

Geodynamic significance of ultramafic xenoliths from Eastern Serbia: Relics of sub-arc oceanic mantle?

Vladica Cvetković^{a,b,*}, Hilary Downes^c, Dejan Prelević^d,
Marina Lazarov^e, Kristina Resimić-Šarić^a

^a Faculty of Mining and Geology, University of Belgrade, Đušina 7, 11000 Belgrade, Serbia

^b Fachbereich für Geographie und Geologie, Fakultät für Naturwissenschaften, Universität Salzburg, Hellbrunnerstraße 34/III, A-5020 Salzburg, Austria

^c Research School of Earth Sciences, Birkbeck College, Malet St., London WC1E 7HX, UK

^d Johannes Gutenberg-Universität, Institut für Geowissenschaften FB 22 Mineralogie, Becherweg 21, 55099 Mainz, Germany

^e Institut für Mineralogie, Johann Wolfgang Goethe-Universität, Seckenberglage 28, 60054 Frankfurt am Main, Germany

Received 2 May 2006; received in revised form 2 November 2006; accepted 6 November 2006

Abstract

A suite of highly depleted peridotite xenoliths in East Serbian Palaeogene basanites represents the lithospheric mantle beneath the Balkan Peninsula. The xenoliths are harzburgites, clinopyroxene-poor lherzolites and rare dunites. They contain mostly <5 vol.% of modal clinopyroxene and are characterized by high Mg# in silicates (>91), high Cr# in spinel (mostly 0.5–0.7), and by distinctively low Al₂O₃ contents in orthopyroxene (mostly 1–2 wt.%). They have experienced some mantle metasomatism which has slightly obscured their original composition. Nevertheless, the general characteristics of the xenoliths imply a composition which is significantly more depleted than most non-cratonic sub-continental mantle xenolith suites, as well as orogenic peridotites and abyssal peridotites. Geological and compositional evidence suggests that the xenoliths do not represent Archean mantle. The existence of Proterozoic mantle cannot be entirely excluded, although it is in disagreement with geological evidence. On the other hand, the studied xenoliths are compositionally very similar to peridotites of modern oceanic sub-arc settings. The existence of such a depleted lithospheric mantle segment is also inferred from the presence of rare orthopyroxene-rich xenoliths in the same suite. These are interpreted to have originated as lithospheric precipitates of high-Mg, SiO₂-saturated magmas that require a highly depleted mantle source. Such source is typically required by boninitic-like magmas of intraoceanic suprasubduction settings. A proposed geodynamic model to explain these observations involves accretion or underplating of the lower parts of the Tethyan oceanic lithosphere during the Upper Jurassic closure of the eastern branch of the Vardar ocean.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Peridotite; Lithosphere; Depletion; Vardar ocean

1. Introduction

Ultramafic xenoliths in alkali basalts and kimberlites can yield significant information about the age and origin of the sub-continental lithospheric upper mantle (e.g. Frey and Green, 1974; Menzies, 1983; Boyd, 1987; Griffin et al.,

* Corresponding author. Tel.: +381 11 630020; fax: +381 11 630020.

E-mail address: cvladica@mkpg.rgf.bg.ac.yu (V. Cvetković).

1998; Downes, 2001). Mineralogical and geochemical variations in such xenoliths are usually interpreted to reflect melt extraction followed by metasomatic re-enrichment (Maaloe and Aoki, 1977; Frey and Prinz, 1978; Herzberg, 1993; Parkinson and Pearce, 1998; Downes, 2001; Herzberg, 2004). Off-cratonic peridotite xenoliths are found in basalts which erupted under various geotectonic conditions and provide valuable information about mantle evolution during earlier geodynamic events. Mantle-derived xenoliths erupted in post-collisional settings may be particularly interesting as they give information about the composition of the deep lithosphere that can lead to a better understanding of terrane amalgamation.

Palaeogene basanites outcrop in a north–south line along the eastern margin of the East Serbian Carpatho-Balkanides (Fig. 1). Parallel to this line, the Carpatho-Balkanide chain is juxtaposed with the Dinaride branch of the Alpine orogen. The asthenospheric-derived magmatic episode occurred between ~60 and ~40 Ma ago, at the beginning of the post-collision collapse of the Dinaride belt (Jovanović et al., 2001; Cvetković et al., 2004b; Prelević et al., 2005). Thus, it post-dates Mesozoic convergent and collision processes related to the closure of the Tethys ocean (Robertson and Karamata, 1994; Karamata, 2006). Information provided by xenoliths entrained in these magmas is therefore important for understanding the earlier convergent/collision processes which produced the present terrane collage.

Mantle-derived xenoliths are found in two localities in East Serbian Carpatho-Balkanides (Fig. 1). Cvetković et al. (2004a) gave the general characteristics of the East Serbian lithospheric mantle (ESLM) inferred from these rocks. They emphasized that most ESLM xenoliths have low contents of modal clinopyroxene and are characterized by uncommonly low Al_2O_3 abundances in their orthopyroxenes, suggesting that the ESLM may be more depleted than ‘normal’ European lithospheric mantle (Downes, 2001 and references therein). In addition, Cvetković et al. (2007) discussed some orthopyroxene-rich xenoliths from the same localities and interpreted them as high pressure products

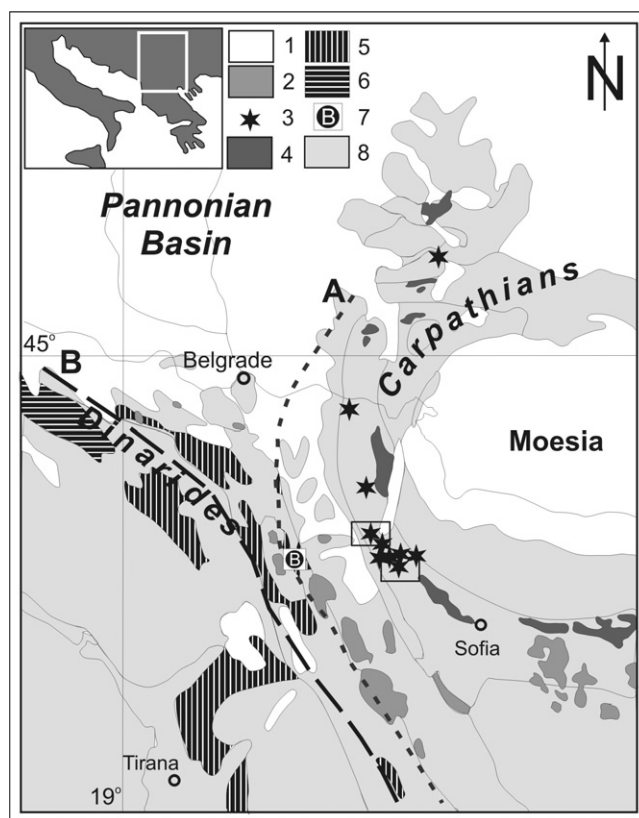


Fig. 1. (A) Simplified geological sketch based on the Geological atlas of Serbia and adjacent regions. *Legend:* (1) Tertiary cover, (2) Tertiary plutonic and volcanic rocks, (3) occurrences of Palaeocene/Eocene East Serbian alkaline rocks, (4) Late Cretaceous calc-alkaline plutonic and volcanic rocks of the Banatite magmatic and metallogenetic belt (Berza et al., 1998), (5) Vardar Zone ophiolites, (6) Dinaride ophiolites, (7) occurrence of Jurassic boninites (Marroni et al., 2004), (8) Mesozoic and pre-Mesozoic units. The locations of studied mantle xenoliths are squared. The positions of the presumed Upper Jurassic (A) and Late Cretaceous (B) sutures are also shown.

of high-Mg and high-Si magmas. Such magmas commonly originate as melts of a highly depleted mantle source (Kushiro, 1969; Morse, 1980) and their presence can imply a fore-arc setting.

Compositional characteristics of mantle peridotites are important because they may be used to infer geodynamic settings (Herzberg, 2004). In general, xenolith suites in non-cratonic continental intraplate regions and peridotites from orogenic massifs indicate a similar limited level of depletion, relative to primitive mantle. In contrast, cratonic, oceanic arc and oceanic island xenolith suites usually are very depleted (e.g. Pearson et al., 2003, and references therein). The aim of this study is to discuss the origin of depletion of the uppermost mantle underneath East Serbia, taking into account any possible effects of metasomatism in order to recognize the least modified samples. Characteristics of the ESLM xenoliths are then compared to the composition of upper mantle material from known geotectonic settings. Finally, the major implications are placed within the regional geotectonic context in order to shed new light on the Pre-Palaeogene geodynamic history of the Balkan Peninsula.

2. Samples of East Serbian lithosphere

According to the slightly modified division of Cvetković et al. (2004a), the ESLM xenoliths can be divided into three groups, each of which has a bearing on specific mantle processes. The first group is most abundant and consists of xenoliths of refractory (depleted) composition (Mg# in silicates > 90). They are the focus of this study and will be hereafter referred as ‘depleted xenoliths’ (D/HZ/L group of Cvetković et al., 2004a). The second group comprises fertile lithologies that ubiquitously contain Al–Ti–clinopyroxene, interpreted as having originated by modification of pre-existing mantle by silicate melt metasomatism. The third group contains rare orthopyroxene-rich xenoliths, thought to have been formed from high magnesian and Si-saturated magmas by igneous fractionation processes in the mantle (Cvetković et al., 2007).

In the following sections we give petrographic and mineral chemistry data on depleted xenoliths from the ESLM and present major characteristics of orthopyroxene-rich cumulitic xenoliths. More detailed mineral chemistry data on the latter xenolith group and an interpretation of their origin can be found in Cvetković et al. (2007). The metasomatic associations found in depleted xenoliths are also seen to a greater degree in the ‘fertile’ group and they will be only briefly discussed in order to recognize effects which have slightly obscured the originally refractory mantle composition.

New mineral compositional analyses on the existing sample suite along with three new samples (see below) were carried out on electron microprobes at the University of Frankfurt and at the University of Mainz. The average mineral analyses including the values for coefficients of variation are shown in Tables 1a–1c. Two orthopyroxene grains from a harzburgite xenolith were studied by a line-scan analysis and demonstrated uniform across-grain chemical composition.

2.1. Characteristics of East Serbian depleted xenoliths

2.1.1. Petrography and modal compositions

In addition to the previous sample collection of depleted xenoliths (Cvetković et al., 2004a) three new samples, labeled M/SB3 (dunite), and M/SB4 and M/SB5 (harzburgite) were also studied. These samples share general petrographic characteristics of the ESLM-depleted xenoliths in having undeformed to slightly sheared protogranular textures. There is no difference in texture between dunite (D) and harzburgite (HZ) and lherzolite (L) except that the dunites are slightly more coarse grained.

The modal analyses and recalculated bulk rock compositions (discussed below) are given in Table 2. Two lherzolite samples (Sb-4 and X-20-1a) from the original xenolith collection of Cvetković et al. (2004a) are exceptionally small (<2 cm in diameter) and therefore their modal composition was omitted from the study. However, these samples show very similar mineral chemistry to that of other ESLM xenoliths and therefore they were included in discussions based on mineral chemical compositions. On triangular diagram of Streckeisen (1973) shown in Fig. 2 twelve samples are spinel harzburgites, five are clinopyroxene-poor lherzolites (<10 vol.% of modal clinopyroxene), and three are clinopyroxene-bearing dunites. Significantly, in terms of modal composition, most of these xenoliths plot within the field of ophiolite peridotites and occupy the most depleted part of the field of abyssal and orogenic peridotites (Bodinier and Godard, 2003). In addition, they are modally more depleted than the average composition of off-cratonic xenoliths given by Pearson et al. (2003).

Table 1a

Average microprobe analyses (number of analyses is given in brackets) and variation coefficients (italic) for olivine from East Serbian depleted xenoliths

Lithology	Dunite						Harzburgite									
Sample	M/SB3 (21)		X-20-3 (15)		Stz-20-6 (6)		X-6 (8)		X-9S (10)		K-13 (6)		K-19 (8)		X-20-15 (7)	
SiO ₂	40.77	0.006	41.35	0.006	41.21	0.003	42.17	0.006	42.00	0.002	40.87	0.005	41.06	0.021	40.90	0.009
FeO	8.72	0.027	8.68	0.002	9.39	0.009	7.51	0.011	8.78	0.013	9.32	0.010	8.04	0.042	8.25	0.061
MnO	0.14	0.107	0.09	0.671	0.07	0.610	0.13	0.105	0.10	0.609	0.08	0.891	0.11	0.832	0.27	1.078
MgO	50.50	0.004	49.82	0.005	48.77	0.007	49.01	0.005	48.29	0.004	48.96	0.005	50.58	0.021	49.08	0.004
CaO	0.09	0.311	0.10	0.703	0.07	0.710	0.07	0.108	0.05	0.713	0.11	0.970	0.08	0.857	0.09	0.933
Cr ₂ O ₃	0.03	0.494	n.a.	–	n.a.	–	n.a.	–	n.a.	–	n.a.	–	0.09	0.867	n.a.	–
NiO	0.36	0.072	0.59	0.137	0.52	0.244	0.58	0.035	0.63	0.203	0.64	0.209	0.41	0.303	0.74	0.347
Total	100.67	0.002	100.63	0.005	100.03	0.005	99.47	0.006	99.85	0.004	99.98	0.005	100.39	0.009	99.42	0.006
Mg# = 100 × MgO/ (MgO + FeO)mol	91.17	0.003	90.51	0.008	90.33	0.029	91.85	0.001	90.74	0.001	90.35	0.001	91.78	0.003	91.38	0.006
Lithology	Harzburgite															
Sample	M/SB4 (23)		M/SB5 (18)		Stz-20-3 (4)		Stz-20-4 (7)		Stz-20-9 (6)		Stz-20-11 (4)		Stz-20-12 (12)			
SiO ₂	40.82	0.008	40.87	0.003	41.23	0.005	41.24	0.003	40.53	0.006	41.68	0.005	40.71	0.020		
FeO	8.20	0.005	8.76	0.038	8.13	0.011	8.60	0.019	9.31	0.152	8.24	0.019	9.93	0.059		
MnO	0.13	0.078	0.13	0.128	0.11	0.411	0.15	0.366	0.09	0.572	0.01	1.140	0.07	0.237		
MgO	50.84	0.006	50.42	0.007	49.38	0.004	49.35	0.006	48.33	0.027	50.28	0.007	47.77	0.001		
CaO	0.04	0.173	0.04	0.238	0.07	0.058	0.11	0.500	0.12	0.550	0.04	0.680	0.05	0.166		
Cr ₂ O ₃	0.01	1.080	0.01	0.925	n.a.	–	n.a.	–	n.a.	–	n.a.	–	n.a.	–		
NiO	0.42	0.051	0.39	0.058	0.49	0.161	0.49	0.251	0.60	0.147	0.59	0.132	0.76	0.087		
Total	100.51	0.005	100.69	0.002	99.41	0.004	99.93	0.005	98.98	0.004	100.84	0.006	99.29	0.004		
Mg#	91.70	0.001	91.11	0.004	91.68	0.001	91.10	0.002	91.22	0.007	91.71	0.001	89.55	0.001		
Lithology	Lherzolite															
Sample	X-11/2 (17)		Sb-4 (11)		X-20-1a (7)		X-20-7 (6)		Stz-20-1 (10)		Stz-20-2 (14)		Stz-20-7 (6)			
SiO ₂	41.93	0.008	40.95	0.007	41.06	0.001	41.43	0.001	41.34	0.005	41.77	0.001	40.88	0.007		
FeO	8.20	0.042	8.08	0.020	8.88	0.016	8.57	0.004	8.74	0.014	9.38	0.023	8.65	0.040		
MnO	0.10	0.244	0.10	0.717	0.10	0.670	0.12	0.116	0.09	0.599	0.10	0.129	0.11	0.423		
MgO	48.60	0.008	50.81	0.014	49.21	0.004	50.05	0.004	49.84	0.004	49.42	0.002	48.68	0.013		
CaO	0.04	0.689	0.06	0.466	0.02	1.589	0.06	0.191	0.06	0.564	0.13	0.146	0.14	0.662		
Cr ₂ O ₃	n.a.	–	0.13	1.291	n.a.	–	n.a.	–	n.a.	–	n.a.	–	n.a.	–		
NiO	0.65	0.200	0.41	0.250	0.52	0.193	0.55	0.029	0.53	0.085	0.61	0.056	0.66	0.282		
Total	99.52	0.010	100.65	0.008	99.79	0.004	100.78	0.003	100.6	0.004	101.41	0.002	99.11	0.007		
Mg#	91.35	0.004	91.81	0.002	90.81	0.001	91.23	0.001	91.00	0.001	90.03	0.001	90.94	0.004		

Table 1b

Average microprobe analyses (number of analyses is given in brackets) and variation coefficients (italic) for pyroxene from East Serbian depleted xenoliths

Mineral	Orthopyroxene (Harzburgite)													
Lithology Sample	X-6 (7)		X-9S (28)		K-13 (8)		K-19 (13)		X 20-15 (6)		M/SB4 (14)			
SiO ₂	58.09	0.006	58.22	0.006	56.86	0.014	58.40	0.010	56.40	0.002	56.50	0.002		
TiO ₂	0.08	0.825	0.05	0.600	0.06	0.773	0.02	0.799	0.02	1.869	0.02	0.284		
Al ₂ O ₃	1.41	0.057	1.88	0.053	1.64	0.267	1.41	0.110	1.51	0.152	1.64	0.012		
FeO	4.91	0.010	5.74	0.025	6.06	0.047	4.98	0.033	5.78	0.024	5.37	0.013		
MnO	0.09	0.379	0.10	0.581	0.18	0.759	0.03	3.606	0.09	0.778	0.13	0.047		
MgO	33.81	0.005	33.18	0.007	33.97	0.015	34.10	0.014	34.38	0.006	35.12	0.002		
CaO	0.54	0.066	0.76	0.182	0.69	0.080	0.58	0.095	0.72	0.098	0.58	0.040		
Na ₂ O	n.a.	—	n.a.	—	0.13	0.241	0.07	0.001	0.62	0.233	0.04	0.071		
Cr ₂ O ₃	0.45	0.137	0.49	0.099	0.50	0.390	0.46	0.155	0.64	0.377	0.42	0.060		
Total	99.38	0.005	100.43	0.006	100.32	0.006	100.03	0.007	99.85	0.004	99.93	0.002		
Mg#	92.33	0.001	91.00	0.003	90.66	0.007	92.38	0.002	91.26	0.001	91.93	0.001		
Mineral	Orthopyroxene (Harzburgite)													
Lithology Sample	M/SB5 (5)		Stz-20-3 (14)		Stz-20-4 (7)		Stz-20-9 (13)		Stz-20-11 (13)		Stz-20-12 (10)			
SiO ₂	56.95	0.001	57.01	0.002	56.71	0.003	56.66	0.007	57.23	0.005	56.47	0.006		
TiO ₂	0.02	0.794	0.03	1.024	0.03	1.178	0.05	1.000	0.07	0.148	0.04	1.176		
Al ₂ O ₃	1.43	0.022	1.73	0.022	1.70	0.026	2.20	0.080	1.80	0.011	1.42	0.126		
FeO	5.62	0.009	5.22	0.035	5.56	0.011	5.35	0.040	5.44	0.012	6.14	0.038		
MnO	0.14	0.109	0.18	0.183	0.21	0.214	0.11	0.005	0.09	1.000	0.24	0.334		
MgO	35.10	0.002	34.55	0.004	34.42	0.004	34.21	0.007	34.89	0.003	33.99	0.006		
CaO	0.58	0.021	0.61	0.067	0.62	0.059	0.70	0.078	0.72	0.005	0.68	0.060		
Na ₂ O	0.03	0.319	0.42	0.085	0.43	0.050	0.35	0.032	0.43	0.011	0.39	0.088		
Cr ₂ O ₃	0.38	0.078	0.43	0.119	0.46	0.121	0.54	0.043	0.43	0.050	0.41	0.093		
Total	100.34	0.001	100.18	0.003	99.92	0.004	100.17	0.007	101.1	0.004	99.52	0.007		
Mg#	91.56	0.001	91.98	0.003	91.40	0.001	91.82	0.003	91.84	0.000	90.48	0.004		
Mineral	Orthopyroxene (Lherzolite)													
Lithology Sample	X-11/2 (16)		Sb-4 (17)		X-20-1a (10)		X 20-7 (6)		Stz 20-1 (8)		Stz 20-2 (11)		Stz 20-7 (13)	
SiO ₂	57.83	0.806	56.55	0.368	56.46	0.147	57.39	0.237	56.98	0.186	56.20	0.611	56.86	0.003
TiO ₂	0.06	0.042	0.02	0.033	0.02	0.028	0.01	0.019	0.01	0.017	0.03	0.006	0.00	0.004
Al ₂ O ₃	1.53	0.128	1.85	0.050	1.64	0.109	1.10	0.068	1.73	0.060	1.75	0.124	1.51	0.162
FeO	5.00	0.087	5.25	0.101	5.73	0.063	5.37	0.125	5.67	0.129	5.20	0.023	4.87	0.006
MnO	0.14	0.069	0.13	0.044	0.15	0.048	0.13	0.079	0.12	0.010	0.20	0.024	0.13	0.016
MgO	34.36	0.465	35.13	0.230	34.50	0.082	34.93	0.317	34.67	0.221	34.81	0.247	34.69	0.010

Table 1b (Continued)

Mineral	Orthopyroxene (Lherzolite)													
Lithology Sample	X-11/2 (16)		Sb-4 (17)		X-20-1a (10)		X 20-7 (6)		Stz 20-1 (8)		Stz 20-2 (11)		Stz 20-7 (13)	
CaO	0.58	0.039	0.55	0.033	0.32	0.025	0.57	0.022	0.65	0.036	0.63	0.034	0.59	0.013
Na ₂ O	0.02	0.021	0.03	0.183	0.42	0.018	0.45	0.057	0.38	0.014	n.a.	–	0.45	0.004
Cr ₂ O ₃	0.56	0.208	0.48	0.072	0.34	0.054	0.42	0.072	0.48	0.072	0.52	0.071	0.53	0.030
Total	100.09	0.656	100.06	0.572	99.58	0.131	100.13	0.353	100.70	0.518	99.35	0.413	99.63	0.303
Mg#	92.26	0.178	92.09	0.159	91.27	0.088	91.89	0.099	91.44	0.135	91.10	0.071	92.27	0.028
Mineral	Clinopyroxene													
Lithology Sample	Dunite				Harzburgite					Lherzolite				
	M/SB3 (13)		K-13 (8)		X-20-15 (8)		M/SB4 (12)		M/SB5 (11)		X 20-7 (6)		Stz 20-1 (5)	
SiO ₂	53.30	0.251	53.22	0.706	53.29	2.687	54.12	0.219	53.98	0.146	54.70	2.814	51.61	1.278
TiO ₂	0.13	0.028	0.16	0.260	0.07	0.827	0.06	0.006	0.04	0.019	0.05	0.217	0.45	0.813
Al ₂ O ₃	2.80	0.180	1.99	0.812	1.79	2.808	1.86	0.091	1.62	0.043	1.49	3.100	3.04	0.702
FeO	2.63	0.146	2.59	0.712	2.50	1.149	2.31	0.057	2.42	0.084	2.37	0.251	2.82	1.597
MnO	0.09	0.017	0.18	0.318	0.10	0.111	0.08	0.005	0.09	0.013	0.13	0.189	0.15	0.062
MgO	17.40	0.137	17.66	0.600	17.64	1.481	17.70	0.163	17.61	0.088	17.08	1.747	16.12	0.833
CaO	21.85	0.491	23.16	1.035	22.91	1.681	22.70	0.156	22.57	0.077	23.33	1.803	22.68	0.975
Na ₂ O	0.57	0.101	0.53	0.090	0.56	0.128	0.47	0.064	0.44	0.018	0.59	0.106	0.62	0.072
Cr ₂ O ₃	0.75	0.047	0.60	0.297	0.69	1.163	0.75	0.047	0.69	0.030	0.49	1.854	1.81	1.198
Total	99.58	0.252	100.10	0.453	99.55	0.433	100.09	0.148	99.53	0.293	100.23	0.658	99.33	0.784
Mg#	91.93	0.373	91.89	1.891	92.31	4.183	92.97	0.229	92.61	0.218	92.13	1.140	90.62	4.874

Table 1c

Average microprobe analyses (number of analyses is given in brackets) and variation coefficients (italic) for spinel from East Serbian depleted xenoliths

Lithology	Dunite						Harzburgite			
Sample	M/SB3 (13)		X 20-3 (14)		Stz-20-6 (11)		X-6 (6)		K-13 (7)	
SiO ₂	0.12	<i>1.517</i>	0.21	<i>0.205</i>	0.28	<i>0.358</i>	0.27	<i>0.076</i>	0.29	<i>0.136</i>
TiO ₂	0.29	<i>0.108</i>	0.30	<i>0.136</i>	0.23	<i>0.425</i>	0.22	<i>0.058</i>	0.39	<i>0.259</i>
Al ₂ O ₃	32.64	<i>0.033</i>	29.88	<i>0.022</i>	35.33	<i>0.025</i>	20.39	<i>0.016</i>	19.67	<i>0.014</i>
Cr ₂ O ₃	33.92	<i>0.024</i>	34.49	<i>0.032</i>	29.54	<i>0.033</i>	47.84	<i>0.005</i>	41.96	<i>0.028</i>
FeOt	15.90	<i>0.019</i>	16.89	<i>0.005</i>	16.58	<i>0.015</i>	18.00	<i>0.010</i>	21.87	<i>0.029</i>
MnO	0.18	<i>0.085</i>	2.81	<i>0.078</i>	2.57	<i>0.056</i>	0.22	<i>0.553</i>	3.39	<i>0.075</i>
MgO	17.61	<i>0.017</i>	15.97	<i>0.005</i>	17.06	<i>0.014</i>	12.99	<i>0.007</i>	12.91	<i>0.010</i>
CaO	0.02	<i>1.661</i>	0.03	<i>0.658</i>	0.03	<i>1.158</i>	0.06	<i>0.485</i>	0.05	<i>0.913</i>
Mg/(Mg + Fe ²⁺)	0.779	<i>0.009</i>	0.768	<i>0.029</i>	0.797	<i>0.031</i>	0.614	<i>0.049</i>	0.699	<i>0.045</i>
Cr/(Cr + Al)	0.411	<i>0.030</i>	0.439	<i>0.031</i>	0.359	<i>0.036</i>	0.611	<i>0.008</i>	0.588	<i>0.016</i>
Lithology	Harzburgite									
Sample	K-19 (14)		X-20-15 (7)		M/SB4 (8)		M/SB5 (14)		Stz-20-3 (13)	
SiO ₂	0.22	<i>2.619</i>	0.21	<i>0.176</i>	0.06	<i>0.921</i>	0.03	<i>0.288</i>	0.20	<i>0.353</i>
TiO ₂	0.08	<i>0.867</i>	0.13	<i>0.431</i>	0.15	<i>0.152</i>	0.17	<i>0.095</i>	0.28	<i>0.532</i>
Al ₂ O ₃	20.33	<i>0.050</i>	21.76	<i>0.016</i>	21.71	<i>0.035</i>	18.24	<i>0.041</i>	21.69	<i>0.058</i>
Cr ₂ O ₃	47.34	<i>0.037</i>	41.51	<i>0.020</i>	43.45	<i>0.015</i>	43.62	<i>0.024</i>	42.00	<i>0.009</i>
FeOt	17.44	<i>0.049</i>	19.98	<i>0.113</i>	19.52	<i>0.023</i>	24.35	<i>0.011</i>	20.68	<i>0.105</i>
MnO	0.22	<i>0.078</i>	3.35	<i>0.032</i>	0.21	<i>0.085</i>	0.26	<i>0.088</i>	3.07	<i>0.017</i>
MgO	15.55	<i>0.048</i>	13.72	<i>0.149</i>	15.01	<i>0.024</i>	13.71	<i>0.016</i>	13.87	<i>0.111</i>
CaO	0.02	<i>1.007</i>	0.04	<i>0.536</i>	0.05	<i>2.203</i>	0.00	<i>1.993</i>	0.01	<i>1.000</i>
Mg/(Mg + Fe ²⁺)	0.735	<i>0.049</i>	0.741	<i>0.138</i>	0.720	<i>0.009</i>	0.687	<i>0.013</i>	0.719	<i>0.099</i>
Cr/(Cr + Al)	0.610	<i>0.033</i>	0.559	<i>0.012</i>	0.573	<i>0.017</i>	0.616	<i>0.024</i>	0.566	<i>0.021</i>
Lithology	Harzburgite									Lherzolite
Sample	Stz-20-4 (13)		Stz-20-9 (13)		Stz-20-11 (4)		Stz-20-12 (13)		X-11/2 (15)	
SiO ₂	0.10	<i>0.787</i>	0.16	<i>0.300</i>	0.39	<i>0.225</i>	0.24	<i>0.239</i>	0.20	<i>2.149</i>
TiO ₂	0.23	<i>0.992</i>	0.16	<i>0.436</i>	0.22	<i>0.436</i>	0.62	<i>0.174</i>	0.22	<i>0.543</i>
Al ₂ O ₃	22.25	<i>0.053</i>	21.01	<i>0.015</i>	18.03	<i>0.143</i>	14.88	<i>0.050</i>	20.92	<i>0.070</i>
Cr ₂ O ₃	42.55	<i>0.014</i>	40.86	<i>0.010</i>	41.84	<i>0.021</i>	43.32	<i>0.016</i>	44.99	<i>0.018</i>
FeOt	19.42	<i>0.049</i>	20.72	<i>0.054</i>	22.29	<i>0.183</i>	26.30	<i>0.088</i>	18.85	<i>0.070</i>
MnO	1.06	<i>0.855</i>	3.280	<i>0.073</i>	3.32	<i>0.043</i>	3.82	<i>0.010</i>	0.21	<i>0.383</i>
MgO	14.56	<i>0.046</i>	14.30	<i>0.009</i>	13.56	<i>0.059</i>	10.93	<i>0.112</i>	15.01	<i>0.068</i>
CaO	0.02	<i>1.323</i>	0.05	<i>0.858</i>	0.01	<i>1.277</i>	0.01	<i>1.382</i>	0.02	<i>1.856</i>
Mg/(Mg + Fe ²⁺)	0.712	<i>0.036</i>	0.766	<i>0.057</i>	0.757	<i>0.066</i>	0.634	<i>0.154</i>	0.715	<i>0.083</i>
Cr/(Cr + Al)	0.562	<i>0.027</i>	0.559	<i>0.002</i>	0.609	<i>0.051</i>	0.661	<i>0.014</i>	0.591	<i>0.033</i>

Table 1c (Continued)

Lithology	Lherzolite							
Sample	Sb-4 (20)		X-20-1a (7)		X 20-7 (4)		Stz-20-7 (3)	
SiO ₂	0.06	1.162	0.27	0.180	0.24	0.584	0.35	0.013
TiO ₂	0.10	0.155	0.05	0.868	0.09	0.803	0.15	1.452
Al ₂ O ₃	24.15	0.026	24.16	0.071	13.94	0.009	16.88	0.113
Cr ₂ O ₃	42.01	0.008	38.68	0.017	49.03	0.006	44.35	0.015
FeOt	18.38	0.015	20.34	0.083	24.03	0.005	24.19	0.142
MnO	0.53	1.830	3.22	0.044	3.94	0.044	3.70	0.029
MgO	15.66	0.033	14.02	0.048	11.65	0.023	11.35	0.145
CaO	0.01	1.711	0.01	0.967	0.14	0.400	0.06	0.185
Mg/(Mg + Fe ²⁺)	0.739	0.009	0.734	0.052	0.664	0.057	0.643	0.153
Cr/(Cr + Al)	0.538	0.012	0.518	0.029	0.702	0.002	0.638	0.036

Table 2

Modal composition and recalculated bulk rock major element composition of East Serbian depleted xenoliths

Lithology	Dunite			Harzburgite						
Sample	X-20-3	Stz-20-6	SB-M-3	X-6	X-9S	K-13	K-19	X-20-15	SB-M-4	SB-M-5
Modal composition (vol.%)										
Ol	0.9	0.975	0.92	0.884	0.778	0.82	0.677	0.701	0.727	0.75
Opx	0	0	0	0.097	0.177	0.13	0.252	0.205	0.21	0.19
Cpx	0.069	0	0.07	0.016	0.045	0.037	0.051	0.081	0.045	0.04
Spl	0.031	0.025	0.01	0.003	0	0.011	0.02	0.013	0.018	0.02
Recalculated bulk rock major element composition (wt.%)										
SiO ₂	40.71	40.16	41.24	43.80	45.19	42.88	45.28	44.56	43.98	43.63
Al ₂ O ₃	1.35	0.88	0.55	0.21	0.69	0.50	0.88	0.74	0.83	0.71
FeO	8.54	9.59	8.36	7.22	7.98	8.77	7.18	7.43	7.54	8.23
MnO	0.17	0.12	0.14	0.13	0.10	0.13	0.09	0.26	0.13	0.14
MgO	46.40	48.07	47.86	46.95	44.09	45.36	44.02	43.06	45.40	45.46
CaO	1.61	0.06	1.61	0.42	1.14	1.03	1.30	2.06	1.18	1.05
Na ₂ O	0.05	0.00	0.05	0.01	0.04	0.02	0.07	0.17	0.04	0.03
Cr ₂ O ₃	1.15	0.74	0.42	0.20	0.23	0.55	1.21	0.73	0.91	0.98
Lithology	Harzburgite				Lherzolite					
Sample	Stz-20-3	Stz-20-4	Stz-20-9	Stz-20-11	Stz-20-12	X-11/2	X-20-7	Stz-20-1	Stz-20-2	Stz-20-7
Modal composition (vol.%)										
Ol	0.688	0.728	0.852	0.86	0.723	0.711	0.7	0.635	0.725	0.806
Opx	0.3	0.233	0.119	0.105	0.242	0.201	0.221	0.299	0.168	0.124
Cpx	0.005	0.032	0.023	0.022	0.032	0.072	0.06	0.061	0.092	0.051
Spl	0.007	0.007	0.007	0.013	0.004	0.017	0.024	0.005	0.015	0.019
Recalculated bulk rock major element composition (wt.%)										
SiO ₂	45.80	44.81	42.44	43.03	44.79	45.23	44.92	46.44	44.72	42.77
Al ₂ O ₃	0.67	0.76	0.46	0.48	0.48	0.93	0.66	0.84	0.46	0.61
FeO	7.25	7.77	8.77	8.01	8.86	7.36	7.88	7.56	8.51	8.17
MnO	0.17	0.17	0.12	0.06	0.13	0.11	0.23	0.10	0.18	0.18
MgO	44.80	44.53	45.73	47.45	43.34	42.89	43.90	43.06	43.54	44.72
CaO	0.34	0.94	0.69	0.58	0.89	1.73	1.56	1.62	2.02	1.23
Na ₂ O	0.00	0.12	0.02	0.02	0.12	0.06	0.13	0.04	0.06	0.03
Cr ₂ O ₃	0.43	0.49	0.38	0.62	0.32	1.00	1.30	0.40	0.84	0.97

2.1.2. Major element data

Electron microprobe data (Tables 1a–1c) reveal that olivines and pyroxenes from harzburgite and lherzolite xenoliths have high Mg#s [$\text{Mg\#} = 100 \times \text{MgO}/(\text{MgO} + \text{FeO}) \text{ mol}$] that lie in narrow ranges (i.e. olivine $\text{Mg\#} = 89.6\text{--}92$; orthopyroxene $\text{Mg\#} = 90.5\text{--}92.5$). Orthopyroxene has unusually low Al_2O_3 contents (1–2 wt.%), while spinel has high Cr# [$\text{Cr\#} = \text{Cr}_2\text{O}_3/(\text{Cr}_2\text{O}_3 + \text{Al}_2\text{O}_3) \text{ mol}$] of 0.36–0.75, mostly > 0.5. Only six of the harzburgite and lherzolite xenoliths contain clinopyroxene which texturally and in terms of major element chemistry can be regarded as primary. They occur as discrete, interstitial grains and have high Mg# (mostly > 92), and low Al_2O_3 (1.4–3.4 wt.%) and variable Cr_2O_3 (0.5–2 wt.%) contents. Al_2O_3 is a convenient depletion index in peridotites and its contents are correlated in coexisting pyroxenes and between orthopyroxene and spinel in these xenoliths (Fig. 3). Such a correlation of depletion parameters suggests a change in residual composition due to progressive melt extraction. The ESLM xenoliths are generally more depleted than mantle unrelated to subduction and plot in the field of subduction-related mantle (see Fig. 5 for data sources and references). The presence of unusually low-Al orthopyroxene is a remarkable characteristic of the ESLM-depleted xenoliths. In comparison, orthopyroxene from xenoliths found in off-cratonic settings commonly contains between 3 and 6 wt.% Al_2O_3 (e.g. Pearson et al., 2003).

Dunite xenoliths from the ESLM have Mg# in olivine in the range 90.2–91.2, slightly less than most of the harzburgite and lherzolite xenoliths, and their spinels are clearly less chromium-rich ($\text{Cr\#} = 0.36\text{--}0.44$) (Tables 1a–1c). In addition, two of them contain more clinopyroxene than do the ESLM harzburgites, implying that these dunites underwent meta-

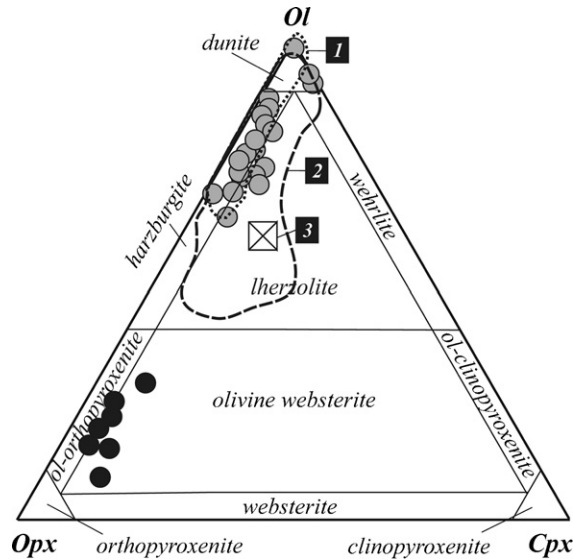


Fig. 2. Modal composition of East Serbian depleted and orthopyroxene-rich xenoliths plotted onto the olivine – orthopyroxene – clinopyroxene diagram (Streckeisen, 1973). The compositional fields of ophiolite peridotites (1), orogenic and abyssal peridotites (Bodinier and Godard, 2003) (2), and an average composition of off-cratonic xenoliths (Pearson et al., 2003) (3) are shown for comparison; gray circles – depleted xenoliths, solid circles – orthopyroxene-rich xenoliths.

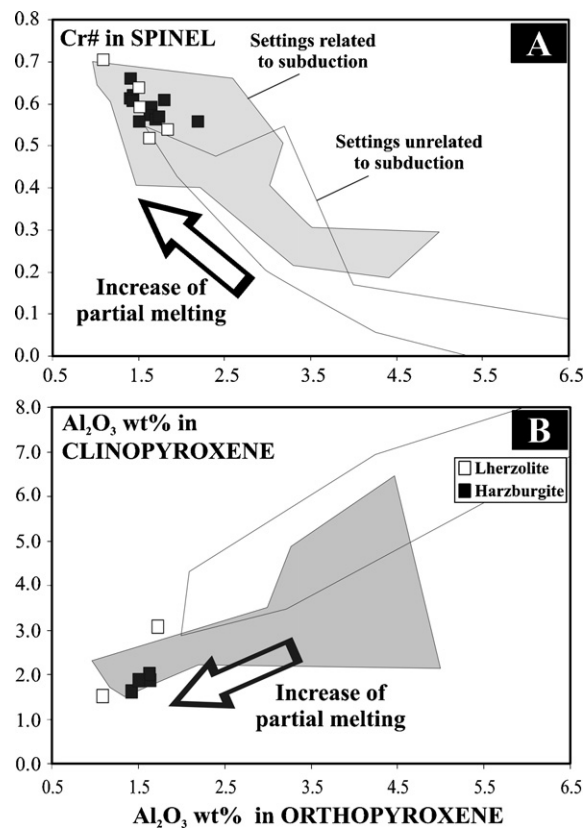


Fig. 3. Al₂O₃ (wt.%) in orthopyroxene vs. Cr# in spinel (A) and Al₂O₃ (wt.%) in clinopyroxene (B) for ESLM-depleted mantle xenoliths. For comparison, composition range of mineral pairs in peridotites related and unrelated to subduction settings are also given; references for data sources are in Fig. 5.

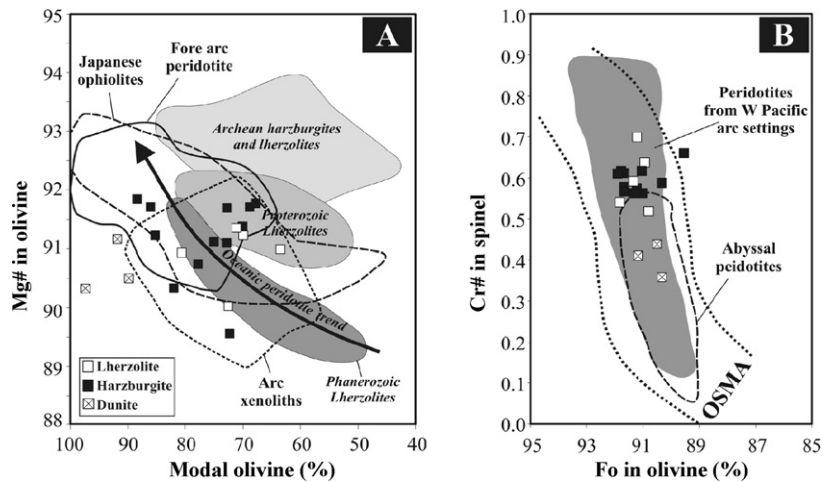


Fig. 4. (A) Olivine mode vs. Mg#, oceanic peridotite trend after Boyd (1987); other fields from Griffin et al. (2003) and reference therein. (B) A forsterite (%) in olivine vs. Cr# in spinel; the olivine–spinel–mantle–array (OSMA) is from Arai (1994); fields of abyssal peridotites and of peridotites from west Pacific arc settings are from Bernstein et al. (1998) and references therein.

somatic addition of clinopyroxene. A specific textural type found in dunite xenoliths are clinopyroxene–spinel–olivine symplectites that texturally resemble metasomatic patches commonly found in harzburgite and clinopyroxene-poor lherzolite ESLM xenoliths (Cvetković et al., 2004a). Spinel in these symplectites is rich in Fe–Ti–Al compared to discrete spinel grains from the same xenolith. In addition, clinopyroxene from the symplectites is similar in composition to clinopyroxene from metasomatic pockets found in ESLM harzburgite xenoliths (Cvetković et al., 2004a). Therefore, these symplectites can be regarded as evidence of metasomatic enrichment of the ESLM by silicate melts. This enrichment has obscured the original depleted nature of the dunites and may have affected the other depleted xenoliths to some extent.

In the diagram combining the modal olivine contents with its Mg# values (Fig. 4A), ESLM-depleted xenoliths scatter around the trend of oceanic peridotites (Boyd, 1987) which is coincident with the field of the Phanerozoic sub-continental mantle. The studied xenoliths plot in the fields of arc- or ophiolite-related peridotites with the exception of three dunite samples that plot towards the left-hand side of the diagram. Nearly half of the samples plot in the overlapping area of Proterozoic and ‘arc’-related mantle fields. The extent of depletion in these xenoliths can be also seen in a plot of forsterite value in olivine versus Cr# in spinel (Arai, 1994) (Fig. 4B). The ESLM xenoliths plot in the upper part of the olivine–spinel–mantle–array (OSMA) suggesting that they are more depleted in comparison to abyssal peridotites and more similar to arc peridotites. In contrast, dunite show lower spinel Cr#s for a given forsterite value of their olivine, implying that some refertilization has occurred in this lithology (discussed also below).

In Fig. 5 the mineral compositions of the studied xenoliths are compared to other xenolith suites and peridotite massifs. Generally, minerals from European mantle xenoliths and those from most peridotite massifs display more fertile characteristics (low Mg#, low Cr#, high Al_2O_3) than do minerals from ESLM xenoliths. Refractory samples do occur at some places (e.g. Vaselli et al., 1995; Beccaluva et al., 2001), but they are extremely rare within these localities and are still less depleted than the ESLM xenoliths. On the other hand, highly depleted xenoliths are far more abundant within the ESLM xenolith suite and their minerals are clearly compositionally similar to minerals from mantle related to subduction settings.

2.1.3. Bulk rock compositions

As pointed out by Herzberg (2004), sub-oceanic arc mantle peridotites and supra-subduction zone ophiolite peridotites are usually Al_2O_3 -depleted and SiO_2 -rich and do not follow major element trends of simple change in residual composition. The ESLM xenoliths are too small to obtain whole-rock chemical analyses. To provide more information about their composition, we calculated their bulk major element abundances (Table 2), using modal abundance and mineral chemistry data from Table 1. For samples in which only secondary clinopyroxene has been found clinopyroxene analyses from Cvetković et al. (2004a) and Cvetković (unpublished) were used. The calculated bulk Al_2O_3 contents are mostly < 1%. Fig. 6 shows an overlap in MgO and Al_2O_3 contents between recalculated bulk rock compositions of

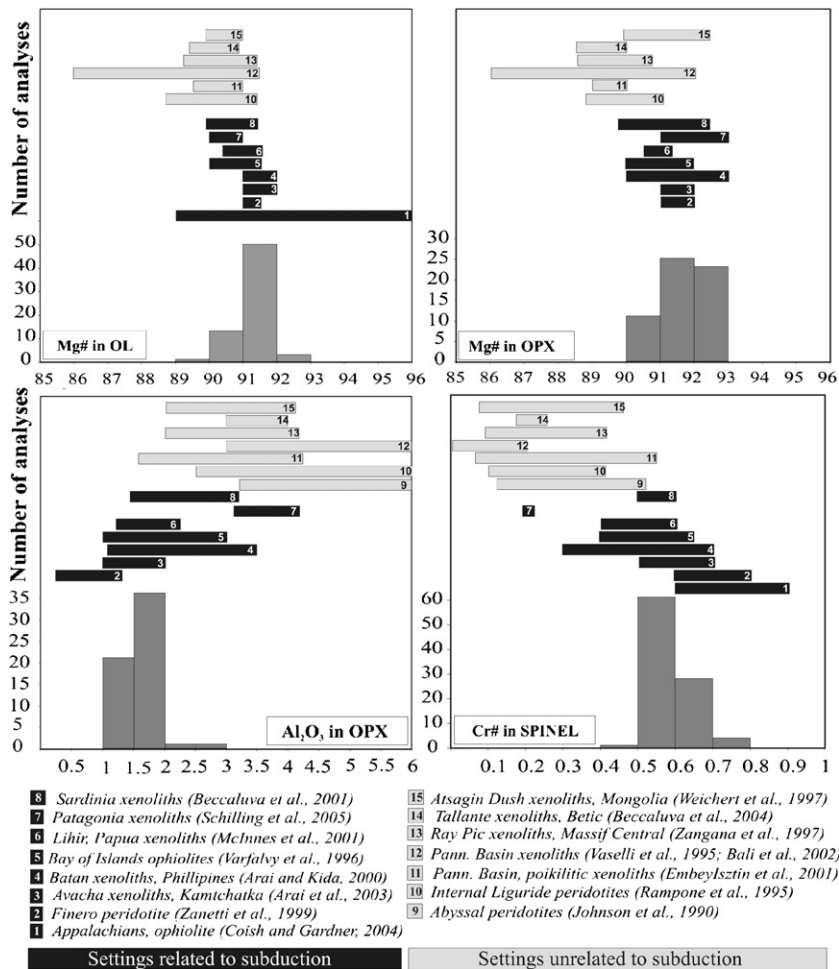


Fig. 5. A comparison between East Serbian depleted mantle xenoliths and peridotites of known geotectonic settings. Adopted mineral chemistry parameters (Mg# in olivine and orthopyroxene, Cr# in spinel and Al_2O_3 contents in orthopyroxene) illustrate the degree of depletion (see refs. Arai et al., 2003; Bali et al., 2002; Beccaluva et al., 2004; Coish and Gardner, 2004; Rampone et al., 1995; Schilling et al., 2005; Zangana et al., 1997).

the studied xenoliths and major element whole-rock composition of peridotites of the Vardar Zone ophiolite (Lenaz, unpublished). Fields of abyssal peridotites, Tethyan ophiolites and peridotites of active subduction zones are also shown (Herzberg, 2004). Similar to the Vardar Zone peridotites, the East Serbian depleted xenoliths depart from the residual line after low-pressure partial melting, which is generally followed by abyssal peridotites, and trend to lower Al_2O_3 concentrations for a given MgO content. The composition of both ESLM xenoliths and Vardar Zone peridotites fall in the field of peridotites of active subduction zones (see inset of Fig. 6).

2.1.4. LA-ICP-MS data

LA-ICP-MS analyses were carried out at the University of Frankfurt. Operating conditions are given in Cvetković et al. (2007). Tables 3a and 3b show trace element contents in orthopyroxene and clinopyroxene from two harzburgite xenoliths (samples M/SB4 and M/SB5).

Orthopyroxene shows a subparallel light rare-earth element (LREE)-depleted pattern with $[\text{La}/\text{Lu}]_N < 0.1$ (Fig. 7A). On primitive mantle-normalized trace element diagrams they show a slight increase of concentrations from incompatible to more compatible elements and exhibit Rb, Th–U and Pb positive anomalies. Absolute trace element concentrations are very similar in orthopyroxenes from both harzburgite xenoliths, although lower trace element concentrations are observed in orthopyroxene with slightly higher Mg#, suggesting a more refractory composition. Gregoire et al. (2001) analysed low-Al orthopyroxene in spinel peridotite xenoliths from a subduction-related setting of Lihir in Papua New

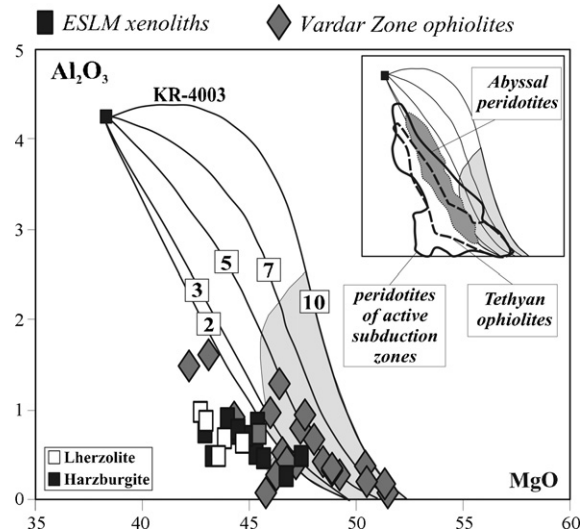


Fig. 6. MgO (wt.%) vs. Al_2O_3 (wt.%) diagram for East Serbian mantle xenoliths (composition recalculated on the basis of modal analyses and mineral chemistry data) and Vardar Zone peridotites (XRF whole rock analyses, Lenaz, unpublished). The curves display change in residual mantle composition after fractional partial melting of fertile peridotite KR-4003 (Walter, 1998). The squared numbers mark pressure values at which partial melting starts. The fields of abyssal peridotites, Tethyan ophiolites and peridotites of active subduction zones are given in the inset (for explanation see Herzberg, 2004).

Guinea. In comparison to these xenoliths, the ESLM orthopyroxene is poorer in most trace elements, especially LREE and LILE.

Trace element patterns of studied clinopyroxenes are illustrated in Fig. 7B. Clinopyroxenes from harzburgites exhibit a moderately LREE-enriched ($[\text{La}/\text{Lu}]_{\text{N}} = 3.5\text{--}10$) pattern and are depleted in HREE (e.g. $\text{Yb} = 1.4\text{--}2.2 \times$ chondrite). On primitive mantle-normalized diagrams they display negative anomalies at Rb–Ba, Zr–Hf and less distinctively at Nb, as well as a pronounced peak at Sr. The trace element patterns of clinopyroxene from samples Sb-4 and X-6 reported by Cvetković et al. (2004a) are also shown. These clinopyroxenes have higher contents of all incompatible elements in

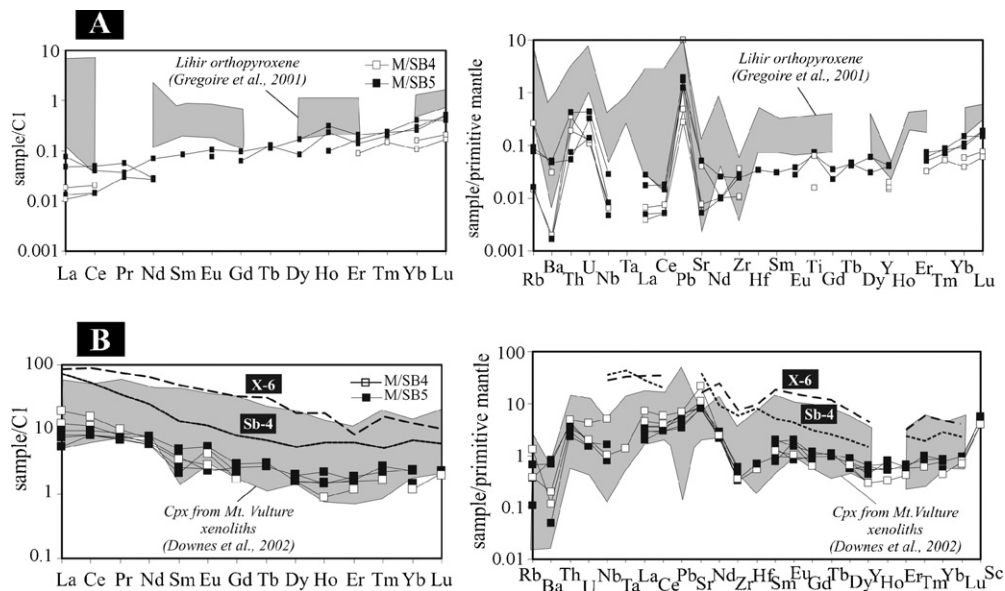


Fig. 7. Chondrite-normalized REE and primitive mantle-normalized multielement variation diagrams for orthopyroxene (A) and clinopyroxene (B) from depleted East Serbian mantle xenoliths (primitive mantle abundances after McDonough and Sun, 1995).

Table 3a
LA-ICP-MS analyses of orthopyroxene from East Serbian depleted xenoliths

Sample no.	M/SB4			M/SB5		
	Opx1	Opx2	Opx3	Opx1	Opx2	Opx3
Li	9.95	4.26	3.52	7.10	10.24	11.69
Sc	14.99	17.91	15.38	18.1	18.87	20.29
Ti	77.4	18.8	81.1	79.9	81.3	88.8
V	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cr	2911.8	2745.4	2938.4	2822.5	2566.8	2675.3
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	853.5	1016.3	851.0	803.9	805.5	819.5
Rb	0.09	0.16	b.d.l.	0.056	0.01	0.05
Sr	0.116	0.793	0.151	1.007	0.104	0.912
Y	0.066	0.086	0.069	0.171	0.174	0.185
Zr	0.108	0.377	0.112	0.252	0.269	0.336
Nb	0.005	b.d.l.	0.004	0.005	0.003	0.019
Ba	0.013	0.205	0.011	0.313	0.011	0.334
La	0.003	b.d.l.	0.004	0.018	0.003	0.011
Ce	0.009	b.d.l.	0.013	0.023	0.009	0.030
Pr	b.d.l.	b.d.l.	b.d.l.	0.003	0.003	0.005
Nd	b.d.l.	b.d.l.	0.013	0.032	0.012	0.013
Sm	b.d.l.	b.d.l.	b.d.l.	0.013	b.d.l.	b.d.l.
Eu	b.d.l.	b.d.l.	b.d.l.	0.006	b.d.l.	0.004
Gd	b.d.l.	b.d.l.	b.d.l.	0.019	0.013	b.d.l.
Tb	b.d.l.	b.d.l.	b.d.l.	0.004	0.005	0.004
Dy	b.d.l.	b.d.l.	b.d.l.	0.021	b.d.l.	0.041
Ho	b.d.l.	b.d.l.	b.d.l.	0.013	0.005	0.017
Er	0.014	b.d.l.	b.d.l.	0.023	0.027	0.033
Tm	0.004	b.d.l.	b.d.l.	0.005	0.006	0.006
Yb	0.017	b.d.l.	0.026	0.048	0.065	0.041
Lu	0.004	b.d.l.	0.005	0.013	0.010	0.012
Hf	b.d.l.	b.d.l.	b.d.l.	0.010	b.d.l.	b.d.l.
Ta	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Pb	0.041	1.489	0.073	0.187	0.254	0.292
Th	0.028	b.d.l.	0.015	0.004	0.006	0.034
U	0.002	b.d.l.	0.003	0.007	0.003	0.009

comparison to the clinopyroxene studied here and that can be related to progressive metasomatic effects in the former. On the other hand, clinopyroxene from depleted peridotite xenoliths of Mt. Vulture, which is interpreted to have undergone extensive partial melting (Downes et al., 2002), has a similar pattern to those displayed by clinopyroxene from samples M/SB4 and M/SB5. Clinopyroxene from the ESLM samples overlaps in composition with the lower range of the clinopyroxene from Mt. Vulture xenoliths.

2.2. Characteristics of orthopyroxene-rich xenoliths

Independent evidence that a highly depleted lithosphere is present underneath East Serbia comes from a group of orthopyroxene-rich cumulate xenoliths (Cvetković et al., 2007). They are undeformed and predominantly composed of tabular orthopyroxene (70 vol.%) (Fig. 2). In between the orthopyroxene crystals exists an interstitial association of olivine, clinopyroxene, Cr-rich spinel ($\text{Cr}\# > 0.8$), Mg-bearing calcite, K-feldspar, apatite and ilmenite.

Cvetković et al. (2007) have made a detailed interpretation of this lithology and recognized two stages in its petrogenesis. The first stage is attributed to high pressure igneous processes, while the second stage is a metasomatic overprint similar to that which affected the depleted xenoliths. Relicts of cumulitic texture and the presence of spinel exsolutions, as well as generally low Mg#s (~ 86) in orthopyroxene and differences between Mg#s in orthopyroxene from coarse- and fine-grained orthopyroxene-rich xenoliths, all imply the role of fractional crystallization. This, in combination with the absence of fibrous orthopyroxene containing olivine inclusions, suggest that these xenoliths did

Table 3b

LA-ICP-MS analyses of clinopyroxene from East Serbian depleted xenoliths

Sample no.	M/SB4		M/SB5				
	Cpx1	Cpx2	Cpx1	Cpx2	Cpx3	Cpx4	Cpx5
Li	36.5	11.4	38.0	42.4	42.0	0.7	0.6
Sc	64.4	64.2	83.0	83.9	89.4	85.9	85.8
Ti	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
V	199	198	166	155	153	140	131
Cr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	25.8	32.3	32.2	21.1	21.8	19.1	19.1
Ni	567	715	757	434	452	429	430
Rb	0.22	0.78	0.39	0.22	0.07	b.d.l.	b.d.l.
Sr	219.3	425.9	169.6	176.5	161.6	160.8	162.4
Y	1.24	1.27	2.72	2.65	1.89	2.31	2.23
Zr	3.51	3.37	6.26	5.56	4.49	3.45	3.63
Nb	3.32	0.66	1.06	0.53	b.d.l.	b.d.l.	b.d.l.
Ba	1.3	0.8	4.5	5.4	b.d.l.	b.d.l.	0.3
La	2.95	4.61	2.40	2.30	1.81	1.30	1.91
Ce	6.92	9.64	6.16	5.99	5.01	5.01	4.95
Pr	0.74	0.93	0.79	0.83	0.70	0.64	0.67
Nd	2.8	3.3	3.5	3.6	3.0	2.7	2.7
Sm	0.5	b.d.l.	0.8	0.8	0.6	0.3	0.4
Eu	0.2	0.2	0.2	0.3	0.1	0.3	0.1
Gd	b.d.l.	0.3	0.6	0.6	0.5	0.4	0.5
Tb	b.d.l.	b.d.l.	0.10	0.11	0.10	b.d.l.	b.d.l.
Dy	0.4	0.4	0.6	0.4	0.5	0.5	0.4
Ho	0.05	b.d.l.	0.10	0.08	0.12	0.08	0.08
Er	0.19	0.26	b.d.l.	0.30	0.26	0.27	0.25
Tm	b.d.l.	0.04	0.04	0.06	0.07	b.d.l.	b.d.l.
Yb	0.2	0.2	0.3	0.4	0.4	0.2	b.d.l.
Lu	0.05	0.05	0.06	b.d.l.	b.d.l.	b.d.l.	0.06
Hf	b.d.l.	0.2	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.2
Ta	b.d.l.	0.1	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Pb	0.8	1.0	0.9	0.7	1.0	0.6	0.5
Th	0.4	0.3	0.3	0.3	0.3	0.2	0.2
U	0.09	0.04	0.04	0.04	b.d.l.	0.03	0.03

not originate due to, for instance, deserpentinization in the upper mantle (e.g. [Arai and Kida, 2000](#)) or metasomatic reactions (e.g. [McInnes et al., 2001](#); [Bell et al., 2005](#)). Hence, it was concluded that these orthopyroxenites were formed by fractionation of a SiO₂-saturated and high-Mg (boninite-like?) primary magma with ~54–55 wt.% SiO₂ and Mg# > 0.65. Such magmas require melting of a highly depleted mantle source which is commonly found in fore-arc settings where melting conditions are provided by a supply of hydrous fluids. In general, the East Serbian orthopyroxene-rich xenoliths are comparable to similar orthopyroxene-rich rocks reported in sub-arc settings (e.g. [Wang et al., 2002](#)) or in ophiolitic sequences ([Edwards and Malpas, 1995](#); [Orberger et al., 1995](#); [Varfalvy et al., 1996, 1997](#)).

3. Discussion

3.1. Metasomatic enrichment

Evidence of metasomatism by mafic alkaline silicate melts is known from many xenolith suites and peridotite massifs and has been interpreted in a similar way (e.g. [Frey and Prinz, 1978](#); [Lloyd, 1987](#); [Harte, 1987](#); [Canil and Scarfe, 1989](#); [McGuire and Mukasa, 1997](#); [Wilshire, 1987](#); [Xu et al., 1996, 1998](#)). A detailed discussion of metasomatic effects is beyond the scope of the paper and will be presented elsewhere. Here we mention only the effects of refertilization which are not easy to distinguish texturally, because they are of prime importance in discussing a depletion signature.

According to variations in chemical compositions of their minerals, it is unlikely that the studied dunite, harzburgite and lherzolite xenoliths are related to progressive partial melting. The variations observed in Figs. 3 and 4 suggest: (i) that harzburgite and lherzolite ESLM xenoliths cannot be distinguished in respect to chemical composition of their minerals, i.e. they show a roughly similar depletion signature, and (ii) that dunites show stronger effects of metasomatism than do the harzburgites and lherzolites. Before we discuss problems of degree of depletion which is inferred from the composition of studied xenoliths, we first briefly address processes of metasomatic refertilization, which are strongest in the dunite xenoliths. The similarity between symplectites in dunite and secondary patchy assemblages found in ESLM harzburgite and clinopyroxene-poor lherzolite xenoliths implies a metasomatic origin. These metasomatic effects can be responsible for slightly lower Mg# in olivine and Cr# in spinel in the dunites. Therefore, in the following discussion we use only the composition of harzburgite and lherzolite xenoliths.

Even in the case of the harzburgites and lherzolites, slight metasomatic effects cannot be excluded. They are primarily related to the possibility that most of the clinopyroxene present in these xenoliths might have had a metasomatic origin or at least might have its composition changed during metasomatism. The problem of discrete addition of clinopyroxene to peridotites during metasomatic events and its implications for nomenclature of xenoliths was, for instance, already pointed out by Erlank et al. (1987). The trace element pattern of interstitial clinopyroxene from the ESLM xenoliths is generally similar to metasomatic clinopyroxene reported by Cvetković et al. (2004a), although the latter shows overall higher contents of all incompatible elements (see Fig. 7B).

3.2. Degree of depletion of the ESLM

Depleted harzburgites and lherzolites predominate in the East Serbian xenolith suite. They display regular variations in mineral chemistry (Fig. 3) that are commonly interpreted in terms of different degrees of partial melting and melt extraction from a fertile mantle source (Mysen and Kushiro, 1977; Jaques and Green, 1980; Frey et al., 1985). In contrast to most European xenolith suites and orogenic peridotites, there is an overlap in mineral chemical composition between the studied xenoliths and peridotites found in intraoceanic arc settings and ophiolites (Figs. 4–6). Finero is the only orogenic peridotite massif showing similar degrees of depletion as ESLM xenoliths, however, it is pervasively modally metasomatized. Zanetti et al. (1999) did not give much information about depletion processes which have affected Finero, but they considered that the metasomatic assemblages suggest a subduction-related setting. Recently, Bodinier et al. (2005) pointed out that the orogenic massif of Lherz was originally depleted (harzburgitic) which subsequently underwent a strong refertilization. Unfortunately, there are little data about the origin and extent of depletion of this lithospheric mantle section. Very recently Wittig et al. (2006) reported very high Lu/Hf and Hf-isotope ratios in clinopyroxene in the xenoliths from beneath the French Massif Central and interpret them as evidence of melt extraction in a mantle wedge during Variscan subduction.

The ESLM xenoliths are very poor in modal clinopyroxene (Fig. 2), like arc-related oceanic peridotites in general. This characteristic is not commonly found in peridotites which were depleted in mid-ocean ridge environments. Experiments show that clinopyroxene is exhausted at melting degrees of 20–30% in the pressure range of 1.5–4 Ga (Herzberg, 1992; Elthon, 1993; Hirose and Kushiro, 1993; Takahashi et al., 1993; Niu et al., 1997; Walter, 1998). In this context, an important part of the interpretation is an estimation of the degree of melting. Trace element composition of residual clinopyroxene has been extensively used for such purposes because clinopyroxene accounts for 70–100% of the HREE and 40–60% of LREE contents of whole rock peridotites (e.g. Wiechert et al., 1997). We used the approach of Norman (1998) to estimate the degree of fractional melting on the basis of Y_N and Yb_N contents in clinopyroxene (Fig. 8A). The obtained values indicate up to 20% of melting which is at the lower end of the melting range for the clinopyroxene-out in the spinel stability field suggested by the experiments. This method assumes that metasomatism does not change the HREE contents of clinopyroxene. This is explained by a much slower HREE chromatographic front associated with melt porous flow (Navon and Stolper, 1987). However, there are examples in which clinopyroxene itself was precipitated from metasomatic melts (Simon et al., 2003). Thus, REE-enriched clinopyroxene could have been produced either via direct precipitation of small isolated crystals or by recrystallization of already present residual clinopyroxene grains. An LREE-enriched pattern and generally elevated incompatible element concentrations in the ESLM clinopyroxene indicate that metasomatism probably resulted in addition of secondary clinopyroxene and it may also have caused a slight elevation of HREE contents in the primary clinopyroxene, perhaps associated with small amounts of trapped melts. In Fig. 8A the plotted Y_N and Yb_N contents of clinopyroxenes of a clear metasomatic origin follow the trend of more fertile residual compositions. This suggests that metasomatic infiltration, at least in some

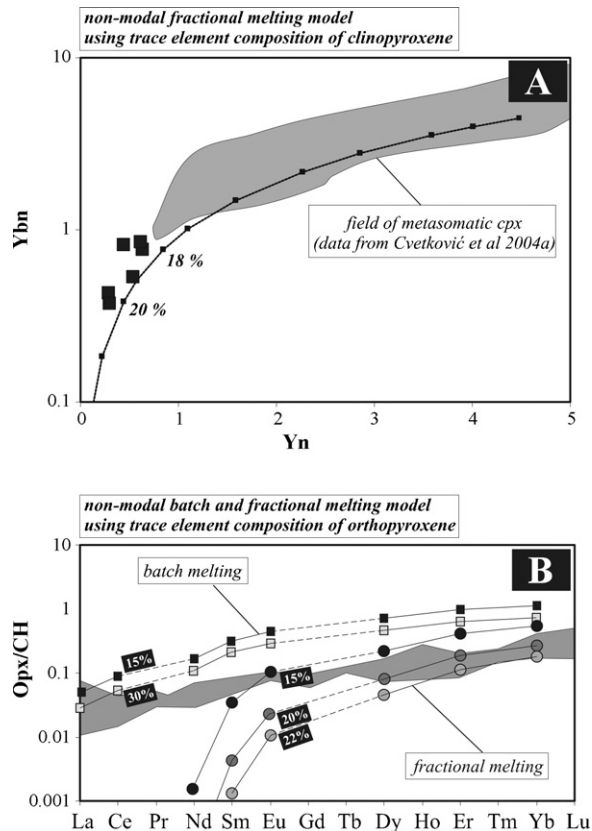


Fig. 8. (A) A fractional melting model showing change in Y_N and Y_{bn} contents in residual diopside assuming a primitive mantle source (McDonough and Sun, 1995). The approach of Norman (1998) with $Melt/CpxD=0.42$ for Y and 0.40 for Yb, and $CpxC_0=0.2$ has been used. (B) Non-modal batch and fractional melting models of REE concentrations in residual orthopyroxene compared with REE contents in orthopyroxene from depleted ESLM xenoliths. A spinel peridotite mantle source with the following modal composition: 0.55 Ol 0.25 Opx, 0.18 Cpx and 0.02 Sp was used; the melting mode was assumed to be 0.1 olivine, 0.2 orthopyroxene, 0.68 clinopyroxene and 0.2 spinel. Melting equations of Johnson et al. (1990) and partition coefficients after Johnson et al. (1990) and Ozawa and Shimizu (1995).

cases, was characterized by complete solidification and equilibration near solidus conditions, resulting in the lack of textural evidence and producing fertile peridotites with compositions that will roughly plot on the element covariation trends related to depletion (Bodinier and Godard, 2003).

Following the approach of Parkinson et al. (2003) we used REE concentrations of orthopyroxene to estimate the extent of melting in the ESLM. The results of non-modal fractional and batch melting models are given in Fig. 8B (see caption for Fig. 8B for explanation and conditions used for modeling). For most REEs only very high degrees of batch melting ($\gg 30\%$) can produce the REE concentrations in orthopyroxene. On the other hand, the observed HREE concentrations in residual orthopyroxene are produced by 20–22% of a non-modal fractional melting. Much higher LREE concentrations in the ESLM orthopyroxene are most likely due to metasomatic overprints.

Summarizing, mineral chemistry data provide strong evidence that the ESLM underwent a very high degree of depletion by extraction of basaltic melts, probably approaching a clinopyroxene-out point. Such high depletion is not normally found in relatively young (<1 Ga) subcontinental lithosphere. Griffin et al. (1999) have shown a striking increase in degree of depletion in the mantle from Phanerozoic (<1 Ga), to Proterozoic (2.5–1 Ga) to Archean (>2.5 Ga) regions. A possibility that the mantle underneath East Serbia is very old (>1 Ga) is not supported by geological evidence. This region consists of Palaeozoic microcontinents which docked to the Moesian platform slightly before the Permian (Krstić and Karamata, 1992). However, it is known that many younger crustal sections overlie mantle segments which reveal old (Proterozoic) Re–Os depletion ages (e.g. Handler et al., 1997; Alard et al., 2002). Therefore, the geological evidence must be taken with some caution, at least until Re–Os isotope data became available for the ESLM.

Table 4
Results of thermometric calculations (in °C)

Sample	Rock	[BKN]	[KB]1	[KB]2	[Wells]	[BM]	[Ca-in-opx]	[cpx]	[OW]
X-6	HZ						955		712
X-9small	HZ						1033		
K-13	HZ	842	1176	1118	870	798	1002	828	664
K-19	HZ						969		770
x 20-15	HZ	862	1142	1206	894	818	1015	849	654
M/SB4	HZ	950	1160	993	949	906	974	944	693
M/SB5	HZ	952	1168	1000	951	907	971	951	639
stz 20-3	HZ						1001		639
stz 20-4	HZ						987		703
stz 20-9	HZ						1025		695
stz 20-11	HZ						1019		630
stz 20-12	HZ	967	1172	1058	943	904	1010	941	620
X-11/2	LHZ						973		727
sb 4	LHZ						959		695
x 20-1a	LHZ						853		640
x 20-7	LHZ	819	1186	1035	857	779	965	805	647
stz 20-1	LHZ	851	1142	1076	861	787	997	815	
stz 20-7	LHZ						979		604

Explanation: [BKN]—Two pyroxene-thermometer of Brey and Köhler (1990); [KB]1—Fe–Mg-ol/cpx thermometer (Brey and Köhler, 1990); [KB]2—Ca-ol/cpx-exchange (Köhler and Brey, 1990) used as thermometer; [Wells]—two pyroxene-thermometer (Wells, 1977); [BM]—two pyroxene-thermometer (Bertrand and Mercier, 1985); [Ca-in-opx]—Ca-in-opx thermometer (Brey and Köhler, 1990); [cpx]—cpx thermometer (Nimis and Taylor, 2000); [OW]—Fe–Mg-ol/sp thermometer (O'Neill and Wall, 1987).

3.3. Thermometric calculations

Table 4 shows temperature estimates for the ESLM harzburgite and lherzolite xenoliths. The thermometric calculations were performed using mineral analyses from Table 1 and applying different thermometers (see explanation of Table 4). The obtained temperatures are somewhat lower than those reported by Cvetković et al. (2004a). The reason for this may be that, in the present study, clinopyroxene which is texturally metasomatic in origin was omitted from the calculations. Thermometers based on the olivine–clinopyroxene cation exchange ([KB1] and [KB2]) reveal less uniform and considerably higher temperatures (above 1000 °C) than the two-pyroxene, single-pyroxene and olivine–spinel thermometers (600–950 °C). This suggests that olivine and clinopyroxene record equilibration during metasomatic events related to host alkaline magmatism. These thermal perturbations produced smaller effects on orthopyroxene and on cation exchange between orthopyroxene and clinopyroxene and between olivine and spinel.

The lower range of the obtained temperatures might indicate temperature conditions in the ESLM before the host alkaline magmatism occurred. In this context, it can be stressed that they are lower than those reported from xenoliths found in adjacent extensional area of the Pannonian basin (e.g. Falus et al., 2000; Embey-Isztin et al., 2001) but are more similar to recent subduction zones (e.g. Franz et al., 2002).

3.4. A possible geodynamic scenario

The composition of the subcontinental lithospheric mantle varies systematically with respect to the age of the last tectonothermal event in the overlying crust (Griffin et al., 2003). Therefore, information about its composition yields important geodynamic constraints. The uncommonly depleted signature displayed by East Serbian xenoliths, especially anomalously low Al₂O₃ in orthopyroxene and high Cr# in spinel, and low temperature estimates calculated on the basis of minerals and mineral pairs unaffected by host alkaline magmatism, indicate that the regions of the ESLM sampled by Palaeogene basanites are akin to a sub-arc oceanic mantle wedge. The observed compositional variations along with geological evidence rules out a possibility that the ESLM can represent an Archean mantle. On the other hand, the compositional and geological evidence is not sufficient to exclude a possibility that in this region Proterozoic mantle slices might be coupled with presumably younger crust, as was reported from other areas (e.g. Handler et al., 1997). However, the presence and character of orthopyroxene-rich xenoliths, interpreted as cumulates from a boninite-

like magmas, can be regarded as an independent evidence that the ESLM represents mantle that originated in an arc environment.

Incorporation of younger mantle to older lithospheric domains is relatively rarely reported (e.g. Xu and Bodinier, 2004). Nevertheless, Boyd (1989) argued that Mg-rich, ultradepleted xenoliths from mafic volcanics erupted in continental areas marginal to cratons may be derived from oceanic lithosphere that has been accreted to Archean nuclei. Furthermore, peridotite xenoliths from the Colorado Plateau were interpreted as fragments of an island-arc or oceanic lithosphere accreted to the continent during the Proterozoic (Roden et al., 1990).

To fully elaborate the problem of relicts of a suboceanic arc wedge beneath East Serbia would require a number of additional geological and geochronological details, particularly the age of mantle depletion. This information is lacking for this xenolith suite. Therefore, this paper offers only a possible scenario for Pre-Palaeogene geodynamics of this region rather than giving an unequivocal explanation. Taking into account the existing terrane framework, we present some evidence suggesting that a slice of the arc-mantle could have been accreted to the subcontinental lithosphere during closure of an Upper Jurassic Tethyan oceanic realm. This idea has also been proposed by Prelević et al. (2007), who established a crucial genetic link between lamproites and oceanic lithospheric mantle originated in a suprasubduction zone environment, which is accreted and further metasomatized during orogenesis by the subduction of crustal sediments (see below).

The Dinaride branch of the Alpine orogen underwent complex convergent-collisional processes at the Mesozoic/Cenozoic transition. This produced a composite suture zone of dismembered ophiolite bodies and sedimentary trench units. The prevailing opinion is that the Mesozoic Tethys consisted of several partly coeval oceanic basins (e.g. Robertson and Karamata, 1994; Flower and Dilek, 2003; Robertson, 2002). This interpretation is mainly based on the ophiolitic evidence for repeated episodes of subduction and backarc opening prior to the final closure of Tethyan oceans. One of the ophiolitic sub-units is the easternmost part of the Vardar zone which continues to the Mures and Guevgueli ophiolites to the north and south, respectively (Anđelković and Lupu, 1967). Eastern Vardar zone ophiolites are associated with a pre-Upper Jurassic trench complex and covered by an Upper Jurassic overstep sequence (Dimitrijević, 1974; Karamata et al., 1996/1997). This unit differs from the other Balkan Peninsula ophiolites because it is almost entirely composed of igneous members of ophiolites with rare cumulitic peridotites and because it contains calc-alkaline intermediate/acid rocks with a volcanic-arc affinity (Bortolotti et al., 2002; Resimić-Šarić et al., 2000). In addition, within the same ophiolitic zone, Marroni et al. (2004) have found boninitic dykes that also suggest subduction processes. Accordingly, the geological evidence implies that the closure of an Upper Jurassic Tethyan oceanic realm, which left behind relicts as the eastern Vardar Zone, was associated with an intra-oceanic subduction, probably followed by immature volcanic arc-continent collision. During this closure, small blocks of the upper oceanic crust may have been scrapped off while the rest of the plate was subducted. Such an event is in accordance with modelling of arc-continent collision by Boutelier et al. (2003). Our study suggests that relicts of the lithosphere related to this earlier intra-oceanic subduction may have been accreted to the subcontinental mantle.

Additional constraints of the nature of lithospheric mantle beneath this region are also provided by later igneous events, in particular by the Oligocene–Pliocene ultrapotassic magmatism which predominantly occurred along the Vardar Zone. Prelević et al. (2005) recognized two distinctive rock suites in the east and west of the zone and argued that they were related to lithospheric segments of different metasomatic history. Very low Al_2O_3 contents and extremely MgO-rich olivines of these volcanic rocks suggest a very high degree of pre-metasomatic depletion of their lithospheric mantle source.

A geodynamic model suggested below is aimed at explaining the presence of an oceanic sub-arc mantle slice within a subcontinental environment. Although this paper focuses on the Upper Jurassic episode, the model comprises the whole period of closure of the Tethyan oceanic realm. The major reason for that is to present the whole tectonomagmatic history of the ESLM, from its formation in Upper Jurassic times until the entrainment in alkaline rocks during the Palaeocene/Eocene. It is, therefore, necessary to underline the geological evidence and assumptions, which are of critical importance for the model. Firstly, we take into account the growing evidence that, after the Upper Jurassic collision along the present eastern Vardar Zone, an oceanic realm still remained open in the west (e.g. Karamata, 2006; Schmid et al., 2005). Accordingly, in our model, closure of the Vardar Tethys ocean occurred in two phases, Middle/Upper Jurassic and Cretaceous one, respectively. Secondly, we suggest an eastward subduction in both phases. For the Jurassic convergence this is suggested by other authors (e.g. Robertson and Karamata, 1994) and is essential for explaining the accretion of a suboceanic mantle slice beneath the southwest European margin. An eastward Late Cretaceous convergence is also suggested by the Late Cretaceous–Palaeogene magmatism in East Serbia, which youngs

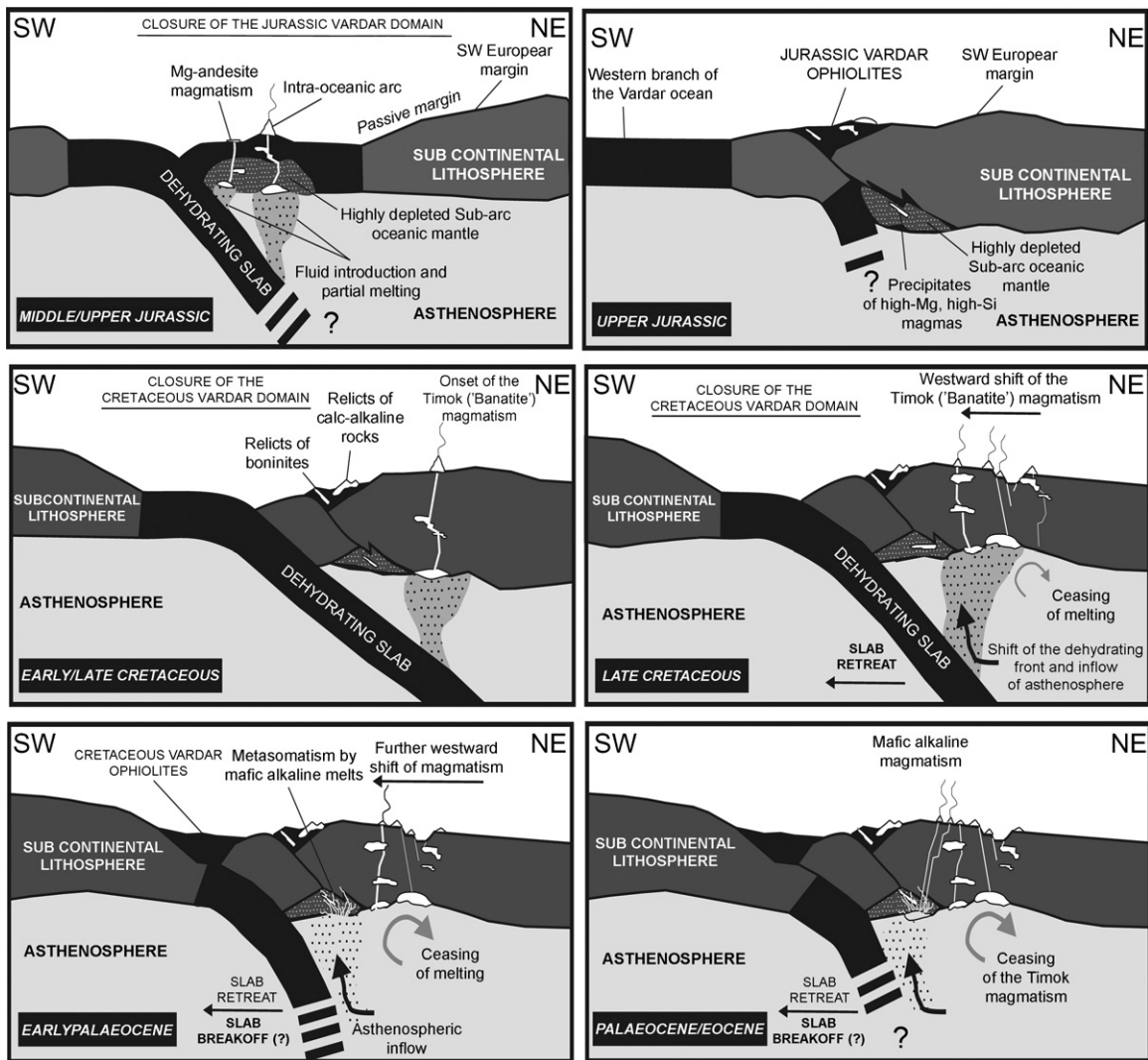


Fig. 9. A possible geodynamic model of the Late Mesozoic/Early Tertiary evolution of the Central Balkan Peninsula. See text for explanations.

towards the west, i.e. towards the presumed trench (von Quadt et al., 2003; Clark and Ullrich, 2004; Cvetković et al., 2004b).

Our model illustrated in Fig. 9 is divided into six stages. The first two display the closure of the Jurassic eastern Vardar ocean. This is related to the formation of an intraoceanic volcanic arc, remnants of which are found in many places as ophiolite slices along the present eastern Vardar zone (Resimić-Šarić et al., 2000). Partial melting in the fore-arc region produced boninites, presently found on the presumed Jurassic suture (see Fig. 1). The orthopyroxene-rich xenoliths found in East Serbian mafic alkaline magmas could possibly be relicts of high pressure cumulates of similar magmas. The upper Jurassic closure terminated by obduction of the upper part of the sub-arc oceanic lithosphere, as well as by accretion of the highly depleted mantle lithosphere. Afterwards, during the Cretaceous, convergence and closure of the western branch of the Vardar ocean occurred. The eastward subducting and dehydrating slab produced a volcanic front along the present easternmost margin of the Timok ('Banatite') calc-alkaline magmatic complex. The Late Cretaceous magmatic events are characterized by a constant westward (trenchward) shift of magmatism that was followed by formation of Palaeogene basanites. This can imply a continual roll-back or even breakoff of the subducting plate. The precursors of basanitic magmatism, i.e. small scale asthenospheric melts, metasomatized the base of the lithosphere and produced the metasomatised xenoliths. Finally, partial melts at the asthenosphere–lithosphere boundary produced basanite magmas which brought to the surface fragments of the highly depleted ESLM.

Although many aspects of this interpretation may be arbitrary or insufficiently constrained, it sheds much light on the terrane organization in the Balkan Peninsula. We suggest here that the formation of terrane collages, usually resulting from complicated convergent/collision/accretion processes, can be better understood if compositional constraints on lithospheric roots of the terranes are available. Information from mantle xenoliths erupted in post-orogenic settings can be a very powerful tool in understanding terrane assembly when integrated into the existing geological data-base. Study of such xenoliths, which are not related to massive extension processes and hot mantle upwellings, can be particularly significant.

4. Concluding remarks

Mantle xenoliths found in Palaeogene basanitic rocks in East Serbia have more depleted modal and mineral chemistry characteristics than do xenoliths of most European off-cratonic suites, as well as most orogenic peridotites. They are compositionally more similar to refractory peridotites found in modern oceanic sub-arc settings and ophiolite peridotites. This suggests that the lithosphere underneath East Serbia likely contains some parts of an oceanic mantle of supra-subduction zone affinity. A possible geodynamic scenario involves an Upper Jurassic closure of the eastern Vardar ocean during which upper parts of the oceanic-arc crust were obducted while parts of the subducting lithosphere were accreted to the subcontinental mantle.

Acknowledgements

This work has been supported by a Lise Meitner Fellowship granted to V. Cvetković by the Austrian Science Foundation (M832 N10) and by Ministry of Science and Environment Protection of the Republic of Serbia (Project 146013). Serbian Academy of Sciences and Arts (Geodynamic Project) is acknowledged. D.P. has been supported through the Deutsche Forschungsgemeinschaft (DFG) within the project Fo 181/18-1. We are thankful to Volker Hoeck for helpful discussions and comments on an earlier version of the manuscript. Helpful reviews from Riccardo Vannucci and Bill Griffin as well as editorial handling of Giorgio Ranalli were greatly appreciated.

References

- Alard, O., Griffin, W.L., Pearson, N.G., Lorand, J.P., O'Reilly, S., 2002. New insights into the Re/Os systematics of sub-continental lithospheric mantle from in-situ analysis of sulfides. *Earth Planet. Sci. Lett.* 203, 651–663.
- Andelković, M., Lupu, M., 1967. Die Geologie der Šumadija und Mures Zone. *Carp. Balc. Assoc. 8th Cong. Rep. I*, 15–28.
- Arai, S., 1994. Characterization of spinel peridotites by olivine–spinel compositional relationships: review and interpretation. *Chem. Geol.* 111, 191–204.
- Arai, S., Ishimaru, S., Okrugin, V., 2003. Metasomatized harzburgite xenoliths from Avacha volcano as fragments of mantle wedge of the Kamchatka arc: implication for the metasomatic agent. *Island Arc* 12, 233–246.
- Arai, S., Kida, M., 2000. Origin of fine-grained peridotite xenoliths from Iraya volcano of Batan Island, Philippines: deserpentinization or metasomatism at the wedge mantle beneath an incipient arc? *Island Arc* 9, 458–471.
- Bali, E., Szabo, C., Vaselli, O., Török, K., 2002. Significance of silicate melt pockets in upper mantle xenoliths from the Bakony-Balaton Highland volcanic field, western Hungary. *Lithos* 61 (1–2), 79–102.
- Beccaluva, L., Bianchini, G., Bonadiman, C., Siena, F., Vaccaro, C., 2004. Coexisting anorogenic and subduction-related metasomatism in mantle xenoliths from the Betic Cordillera (southern Spain). *Lithos* 75, 67–87.
- Beccaluva, L., Bianchini, G., Coltorti, M., Perkins, W.T., Siena, F., Vaccaro, C., Wilson, M., 2001. Multistage evolution of the European lithospheric mantle: new evidence from Sardinian peridotite xenoliths. *Contrib. Mineral. Petrol.* 142 (3), 284–297.
- Bell, D.R., Gregoire, M., Grove, T.L., Chatterjee, N., Carlson, R.W., Buseck, P.R., 2005. Silica and volatile-element metasomatism of Archean mantle: a xenolith-scale example from the Kaapvaal Craton. *Contrib. Mineral. Petrol.* 150, 251–267.
- Bernstein, S., Kelemen, P.B., Brooks, B., Kent, C.K., 1998. Depleted spinel harzburgite xenoliths in Tertiary dykes from East Greenland: restites from high degree melting. *Earth Planet. Sci. Lett.* 154 (1–4), 221–235.
- Bertrand, P., Mercier, J.-C.C., 1985. The mutual solubility of coexisting ortho- and clinopyroxene: toward an absolute geothermometer for the natural system? *Earth Planet. Sci. Lett.* 76, 109–122.
- Berza, T.E., Constantinescu, E., Vlad, S.N., 1998. Upper Cretaceous magmatic series and associated mineralisation in the Carpathian-Balkan Orogen. *SRG-SEG Joint Symposium on Granite types and mineralization, Tokyo, Japan. Soc. Res. Geol.* 48, 291–306.
- Bodinier, J.-L., Godard, M., 2003. Orogenic, ophiolitic, and abyssal peridotites. In: Carlson, R.W. (Ed.), *Treatise on Geochemistry, Mantle and Core*, vol. 2. Elsevier Science Ltd., pp. 103–170.
- Bodinier, J.L., Le Roux, V., Lenoir, X., Alard, O., Garrido, C., Tommasi, A., Dautria, J.-M., Vauchez, A., Lorand, J.-P., Gervilla, F., 2005. Partial melting in Ronda versus refertilization in Lherz: two contrasting effects of lithospheric thermal erosion documented in orogenic peridotites. *Lanzo Peridotite Workshop Abstr.* 30 (2), 177–178.

- Bortolotti, V., Marroni, M., Nicolae, I., Pandolfi, L., Principi, G., Saccani, E., 2002. Geodynamic implications of Jurassic Ophiolites associated with Island-Arc Volcanics, South Apuseni Mountains, Western Romania. *Int. Geol. Rev.* 44 (10), 938–955.
- Boutelier, D., Chemenda, A., Burg, J.P., 2003. Subduction versus accretion of intra-oceanic volcanic arcs: insight from thermo-mechanical analogue experiments. *Earth Planet. Sci. Lett.* 212, 31–45.
- Boyd, F.R., 1987. High- and low-temperature garnet peridotite xenoliths and their possible relation to the lithosphere–asthenosphere boundary beneath southern Africa. In: Nixon, P.H. (Ed.), *Mantle Xenoliths*. John Wiley, Chichester, pp. 403–412.
- Boyd, F.R., 1989. Compositional distinction between oceanic and cratonic lithosphere. *Earth Planet. Sci. Lett.* 96 (1–2), 15–26.
- Brey, G.P., Köhler, T.P., 1990. Geothermobarometry in four phases lherzolites. II. New thermobarometers and practical assessment of existing thermobarometers. *J. Petrol.* 31, 1353–1378.
- Canil, D., Scarfe, C.M., 1989. Origin of phlogopite in mantle xenoliths from Kostal Lake, Wells Gray Park, British Columbia. *J. Petrol.* 30, 1159–1179.
- Clark, A.H., Ullrich, T.D., 2004. ^{40}Ar – ^{39}Ar age data for andesitic magmatism and hydrothermal activity in the Timok Massif, eastern Serbia: implications for metallogenetic relationships in the Bor copper–gold subprovince. *Mineralium Deposita* 39, 256–262.
- Coish, R.A., Gardner, P., 2004. Suprasubduction-zone peridotite in the northern USA Appalachians: evidence from mineral composition. *Mineral. Mag.* 68 (4), 699–708.
- Cvetković, V., Lazarov, M., Downes, H., Prelević, D., 2007. Modification of the subcontinental mantle beneath east Serbia: evidence from orthopyroxene-rich xenoliths. *Lithos*, in press.
- Cvetković, V., Downes, H., Prelević, D., Jovanović, M., Lazarov, M., 2004a. Characteristics of the lithospheric mantle beneath east Serbia inferred from ultramafic xenoliths in Palaeogene basanites. *Contrib. Mineral. Petrol.* 148 (3), 335–357.
- Cvetković, V., Prelević, D., Downes, H., Jovanović, M., Vaselli, O., Pecskey, Z., 2004b. Origin and geodynamic significance of Tertiary postcollisional basaltic magmatism in Serbia (central Balkan Peninsula). *Lithos* 73, 161–186.
- Dimitrijević, M.D., 1974. Dinarides: a model based on New Global Tectonics. In: *Metallogeny and Concept of Geotectonic Development of Yugoslavia*. Faculty of Mining and Geology, University of Belgrade, Department of Economic Geology, Belgrade, pp. 119–151.
- Downes, H., Kostoula, T., Jones, A.P., Beard, A.D., Thirlwall, M.F., Bodinier, J.-L., 2002. Geochemistry and Sr–Nd isotopic compositions of mantle xenoliths from the Monte Vulture carbonatite-melilitite volcano, central southern Italy. *Contrib. Mineral. Petrol.* 144 (1), 78–92.
- Downes, H., 2001. Formation and modification of the shallow sub-continental lithospheric mantle: a review of geochemical evidence from ultramafic xenolith suites and tectonically emplaced ultramafic massifs of Western and Central Europe. *J. Petrol.* 42, 230–250.
- Edwards, S.J., Malpas, J., 1995. Multiple origins for mantle harzburgites: examples from the Lewis Hills, Bay of Islands ophiolite, Newfoundland. *Can. J. Earth Sci.* 32, 1046–1057.
- Elthon, D., 1993. Crystallization of mid-ocean ridge basalts. *Eur. J. Mineral.* 5, 1025–1037.
- Embey-Isztin, A., Dobosi, G., Altherr, R., Meyer, H.P., 2001. Thermal evolution of the lithosphere beneath the western Pannonian Basin; evidence from deep-seated xenoliths. *Tectonophysics* 331 (3), 285–306.
- Erlank, A.J., Waters, F.G., Hawkesworth, C.J., Haggerty, S.E., Allsopp, H.L., Rickard, R.S., Menzies, M., 1987. Evidence for mantle metasomatism in peridotite nodules from the Kimberley pipes South Africa. In: Menzies, M., Hawkesworth, C.J. (Eds.), *Mantle Metasomatism*. Academic Press, London, pp. 221–309.
- Falus, G., Szabo, Cs., Vaselli, O., 2000. Mantle upwelling within the Pannonian Basin: evidence from xenolith lithology and mineral chemistry. *Terra Nova* 12, 295–302.
- Flower, M.F.J., Dilek, Y., 2003. Arc-trench rollback and forearc accretion. 1. A collision-induced mantle flow model for Tethyan ophiolites. In: Dilek, Y., Robinson, P.T. (Eds.), *Ophiolites in Earth History*, vol. 218. Geological Society Spec. Publ., London, pp. 21–41.
- Franz, L., Becker, K.-P., Kramer, W., Herzig, P.M., 2002. Metasomatism mantle xenoliths from the Bismarck Microplate (Papua New Guinea)—thermal evolution, geochemistry and extent of slab-induced metasomatism. *J. Petrol.* 43 (2), 315–343.
- Frey, F., Green, D.H., 1974. The mineralogy, geochemistry and origin of lherzolite inclusions in Victorian basanites. *Geochim. Cosmochim. Acta* 38, 1023–1059.
- Frey, F.A., Prinz, M., 1978. Ultramafic inclusions from San Carlos, Arizona: petrologic and geochemical data bearing on their petrogenesis. *Earth Planet. Sci. Lett.* 38, 129–176.
- Frey, F.A., Suen, C.J., Stockman, H.W., 1985. The Ronda high temperature peridotite: geochemistry and petrogenesis. *Geochim. Cosmochim. Acta* 49, 2469–2491.
- Gregoire, M., McInnes, B.I.A., O'Reilly, S., 2001. Hydrous metasomatism of oceanic sub-arc mantle, Lihir, Papua New Guinea. Part 2. Trace element characteristics of slab-derived fluids. *Lithos* 59, 91–108.
- Griffin, W.L., Shee, S.R., Ryan, C.G., Win, T.T., Wyatt, B.A., 1999. Harzburgite to lherzolite and back again: metasomatic processes in ultramafic xenoliths from the Wesselton Kimberlite, Kimberley, South Africa. *Contrib. Mineral. Petrol.* 134 (2–3), 232–250.
- Griffin, W.L., O'Reilly, S.Y., Abe, N., Aulbach, S., Davies, R.M., Pearson, N.J., Doyle, B.J., Kivi, K., 2003. The origin and evolution of Archean lithospheric mantle. *Precamb. Res.* 127, 19–41.
- Griffin, W.L., O'Reilly, S.Y., Ryan, C.G., Gaul, O., Ionov, D., 1998. Secular variation in the composition of subcontinental lithospheric mantle. In: Braun, J., Dooley, J.C., Goleby, B.R., van der Hilst, R.D., Klootwijk, C.T. (Eds.), *Structure and Evolution of the Australian Continent, Geodynamics*, vol. 26. American Geophysics Union, Washington, DC, pp. 1–26.
- Handler, M.R., Bennett, V.C., Esat, T.M., 1997. The persistence of off-cratonic lithospheric mantle: Os isotopic systematics of variably metasomatized southeast Australian xenoliths. *Earth Planet. Sci. Lett.* 151, 61–75.
- Harte, B., 1987. Metasomatic events recorded in mantle xenoliths: an overview. In: Nixon, P.H. (Ed.), *Mantle Xenoliths*. John Wiley, Chichester, pp. 625–640.
- Herzberg, C., 1992. Depth and degree of melting of komatiites. *J. Geophys. Res.* 97, 4521–4540.
- Herzberg, C.T., 1993. Lithosphere peridotites of the Kaapvaal craton. *Earth Planet. Sci. Lett.* 120, 13–29.

- Herzberg, C., 2004. Geodynamic information in peridotite petrology. *J. Petrol.* 45 (12), 2507–2530.
- Hirose, K., Kushiro, I., 1993. Partial melting of dry peridotites at high pressures: determination of compositions of melts segregated from peridotite using aggregates of diamond. *Earth Planet. Sci. Lett.* 114, 477–489.
- Jaques, A.L., Green, D.H., 1980. Anhydrous melting of peridotite at 0–15 kb pressure and the genesis of tholeiitic basalts. *Contrib. Mineral. Petrol.* 73, 287–310.
- Johnson, K.T.M., Dick, H.J.B., Shimizu, N., 1990. Melting in the oceanic upper mantle: an ion microprobe study of diopsides in abyssal peridotites. *J. Geophys. Res. B Solid Earth Planets* 95 (3), 2661–2678.
- Jovanović, M., Downes, H., Vaselli, O., Cvetković, V., Prelević, D., Pecsckay, Z., 2001. Paleogene mafic alkaline volcanic rocks of East Serbia. *Acta Vulcanol.* 13 (1–2), 159–173.
- Karamata, S., 2006. The geological framework of the Balkan peninsula: its origin due to the approach, collision and compression of Gondwanian and Eurasian units. *Geol. Soc. Lond. Spec. Publ.*, In: Robertson, A.H.F., Mountrakis, D. (Eds.), *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications 260, 155–178.
- Karamata, S., Krstić, B., Dimitrijević, D.M., Dimitrijević, M.N., Knežević, V., Stojanov, R., Filipović, I., 1996/1997. Terranes between the Moesian plate and the Adriatic sea. IGCP Project No. 276, terrane maps and terrane descriptions. *Ann. Geol. Pays Hellen.* 37, 429–477.
- Köhler, T.P., Brey, G.P., 1990. Calcium exchange between olivine and clinopyroxene calibrated as a geothermometer for natural peridotites from 2 to 60 kb with applications. *Geochim. Cosmochim. Acta* 54, 2375–2388.
- Krstić, B., Karamata, S., 1992. Terranes of the Carpatho-Balkanides of the eastern Serbia. *Comptes rendus des Séances de la Société Serbe de Géologie. Livre Jubilaire 1891–1991*, 57–74.
- Kushiro, I., 1969. The System Forsterite-Diopside-Silica With and Without Water at High Pressures, The Schairer volume 267-A. Kline Geology Laboratory Yale University, New Haven, CT, United States, pp. 269–294.
- Lloyd, F.E., 1987. Mantle metasomatic fluids in spinel lherzolites and alkali clinopyroxenites from the West Eifel and southwest Uganda. In: Menzies, M., Hawkesworth, C.J. (Eds.), *Mantle Metasomatism*. Academic Press, London, pp. 91–123.
- Maaloe, S., Aoki, K., 1977. The major element composition of the upper mantle estimated from the composition of lherzolites. *Contrib. Mineral. Petrol.* 63, 161–173.
- Marroni, M., Pandolfi, L., Saccani, E., Zelić, M., 2004. Boninites from the Kopaonik area (southern Serbia): new evidences for suprasubduction ophiolites in the Vardar Zone. *Ophioliti* 29 (2), 251–254.
- McInnes, B.I.A., Gregoire, M., Binns, R.A., Herzig, P.M., Hannington, M.D., 2001. Hydrous metasomatism of oceanic sub-arc mantle, Lihir Papua New Guinea: petrology and geochemistry of fluid-metasomatised mantle wedge xenoliths. *Earth Planet. Sci. Lett.* 188 (1–2), 169–183.
- McDonough, W.F., Sun, S.-s., 1995. The composition of the Earth. *Chem. Geol.* 120, 223–253.
- McGuire, A.V., Mukasa, S.B., 1997. Magmatic modification of the uppermost mantle beneath the Basin and Range to Colorado Plateau transition zone: evidence from xenoliths, Wikieup, Arizona. *Contrib. Mineral. Petrol.* 128 (1), 52–65.
- Menzies, M.A., 1983. Mantle ultramafic xenoliths in alkaline magmas: evidence for mantle heterogeneity modified by magmatic activity. In: Hawkesworth, C.J., Norry, M.J. (Eds.), *Continental Basalts and Mantle Xenoliths*. Shiva, Nantwich, pp. 92–110.
- Morse, S.A., 1980. Kiglapait mineralogy. II: Fe–Ti oxide minerals and the activities of oxygen and silica. *J. Petrol.* 21 (4), 685–719.
- Mysen, B.O., Kushiro, I., 1977. Compositional variations of coexisting phases with degree of melting of peridotite in the upper mantle. *Am. Mineral.* 62, 843–865.
- Navon, O., Stolper, E., 1987. Geochemical consequences of melt percolation: the upper mantle as a chromatographic column. *J. Geol.* 95, 285–307.
- Niu, Y., Langmuir, C.H., Kinzler, R.J., 1997. The origin of abyssal peridotites: a new perspective. *Earth Planet. Sci. Lett.* 152 (1–4), 251–265.
- Nimis, P., Taylor, W.R., 2000. Single clinopyroxene thermobarometry for garnet peridotites. Part I. Calibration and testing of a Cr-in-Cpx barometer and an enstatite-in-Cpx thermometer. *Contrib. Mineral. Petrol.* 139, 541–554.
- Norman, M.D., 1998. Melting and metasomatism in the continental lithosphere: laser ablation ICPMS analysis of minerals in spinel lherzolites from eastern Australia. *Contrib. Mineral. Petrol.* 130 (3–4), 240–255.
- O'Neill, H.St.C., Wall, V.J., 1987. The Olivine–Orthopyroxene–Spinel oxygen geobarometer, the nickel precipitation curve, and the oxygen fugacity of the Earth's Upper Mantle. *J. Petrol.* 28 (6), 1169–1191.
- Orberger, B., Lorand, J.P., Girardeau, J., Mercier, J.C.C., Pitragool, S., 1995. Petrogenesis of ultramafic rocks and associated chromitites in the Nan Uttaradit ophiolite, Northern Thailand. *Lithos* 35, 153–182.
- Ozawa, K., Shimizu, N., 1995. Open-system melting in the upper mantle: constraints from the Hayachine-Miyamori ophiolite, northeastern Japan. *J. Geophys. Res.* 100 (B11), 22,315–22,335.
- Parkinson, I.J., Arculus, R.J., Eggins, S.M., 2003. Peridotite xenoliths from Grenada, Lesser Antilles, Island Arc. *Contrib. Mineral. Petrol.* 146, 241–262.
- Parkinson, I.J., Pearce, J.A., 1998. Peridotites from the Izu–Bonin–Mariana forearc (ODP Leg 125): evidence for mantle melting and melt–mantle interaction in a supra-subduction zone setting. *J. Petrol.* 39, 1577–1618.
- Pearson, D.G., Canil, D., Shirey, S.B., 2003. Mantle samples included in volcanic rocks: xenoliths and diamonds. In: Holland, H.D., Turekian, K.K. (Eds.), *Treatise on Geochemistry*, vol. 2. Elsevier, pp. 171–275.
- Prelević, D., Foley, S.F., Cvetković, V., 2007. A review of petrogenesis of Mediterranean Tertiary lamproites: a perspective from the Serbian ultrapotassic province. *Geol. Soc. Am. Spec. Publ.*, In: Beccaluva, L., Bianchini, G., Wilson, M. (Eds.), *Cenozoic Volcanism in the Mediterranean Area*. Geological Society of America Special Paper 418, pp. 113–129.
- Prelević, D., Foley, S., Romer, R.L., Cvetković, V., Downes, H., 2005. Tertiary Ultrapotassic volcanism in Serbia: constraints on petrogenesis and mantle source characteristics. *J. Petrol.* 46 (7), 1443–1487.
- Rampone, E.A., Hofmann, A.W., Piccardo, G.B., Vannucci, R., Bottazzi, P., Ottolini, L., 1995. Petrology, mineral and isotope geochemistry of the external Liguride peridotites (Northern Apennines, Italy). *J. Petrol.* 36 (1), 81–105.

- Resimić-Šarić, K., Cvetković, V., Karamata, S., 2000. Ophiolites of the Main Vardar basin: the Ophiolitic complex of Ždraljica (central Serbia) as an example. *Slov. Geol. Mag.* 6 (2–3), 314–315.
- Robertson, A.H.F., 2002. Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region. *Lithos* 65, 1–67.
- Robertson, A.H.F., Karamata, S., 1994. The role of subduction-accretion processes in the tectonic evolution of the Mesozoic Tethys in Serbia. *Tectonophysics* 234, 73–94.
- Roden, M.F., Smith, D., Murthy, V.R., 1990. Chemical constraints on lithosphere composition and evolution beneath the Colorado Plateau. *J. Geophys. Res.* 95, 2811–2831.
- Schmid, S.M., Fügenschuh, B., Ustaszewski, K., Spakman, W., Kissling, E., 2005. The Alps-Carpathians-Dinarides System: major tectonic units and deep structure. In: *Seventh Workshop on Alpine Geological Studies, Croatia*, pp. 185–186 (abstracts).
- Schilling, M., Conceicao, R.V., Mallmann, G., Koester, E., Kawashita, K., Herve, F., Morata, D., Motoki, A., 2005. Spinel-facies mantle xenoliths from Cerro Redondo, Argentine Patagonia: petrographic, geochemical, and isotopic evidence of interaction between xenoliths and host basalt. *Lithos* 82, 485–502.
- Simon, N.S.C., Irvine, G., Davies, G.R., Pearson, D.G., Carlson, R.W., 2003. The origin of garnet and clinopyroxene in ‘depleted’ Kaapvaal peridotites. *Lithos* 71, 289–322.
- Streckeisen, A., 1973. Plutonic Rocks. Classification and nomenclature recommended by the IUGS Subcommittee on the Systematics of Igneous Rocks. *Geotimes* 18 (10), 26–30.
- Takahashi, E., Shimazaki, T., Tsuzaki, Y., Yoshida, H., 1993. Melting study of a peridotite KLB-1 to 6.5 GPa, and the origin of basaltic magmas. In: Cox, K.G., McKenzie, D., White, R.S. (Eds.), *Melting and Melt Movement in the Earth*, vol. A342. Oxford University Press, Oxford, pp. 105–120.
- Varfalvy, V., Hébert, R., Bedard, J.H., 1996. Interactions between melt and upper-mantle peridotites in the North Arm Mountain massif, Bay of Islands ophiolite, Newfoundland Canada: Implications for the genesis of boninitic and related magmas. *Chem. Geol.* 129, 71–90.
- Varfalvy, V., Hébert, R., Bédard, J.H., Laflèche, M.R., 1997. Petrology and geochemistry of pyroxenite dykes in upper mantle peridotites of the North Arm Mountain massif, Bay of Islands ophiolite Newfoundland: Implications for the genesis of boninitic and related magmas. *Can. Mineralogist* 35, 543–570.
- Vaselli, O., Downes, H., Thirlwall, M., Dobosi, G., Coradossi, N., Seghedi, I., Szakacs, A., Vannucci, R., 1995. Ultramafic xenoliths in Plio-Pleistocene alkali basalts from the Eastern Transylvanian Basin: depleted mantle enriched by vein metasomatism. *J. Petrol.* 36 (1), 23–53.
- von Quadt, A., Peytcheva, I., Heinrich, Ch., Frank, M., Cvetković, V., Banješević, M., 2003. Evolution of the Cretaceous magmatism in the Apuseni-Timok-Srednogie metallogenic belt and implications for the geodynamic reconstructions: new insight from geochronology, geochemistry and isotope studies. In: *Final GEODE-ABCD Workshop Programme and Abstracts*, p. 60.
- Walter, M.J., 1998. Melting of garnet peridotite and the origin of komatiite and depleted lithosphere. *J. Petrol.* 39, 29–60.
- Wang, K.L., Chung, S.L., Chen, Ch.H., Chen, Ch.H., 2002. Geochemical constraints on the petrogenesis of high-Mg basaltic andesites from the Northern Taiwan Volcanic Zone. *Chem. Geol.* 182, 513–528.
- Wells, P.R.A., 1977. Pyroxene thermometry in simple and complex systems. *Contrib. Mineral. Petrol.* 62, 129–139.
- Wiechert, U., Ivanov, D.A., Wedepohl, K.H., 1997. Spinel peridotite xenoliths from the Atsagin-Dush Volcano, Dariganga lava plateau Mongolia: a record of partial melting and cryptic metasomatism in the upper mantle. *Contrib. Mineral. Petrol.* 126 (4), 345–364.
- Wilshire, H.G., 1987. A model of mantle metasomatism. In: Morris, E.M., Pasteris, J.D. (Eds.), *Mantle Metasomatism and Alkaline Magmatism*, vol. 215. *Geol. Soc. Am. Spec. Pap.*, pp. 47–60.
- Wittig, N., Baker, J.A., Downes, H., 2006. Dating the mantle roots of young continental crust. *Geology* 34 (4), 237–240.
- Xu, Y.G., Bodinier, J.-L., 2004. Contrasting enrichments in high- and low-temperature mantle xenoliths from Nushan Eastern China: results of a single metasomatic event during lithospheric accretion? *J. Petrol.* 45 (2), 321–341.
- Xu, Y., Mercier, J.-C.C., Menzies, M., Ross, J.V., Harte, B., Lin, C., Shi, L., 1996. K-rich glass-bearing wehrlite xenoliths from Yitong Northeastern China: petrological and chemical evidence for mantle metasomatism. *Contrib. Mineral. Petrol.* 125, 406–420.
- Xu, Y.G., Menzies, M.A., Bodinier, J.-L., Bedini, R.M., Vroon, P., Mercier, J.C., 1998. Melt percolation-reaction atop the plume: evidence from poikiloblastic spinel harzburgite xenoliths from Boree (Massif Central France). *Contrib. Mineral. Petrol.* 132, 65–84.
- Zanetti, A., Mazzucchelli, M., Rivalenti, G., Vannucci, R., 1999. The Finero phlogopite-peridotite massif: an example of subduction-related metasomatism. *Contrib. Mineral. Petrol.* 134 (2–3), 107–122.
- Zangana, N.A., Downes, H., Thirlwall, M.F., Hegner, E., 1997. Relationship between deformation, equilibration temperatures, REE and radiogenic isotopes in mantle xenoliths, (Ray Pic, Massif Central France): an example of plume–lithosphere interaction? *Contrib. Mineral. Petrol.* 127 (1–2), 187–203.