECURSOR ROCK AND ORIGIN OF CORDIERITIC XENOLITHS FROM THE VECHEC ANDESITE QUARRY, EASTERN SLOVAKIA

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Abstract

The composition of dark coloured enclosures from andesitic rocks, found in the Vechec quarry, was investigated, using the combination of microscopic, XRD and EPMA methods. The xenoliths are formed mainly of cordierite (X_{Fe} = 0.23-0.47), associated with plagioclase, Fe-spinel (up to hercynite) and minor anorthoclase, biotite and ilmenite. The Na_2O and K_2O amounts (up to 1.28%), the plagioclase of $Ab_{82.5–74.99}$ composition and the very low contents of Ni and Cr even in Fe-spinels emphasize an alkalis contamination of the precursor magma; therefore, the precursor rock is assumed to be derived from an upper crustal material. Among the numerous basement xenoliths, including argillaceous ones, the dark-gray, slightly laminated xenolith is the only highly aluminous one, with contents close to that of the cordieritic type. The plagioclase-rich protoliths, with common purple spinel octahedrons and Ti-minerals, show some magma imprint. The cordierite-rich rock is assumed to be formed from the dark Al-Fe-Mg(Ti)-rich melt, in the inner aureole of the magma chamber.

Keywords: andesite, xenoliths, precursor rock, X-ray diffraction, phase composition.

Introduction

The locality of Vechec represents the central neck of a parasitic andesite volcano, exposed at the eastern margin of the Slanske vrchy Mts. The latter constitute a range of Neogene calc-alkaline composite volcanoes, stretching through Eastern Slovakia, to NE

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Hungary. The locality belongs to the Makovica composite volcano, built up by effusive or extrusive products, predominantly of Sarmatian age. The Vechec quarry is well-known for the occurrences of tridymite crystals and rare minerals such as tobermorite, gyrolite, apophyllite etc., filling andesite cracks and cavities. Some carbonates, sulfides (calcite, aragonite, pyrite etc.) and zeolites (stilbite, heulandite etc.; Košuth, 1999) form part of various enclosed xenoliths, as well. The quarrying rock is a grey pyroxene andesite with a 15% ratio of plagioclase phenocrysts; augite (5%) prevails over hypersthene-opx (Kaličiak et al., 1991). This andesite is the product of a relatively dry Ca-alkaline magma, of volcanic arc type; in the area, layers of older Neogene sediments, with some evaporite slices were found. Andesite analyses show 55.91÷57.51% SiO_2 contents, along with 3.81÷4.29% Na_2O + K_2O (tab. 1).

The present article focuses primarily on the cordierite-bearing xenoliths, which we consider the most interesting among the wide suite of enclosed basement rocks. Vechec is the first locality where such a xenolith has been described (as sekaninaite; Ďuďa et al., 1981); its occurrence is even more common today. During the last decade, analogous dark-coloured xenoliths were also discovered in four other quarries along the Slanske vrchy Mt. range (Košuth, 2006).

Analytical method

The petrographic character and the mineral composition of all polymineral xenolith samples were studied using the thin-section microscopy. Valuable information on phase composition was revealed through the X-ray powder diffraction method (XRD), especially in the case of very fine-grained xenoliths; the identity of unusual mineral novelties, originated as a consequence of the caustic effect of magma. Apart from the determination of both major and minor minerals and their mutual ratio, the carbonatization or zeolitization processes could be detected. The samples were analyzed (by means of a Mikrometa 2 XRD diffractometer), at the Institute of Geosciences (Faculty B.E.R.G., Košice). A CoKα target (λ = 0.1790nm) and a monochromatic Fe-filter were used; the recorded 4-70° 2θ angle positions of each peak were recalculated to d_m (nm), by means of the Cheman software, and then formatted onto a .xls graph. The d_m/I_m- diffraction data lines were compared with the d_t/I_t peaks of the mineral standards in use, namely with the JCPDS tabs of the American Mineralogist Structure (AMS) Database.

The identities of the selected cordierite crystals and of other minerals were proven through electron probe microanalyses (EPMA). After having been examined through EDS, the spectra of all the components were measured using the WDS method, being quantitatively calibrated to natural standards. All EPMA analyses, recalculated through the use of the Getana software, were performed at the EM Laboratory of the State Geological Institute in Bratislava, and operated on a Cameca SX-100 X-ray microanalyser.

The cordierite enclosures

Trapped in Vechec andesite, the cordierite-bearing rocks are extraordinary among the all other types of hosted xenoliths. Given their different texture, we cannot assign them either to frequent xenoliths of sedimentary rocks, or to magmatic enclaves. Their bluish-black, even dark gray colour (fig. 1a,b), with waxy luster, is in contrast with the enclosing andesite. This hornfels-like xenolith is mostly compact, homogeneous, without distinct granular fabric or any textural orientation. The only VX2-sample with signs of partial melting on its margin is porous, with a crystallized honeycomb arrangement. Among other crystallites, the cavities can partly be filled with colourless glassy stilbite.

Tab. 1 Comparison between the bulk chemical composition of andesite and relevant xenoliths

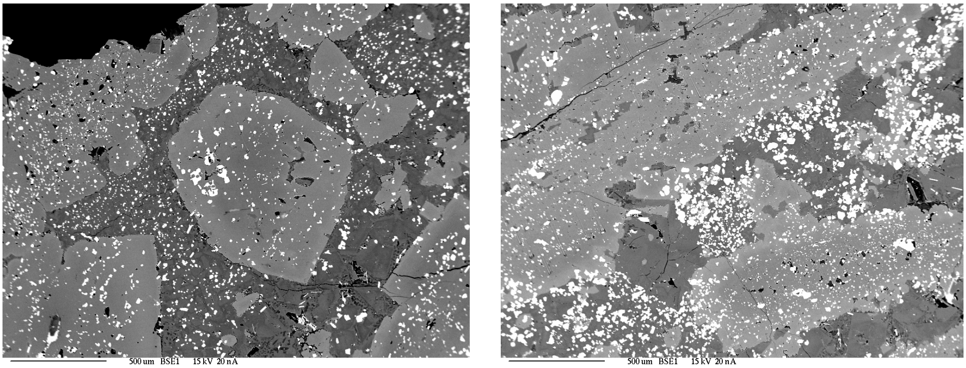
Sample	andesite	andesite	andesite	andesite	cord.xen.	spinel-bearing xen.	
	18 /9	neck 2	neck 3	neck 4	VX 2	VX 7	VX 7A
SiO_2	58.58	56.92	57.51	57.30	45.82	39.29	40.23
TiO_2	0.49	0.79	0.85	0.72	tr.	1.00	1.00
Al_2O_3	17.29	18.17	19.96	18.32	30.50	28.80	28.03
Fe_2O_3	1.63	6.36	5.85	6.91	4.96	4.77	4.77
P_2O_5	0.43	0.18	0.15	0.15	0.00	st.	st.
FeO	4.95	*	*	*	4.59	5.60	5.60
MnO	0.05	0.15	0.14	0.14	0.00	0.00	0.00
CaO	7.52	8.41	7.57	7.88	4.45	9.25	9.25
MgO	3.28	3.43	2.82	4.03	4.80	5.04	5.04
K_2O	1.49	1.50	1.70	1.43	1.80	0.40	0.40
Na_2O	2.48	2.42	2.59	2.46	3.00	1.61	1.61
H_2O –	1.40	—	—	—	0.02	1.68	1.68
H_2O +	0.43	—	—	—	0.04	2.10	2.10
Total %	99.73	99.33	99.14	99.34	99.98	99.54	99.71

(a) (b)

Fig.1a (left). Compact cordierite xenolith with the host andesite, Vechec; (photo cut: 8 × 5 cm). Fig.1b (right, VX2). Porous cordierite xenolith containing microscopic Na-stilbite crystals; the right margin displays traces of partial melting, Vechec; (sample: 7.7 × 5 cm).

The mineral compositions of fine-grained, cordierite-bearing polymineral aggregates were identified through X-ray analyses. Each XRD record indicated two prevailing phases: α-cordierite and plagioclase (tab. 2). The analyzed samples contain only small amounts of associated minerals: several diffraction patterns indicate the presence of Fe-spinel and biotite. The identification of the main phases and accessory phases was confirmed by the EPMA data.

Detailed investigation carried out on polished thin-sections revealed the common presence of disseminated and opaque Fe-spinel (fig. 2), ilmenite and platy Ti-hematite, together with xenoblasts of K-feldspar, rarely apatite, ankerite, and one of the Al_2SiO_5 polymorphs; given the position of the andesite lava that encloses the polymorphs (under conditions of high temperature/low pressure) and the shape of some crystal from an Al_2SiO_5 equivalent phase, found in similar rocks from the Fintice quarry (Košuth, 2000), we could determine them as andalusite. Apart from a crystalline phase, an amorphous glassy phase was found as well.



(a) (b)

Fig. 2a, b. Back scattered electron images of cordierite-bearing xenolith from Vechec. Cordierite forms larger porphyroblasts in the crystalline matrix; inclusions of younger plagioclases (dark grey) and common dissaminated Fe-spinel (white) can be seen; Cameca SX-100 images.

The bulk chemical composition of the xenoliths was determined through classical CHA, and the same method was used for representative andesite samples (tab. 1). The highly aluminous character of cordierite-bearing xenoliths, with a SiO_2 content just above 45%, is proportional to the composition of the main mineral (α-cordierite), as EPMA data show (tab. 3). The analyzed cordierite xenoliths are not uniform, having slightly higher/lower MgO (1÷3%) or FeO contents, as well as Al stoichiometric changes. In all cases, the Mg vs. Fe ratio indicates the prevalence of cordierite over the sekaninaite end-member. The X_{Fe} (apfu) value expresses ranges between 0.2305 and 0.4676; the (Fe + Mn)/(Mg + Fe + Mn) ratio (based on 12 analyses) is within the 0.2370 ÷ 0.4714 interval. Minimal contents of coherent elements (Ni, Cr less than 0.06 %), along with some contamination with alkalis (Na_2O up to 0.38% and K_2O up to 1.28%), points out to the upper crust as origin of their precursor. Three cordierite crystals were investigated regarding their zoning growth; while the VX21 sample shows clear differences between core and rim, and its crystallization growth is in agreement with the progressive contamination trend, the similar sample VX22 does not display the same trend.

Beside α-cordierite, detailed microprobe analyses were also carried out for feldspars, spinel, biotite and andalusite. The analyzed anhedral plagioclase grains (tab. 3) are of albite type, with some K and Ba amounts, the end-member being as following:

21-pl-1: $Ab_{67.5}Or_{9.80}An_{22.51}Cs_{0.08}$, and

22-pl-2: $Ab_{66.5}Or_{18.05}\ An_{14.09}Cs_{1.36}$.

Tab. 2 Results of X-ray diffraction analyses of 2 cordierite-bearing xenoliths from Vechec VX2

Measured samples				AMS tabular				JCPDS tabular		
VX2		VX21		Cordierite		Plagioclase		Other minerals		
d_m	I_m	d_m	I_m	d_t	I_t	d_t	I_t		d_t	I_t
		0.9899	10	*Swizz.*		*An48*		phlogopite	0.994	100
		0.9094	15?					Na-stilbite	0.904	100
0.853	87	0.8541	61	0.8530	58					
0.635	19	0.6519	8	↑0.8471↑	100				0.3784	47
		0.6466	9			0.6465	8			
0.553	61							Na-stilbite	0.543	6
0.491	20	0.4926	14	0.4913	9					
		0.4759	6					Fe-spinel	0.473	20
0.465	17	0.4675	6	0.4661	8					
		0.4241	20?					K-feldsp.?		
0.409	51	0.4091	45	0.4084	60	0.4045	85	Na-stilbite	0.407	95
		0.3897	9			0.3896	19			
0.375	27	0.3760	37			0.3755	41	ilmenite	0.3736	35
		0.3653	14			0.3645	35			
		0.3458	9			0.3475	14			
0.338	40	0.3385	47	0.3382	57	0.3370	25	phlogopite	0.3390	20
		0.3345	35			↓0.3207↓	95	phlogopite	0.3348	100
0.319	100	0.3206	100	↓0.3146↓	18	0.3183	100			
0.314	63	0.3140	28	0.3135	51	0.3139	42			
0.305	65	0.3054	33	0.3044	37			Na-stilbite	0.304	70
		0.3020	29	0.3023	37	0.3022				
		0.2949	12			0.2951	27			
0.287	64	0.2890	15					Fe-spinel	0.290	40
0.277	31							Na-stilbite	0.2780	35
		0.2745	9					ilmenite	0.2751	100
0.266	27	0.2651	21	0.2650	14	0.2655	14			
0.253	14	0.2516	12			0.2523	30	ilmenite	0.2544	69
0.245	70	0.2462	39	0.2457	7			Fe-spinel	0.247	100
0.233	20	0.2333	12	0.2328	11	0.2305	6			
		0.2236	10					ilmenite	0.2237	23
0.217	63	0.2175	10	0.2173	8					
		0.2143	16			0.2142	10			
		0.2097	12	0.2101	5	0.2105	8			
0.203	27	0.2042	9					Fe-spinel	0.205	45
0.197	16	0.1959	5					phlogopite	[illegible]	30
0.187	24	0.1880	14	0.1877	6	0.1880	8	ilmenite	0.1868	36
0.181	16	0.1800	8	0.1797	6					
0.171	14	0.1718	9	0.1706	5	0.1716	6	ilmenite	0.1725	50
0.169	20	0.1695	22	0.1691	21					
		0.1650	5			01655	4	Fe-spinel	0,1662	10

Taking into account only the isomorphic plagioclase-series, it varies within the "oligoclase" range ($Ab_{82.5}$ to $Ab_{74.99}$). Similarly, the K-feldspar composition (tab. 3) can be precisely expressed by its end-member ratio:

21-Kf-1: $Or_{43.60}Ab_{53.26}An_{3.10}Cs_{0.04}$;
21-Kf-2: $Or_{54.14}Ab_{43.59}$ $An_{2.23}$ $Cs_{0.04}$, and
22-Kf-2: $Or_{55.14}Ab_{42.92}An_{1.67}Cs_{0.27}$.

The studied potassium feldspars are all of anorthoclase type, with mutual ratios of albite vs. sanidine (K-feldspar polymorph related to the volcanic background) close to 1:1.

Out of the 11 spinels investigated through EMPA, 6 analyses were included in table 3 as representative. The real iron contents in the $A^{2+}{}_6$ formula position are lower than in table 3, due to the amount of Fe incorporated in the $B^{3+}{}_{12}$ position, if the O_{24} basis (apfu) is considered. Generally, subhedral VX22-spinels contain 3.25 to 7.29% Fe_2O_3; two types of highly ferrous spinels can be distinguished, with a ratio of about 0.65÷0.69 (Fe+Mn)/(Mg+Fe+Mn) (mainly VX-22-sp), while samples 21sp are true hercynite. With the exception of one sample, all Fe-spinels are nearly Cr-free, with Cr_2O_3 contents below 0.23%.

Biotite lepidoblasts are not uniform, some being close to phlogopite (VX22), with prevailing MgO contents (15.8÷16.5%) over FeO (~13.5%); their (Fe+Mn)/Mg+Fe+Mn ratio is 0.323÷0.326. An interesting feature is the higher amount of incorporated TiO_2 (4.20÷4.64%), and, in some cases, the higher content of fluorine as well (up to 3%). The Ti amount in the entire xenolith should be closely related to quite frequently disseminated ilmenite and Ti-hematite ($Hem_{80}Ilm_{18}Crn_2$). Random subhedral grains of andalusite (Al_2SiO_5-phase) were analyzed in the VX22 thin sections. The Al and Si amounts are close to the theoretical data, with slight SiO_2 excess and Fe impurities of only tenths of a percent. The zonal development across this Al-phase was investigated as well, but only weak changes were registered, although the nearly trace contents of Ca and K in the rim are double if compared to the core. Together with the same trend of Fe (0.465% in the rim / 0.270% Fe in the core), they indicate a contaminating influence of magma, during the crystallization process. The polyphasic xenolith contains rare tridymite, Al-rich glass and apatite.

Discussion on possible protolith

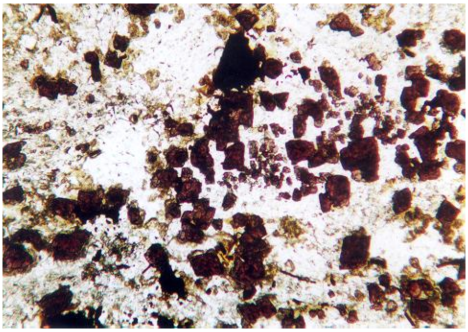
The Vechec quarry is known for numerous basement wallrock fragments, enclosed in andesite, in some cases even partly melted; we believe that they mostly belong to various sedimentary rocks (including those from the shallow volcano-sedimentary layers). Some xenoliths are highly acidic, formed dominantly by quartz, with minor feldspar and post-volcanic hydrothermal minerals (calcite, opal, tobermorite etc.).

Among these fragments, there is none that could be accepted as the precursor rock of the described cordierite-bearing, hornfels-like xenoliths. All light-coloured sedimentary xenoliths, including the argillaceous ones, contain much less Al_2O_3 in its bulk composition (10.83÷19.11%), and, just as andesite magma, do not contain enough Mg+Fe. The only relevant protolith can be the dark-xenolith VX7, quite rare in Vechec (fig. 3a). Because of its low SiO_2 content (tab. 1), it is comparable to the ultrabasic rocks; the MgO+Fe_{total} content coincides with the level found out in the VX2 cordierite-bearing xenolith.

Tab. 3 Microprobe analyses of main minerals, forming the cordierite xenoliths, samples VX21 and VX22

Mineral						Cordierite						
Sample	21-c1core	21-c1rim	21-c2core	21-c2rim	21-c3	21-c4	21-c5	22-c1core	22-c1rim	22-c2	22-c3	22-c4
SiO_2	47.581	47.899	48.321	47.669	48.845	47.341	46.605	48.353	47.221	48.987	46.383	45.767
TiO_2	0.035	0.033	0.033	0.019	0.021	0.048	0.029	0.035	0.054	0.008	0.089	0.057
Al_2O_3	33.103	32.995	33.618	33.449	33.026	33.112	33.333	33.743	34.781	33.717	34.590	34.074
Cr_2O_3	0.000	0.009	0.007	0.013	0.007	0.013	0.027	0.004	0.000	0.000	0.000	0.002
FeO	9.531	10.624	8.323	11.250	9.368	10.457	10.380	6.952	5.567	7.532	7.552	7.122
MnO	0.140	0.147	0.118	0.246	0.269	0.275	0.354	0.361	0.203	0.413	0.253	0.193
MgO	8.274	7.518	9.079	7.184	7.984	7.445	7.921	9.531	10.423	9.159	9.114	9.285
CaO	0.010	0.036	0.030	0.034	0.004	0.008	0.032	0.050	0.063	0.036	0.034	0.031
Na_2O	0.072	0.115	0.078	0.081	0.039	0.128	0.107	0.113	0.361	0.035	0.336	0.385
K_2O	0.398	0.332	0.324	0.363	0.056	0.199	0.297	0.430	1.212	0.211	1.152	1.278
NiO	0.000	0.005	0.000	0.036	0.008	0.052	0.000	0.005	0.000	0.000	0.000	0.000
F	0.075	0.001	0.138	0.024	0.052	0.123	0.033	0.000	0.000	0.067	0.059	0.187
Cl	0.017	0.014	0.006	0.000	0.015	0.004	0.017	0.024	0.045	0.013	0.014	0.028
Total (%)	99.237	99.865	100.075	100.478	99.865	96.8745	96.7938	99.590	99.928	100.178	99.577	98.407
Mineral	Plagioclase		K-feldspar			Mineral			Fe-spinel			
Sample	21-pl-1	22-pl-2	21-Kf-1	21-Kf-2	22-Kf-1	Sample	21-sp3	21-sp4	21-sp5	22-sp1	22-sp2	22-sp3
SiO_2	61.547	62.253	65.168	65.337	65.503	SiO_2	0.017	0.081	0.075	0.062	0.073	0.049
Al_2O_3	23.384	22.026	19.743	18.887	19.336	TiO_2	1.036	1.165	1.211	0.466	0.429	0.567
FeO	0.163	0.331	0.096	0.042	0.256	Al_2O_3	53.838	51.437	52.850	57.282	59.108	56.684
CaO	4.622	2.956	0.645	0.457	0.342	Cr_2O_3	0.139	0.231	0.109	0.059	0.069	0.088
SrO	0.093	0.036	0.042	0.000	0.070	FeO	41.257	42.161	41.349	31.816	29.771	31.232
BaO	0.483	0.778	0.246	0.017	0.152	MnO	0.354	0.452	0.422	0.369	0.481	0.455
Na_2O	7.659	7.710	6.133	4.941	4.853	MgO	3.781	3.965	4.079	8.357	8.725	8.815
K_2O	1.707	3.181	7.631	9.330	9.474	CaO	0.001	0.035	0.009	0.083	0.037	0.022
Rb_2O	0.112	—	0.042	0.033	—	NiO	0.000	0.066	0.071	0.000	0.000	0.000
P_2O_5	0.179	—	0.405	0.116	—	ZnO	0.055	0.132	0.066	0.832	0.516	0.511
Total (%)	99.949	99.271	100.151	99.160	99.986	Total (%)	100.478	99.725	100.241	99.317	99.209	98.423

(a)



(b)

Fig. 3a (left). Fragment of the dark VX7 xenolith, with acicular Mn-calcite, Vechec; (photo cut: 4.5 × 4 cm).
Fig. 3b (right). Purple spinel octahedra (0.1-0.2 mm) in carbonatized plagioclase matter; thin section of the VX7 xenolith (║nicols, magn.72×).

Despite the non-compact laminated texture of VX7, it has a uniform dark-gray to black colour. In thin-section, along with the laminated plagioclases of the crystalline matrix (frequently resorbed), tiny, purple, spinel crystals were observed (fig. 2b). The andesite/xenolith contact zone is sharp, narrow, locally with Mn-calcite or limonite rust, and a coarser granular exocontact fabric, because of the plagioclase recrystallization; just as the hornfels xenolith VX2, this rock is quartz-free.

Apart from a microscopic study, the investigation of the VX7 spinel-bearing rock was based on XRD and EPMA. However, only approximate information regarding the mineral composition was revealed by the diffraction patterns: a suite of An-plagioclase and main spinel reflexes. The presence of other minerals (sanidine, Mn-calcite, Fe-opx) was not fully proven, being hidden by the plagioclase-diffraction patterns. Of utmost importance in the identification of minor to accessory minerals (sanidine, ilmenite, apatite) were EPMA, used also to follow the wide-range composition of the main phases. The composition of An-plagioclase from the VX7 xenolith is in relation with the shade of more pale or darker grey anhedral particles/fields, seen on the BEI images; thus, the presence of two different generations is clear:

The lighter shade belongs to highly calcic anorthite, whose end-members range from $Ab_{20.0}Or_{0.83}An_{79.15}Cs_{0.02}$ to $Ab_{3.21}Or_{0.24}An_{96.55}Cs_{0.0}$, showing the presence of bytownite term (An_{78} to An_{83}), or even that of marginal anorthite ($An_{96.8}$). These Ca-plagioclases contain 14.62÷19.95% CaO and only up to 2.28% Na_2O, with nearly no K_2O (less than 0.213%).

The darker plagioclase is richer in albite molecules, expressed within the following range: $Ab_{56.27}Or_{6.92}An_{36.53}Cs_{0.27}$ to $Ab_{47.71}Or_{3.70}An_{48.46}Cs_{0.12}$; it can be identified as an andesine term ($An_{39.3}$ to $An_{50.4}$). These medium-balanced plagioclase generations contain 5.32 to 6.43% Na_2O, less than 9.79% CaO and a noticeable K_2O amount (up to 1.57%), with little barium. The thin sections revealed K-feldspars as well, which are partly interesting for their penetrating position relative to the spinels from the matrix. Their composition can be assumed to be that of an anorthoclase, displaying the following end-member ratios: $Or_{67.94}Ab_{28.09}An_{3.36}Cs_{0.61}$; $Or_{59.78}$ $Ab_{34.78}An_{5.43}$; and $Or_{57.61}Ab_{36.95}$ $An_{5.43}$; two of them resemble to those of VX2.

The investigation of the most interesting spinel grains was performed through 10 WDX-analyses, including crossing profiles. Within the translucent purple crystal, no remarkable core-rim zonal difference was observed. Spinel crystals, investigated through EMPA, show constant amounts of MgO (around 12.5%), low contents of Cr_2O_3 (up to 0.31% – usually only 0.0X%); the same amounts were identified for NiO and CaO. Given the (Fe+Mn)/(Mg+Fe+Mn) ratios, which range within the 0.493÷0.508 interval, we can evaluate them as medium Mg-Fe^{2+} spinels, different in comparison with those from the VX2 xenolith. The dark minerals here represent Ti-minerals: ilmenite with rare titanite, and highly calcic clinopyroxenes (diopside ÷ hedenbergite with around 16.5 or 23.0% CaO); accessory fluorapatite was confirmed.

The VX7 metamorphic processes, controlled by hot andesite magma, could not occur under isochemical conditions. Due to the caustic imprint of magma and additives, we assume that the partial melting of such plagioclase+spinel-bearing precursor rock has formed an Al-Fe-Mg-rich melt. Mutual enrichment/extraction of some components before and during the crystallization of the melt is highly probable, as shown by the zonal composition of cordierite, presented in table 3. We suggest that the compact fabric of the cordierite hornfels xenolith crystallized from dark glassy phases (near the liquidus/solidus edge). Glass relics were confirmed in sample VX2, through EPMA. The formation of cordierite during a devitrification stage was proven, for instance, by Grapes (1985), and is often present in the process of its artificial fabrication (Shu et al., 2002). Thus, we assume the formation of cordierite xenoliths of the VX2-type from the precursor rock of VX7 composition, as follows:

Pl + spinel + K–mfs. + Cpx + F,Cl (apatite) ± H_2O? → Al–Fe–Mg(Ti)–rich melt

Melt / Al–glass + Na^+,K^+ → cordierite + feldspars(pl, anorthoclase) + Fe–spinel + ilmenite + Al_2SiO_5

The formation of α-cordierite under low-pressure conditions (0.5÷4.0 kbar) is possible within a wide temperature range (Winkler, 1976). Its artificial sintering is known during the industrial fabrication of cordierite ceramics of similar equigranular fabric. Such cordierite originates usually at temperatures higher than 1000°C, through an amorphous glassy stage (Shu et al., 2002; Kobayashi et al., 2000), or by its crystallization from intermediate silicate phases with spinel (McRae and Nesbitt, 1980; Renzulli et al., 2003); its more endothermic Fe-rich varieties are only formed at 900°C (Deer et al., 1992). Wörner et al. (1982) stated that, at higher pressure (up to 2.6 kbar), the formation of cordierite is due to the caustic metamorphosis of Mg-Fe-rich rocks. If xenoliths contain sanidine (anorthoclase), the partial melting occurs at ~850°C; if it is associated with hercynite, the melting can even occur at lower temperatures (500÷680°C), while, at the 650÷700°C upper stability edge, an Al_2SiO_5 phase can also originate. Some additional fluids, such as Cl(+F)-bearing fluids, are able to decrease the melting temperature; the content of relic Cl and F (average of 0.045%) in the cordierite samples (tab. 3) seems to confirm this hypothesis. We assume that the most suitable conditions for the formation of cordierite-bearing xenoliths are found around a not very deep magma chamber; the assumption is in agreement with the generally-accepted postulate about the conditions required by the formation of Or-Crd-Px hornfelses, within the inner contact aureole developed around a diorite intrusion body. The shape of cordierite and plagioclase XRD patterns, together with the relatively sharp bands of infrared spectra of VX2 sample, indicate intermediate to fully-ordered α-cordierite internal structures, as a consequence of a gradual crystallization before a magma upraise.

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