

Slab melt and intraplate metasomatism in Kapfenstein mantle xenoliths (Styrian Basin, Austria)

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Abstract

Anhydrous and amphibole-bearing mantle peridotite xenoliths from Kapfenstein (Styrian Basin) have been studied with the aim of understanding both the processes responsible for amphibole formation and the nature of metasomatizing agents which affected this portion of lithosphere. This area of the Pannonian Basin underwent a subduction event which was followed after about 15 Ma, by alkaline intraplate magmatism. Primary clinopyroxene (cpx1) in four-phase lherzolite xenoliths is characterized by LREE-depleted to slightly LREE-enriched patterns. LREE-depleted cpx1 have low Th and U contents and Zr (and Hf) anomalies varying from slightly negative to positive. LREE-enriched cpx have high Th and U contents and remarkable positive anomalies of Zr and Hf. Primary clinopyroxenes in amphibole-bearing lherzolites present a comparable compositional variation from LREE (and Th, U, Zr, Hf)-depleted type to LREE (and Th, U, Zr, Hf)-enriched type. LREE-depleted cpx1, with strong negative Zr and Ti anomalies, are also recognized in the peridotite matrix of a composite sample cut by a large amphibole vein. Textural and geochemical evidence indicates that amphibole disseminated within the matrix grew at the expense of primary spinel and clinopyroxene, mimicking the trace element patterns of the latter. As a consequence, the geochemical features of amphibole vary in relation to those of clinopyroxene, from enriched to depleted. On the other hand, the composition of vein amphibole in the composite xenolith compares well with amphibole megacrysts and microphenocrysts, suggesting that it represents a fractionation product of alkaline melt that passed through the lithosphere. Two kinds of metasomatism, superimposed on a slightly depleted lithospheric mantle, were identified. A slab-derived melt (proto-adakite?) metasomatic agent was responsible for the first enrichment in Th, U, Zr and Hf observed in clinopyroxene, whereas an alkaline within-plate metasomatic agent caused the formation of the Nb (and Ta)-rich disseminated amphibole. The final process was the alkaline magmatism, which was responsible for the formation of the large amphibole vein and megacrysts. It is proposed that the Nb-poor and Nb-rich amphiboles record the transition between the suprasubduction slab melt-related and the intraplate alkaline metasomatism.

These geochemical features are consistent with a lithospheric portion enriched in slab melt components which was subsequently metasomatized by alkaline melt. Alternatively an asthenospheric uprising could have scavenged a previously slab melt-enriched region of the lithosphere.

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1. Introduction

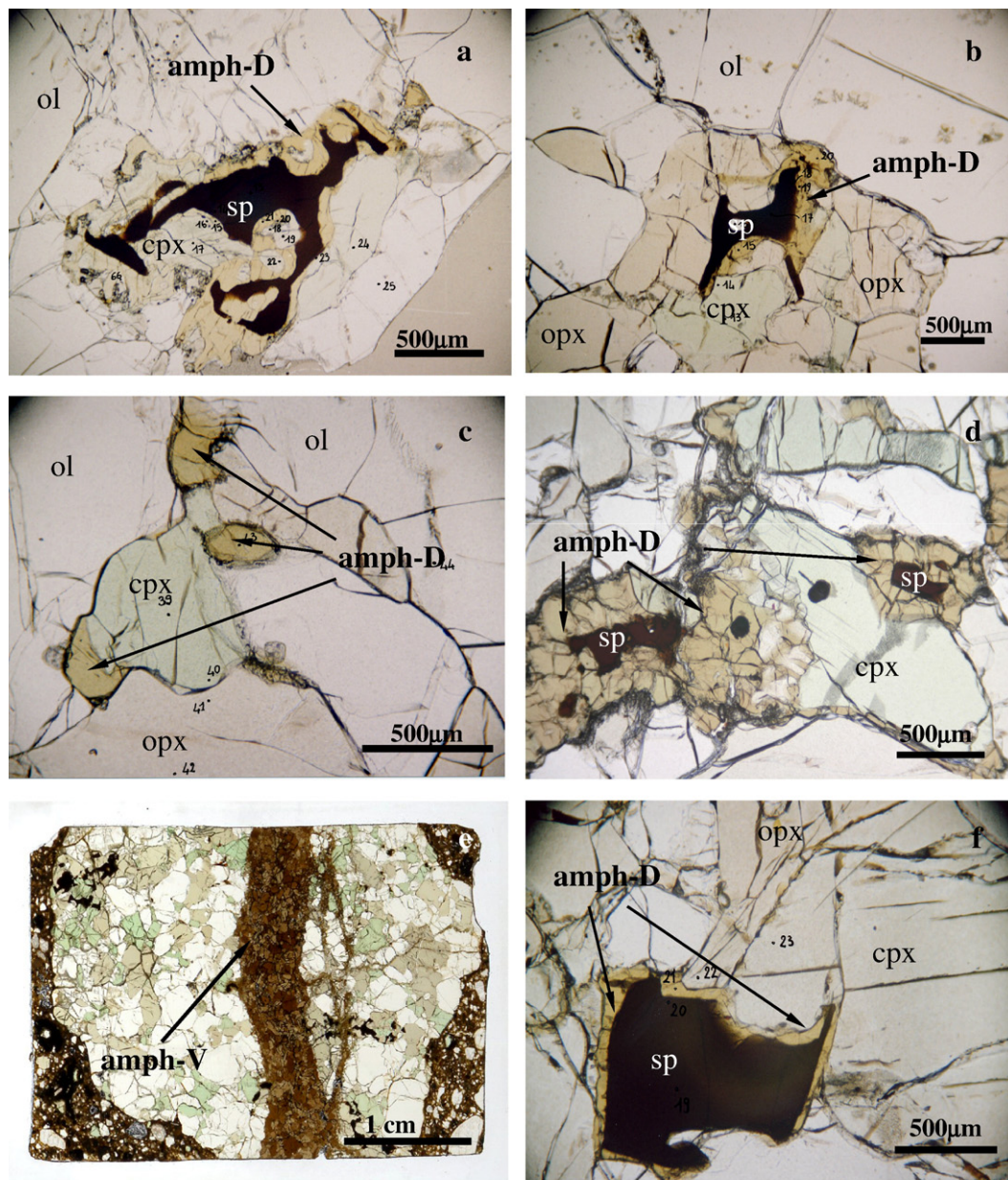
The widespread Miocene to Pleistocene alkaline volcanism of the Pannonian Basin is characterized by the

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occurrence of abundant mantle xenoliths (Kurat et al., 1980; Embey-Isztin et al., 1989; Kurat et al., 1991; Downes et al., 1992; Szabó et al., 1992, 1995; Embey-Isztin and Dobosi, 1995; Downes and Vaselli, 1995; Vaselli et al., 1995, 1996; Chalot-Prat and Bouillier,

1997). This volcanism was preceded by the eruption of a large variety of calc-alkaline s.l. magmatic products in the Carpathian Arc and Pannonian Basin. Spatial-time relationships between alkaline and calc-alkaline s.l. magmatism are very complicated (Pécskay et al., 1995;



ol: olivine
opx: orthopyroxene
cpx: clinopyroxene

sp: spinel
amph-D: disseminated amphibole
amph-V: vein amphibole

Fig. 1. Photomicrographs of Kapfenstein peridotite xenoliths. a) “holly-leaf” spinel surrounded by disseminated amphibole (Be-1C); b) disseminated amphibole sandwiched between spinel and clinopyroxene (Be-1A); c) disseminated amphibole surrounding clinopyroxene (KAP68); d) disseminated amphibole surrounding spinel and clinopyroxene (KF4); e) amphibole vein cutting through olivine and orthopyroxene (KAP1); f) disseminated amphibole growing around spinel near the vein (KAP1).

Harangi, 2001a,b; Seghedi et al., 2004a,b). In the western part of the Basin small alkaline volcanic centres outcrop in Styrian Basin, Burgenland, Little Hungarian Plain and Lake Balaton. Volcanism in Burgenland yields ages between 11.7 and 10.8 My, while at Lake Balaton it occurred between 6 and 2 My. In both localities alkaline volcanism was preceded by Early to Middle Miocene potassic magmatism (Harangi et al., 1995a). The youngest alkaline volcanic activity, dated between 3.8 and 1.7 My, occurred in the Styrian basin (Balogh et al., 1986; Embey-Isztin et al., 1993; Balogh et al., 1994; Pécskay et al., 1995; Harangi et al., 1995b; Seghedi et al., 2004a,b). Early to Middle Miocene shoshonitic magmas were also erupted in the Styrian Basin, pre-dating the alkaline magmatic event by about 15 My (Harangi et al., 1995a; Harangi, 2001b). Embey-Isztin et al. (1993), Harangi (2001a) and Seghedi et al. (2004a) reviewed the Neogene–Quaternary alkalic basalts of the Carpathian–Pannonian Region, and recognized both lithospheric and asthenospheric signatures in their mantle source, as well as subduction-related components. Based on Ce/Pb and La/Nb ratios, some alkaline magmas from the Styrian Basin (at Neuhaus) and Little Hungarian Plain (at Gussing) appear to be the most contaminated by subduction-related components.

The main volcanic outcrops in the Styrian Basin (Neuhaus, Steinberg, Kapfenstein, Stradner Kogel,

Klöch, Tieschen and Gräd) consist of both massive basalts and altered and reworked tuff deposits; these latter containing megacrysts and xenoliths of peridotite, pyroxenite and hornblendite. All the studied xenoliths (maximum 5–10 cm in size) come from the famous locality of Kapfenstein (Kurat et al., 1980, 1991; Vaselli et al., 1996). Previous studies showed the existence of clinopyroxene and amphibole with either enriched or depleted REE patterns. Several questions were raised regarding the origin of disseminated and vein amphiboles, as well as the formation of the remarkably REE-enriched amphibole. However Vaselli et al. (1996) concluded that both kinds of amphiboles were the result of alkaline metasomatism and excluded any influence of subduction metasomatism.

Our study is based on small xenoliths generally characterized by the presence of disseminated amphibole with one exception in which an amphibole vein sharply cuts the peridotite. Few anhydrous samples are also present. Their size did not allow whole-rock analyses or isotopic determinations on mineral separates. This study therefore focuses on major and trace element compositions of clinopyroxene and amphibole in different textural occurrences. These data, in particular the wide range of trace elements analysed, enhance our understanding of the petrogenesis of disseminated and vein amphiboles and yield evidence of an additional

Table 1

Major element compositions of olivines from anhydrous lherzolites (Lh), amphibole-bearing lherzolites [Lh(a)], amphibole-bearing harzburgite [Hz(a)] and veined-lherzolite [Lh(v)] of Kapfenstein lithospheric mantle xenoliths

Sample	KAP2	KF7	BE-1	BE-1A	BE-1C		KF2	KF4	KF6	KF14		KAP68	KAP1
	Lh	Lh	Lh(a)	Lh(a)	Lh(a)		Lh(a)	Lh(a)	Lh(a)	Hz(a)		Hz(a)	Lh(v)
Phase	ol 1	ol1	ol1	ol1	ol1	ol2	ol1	ol1	ol1	ol1	ol2	ol1	ol1
	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core		Core	Core
SiO ₂	41.19	41.13	40.93	40.87	40.84	41.22	40.76	40.91	40.35	41.06	40.31	41.13	40.59
TiO ₂			0.02	0.01	0.04	0.02					0.04		0.01
Al ₂ O ₃	0.03	0.04	0.02	0.02	0.02	0.03	0.02	0.02	0.01	0.02	0.02	0.01	0.01
FeO	9.66	9.24	9.69	10.25	10.14	8.67	10.54	9.41	9.76	8.79	7.86	8.26	11.27
MnO	0.14	0.13	0.16	0.15	0.16	0.12	0.20	0.13	0.16	0.11	0.11	0.13	0.12
MgO	49.58	50.01	48.76	48.87	49.46	50.37	49.42	50.23	49.78	50.55	51.02	50.62	48.10
CaO	0.07	0.06	0.08	0.09	0.08	0.22	0.06	0.06	0.03	0.06	0.14	0.05	0.08
NiO	0.37	0.42	0.33	0.39	0.39	0.25	0.38	0.42	0.38	0.36		0.38	0.34
Tot	101.05	101.03	99.99	100.65	101.13	100.90	101.38	101.18	100.48	100.98	99.50	100.57	100.52
Si	0.999	0.997	1.003	0.998	0.993	0.996	0.991	0.991	0.987	0.994	0.986	0.996	0.997
Ti			0.000	0.000	0.001	0.000					0.001		0.000
Al	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Fe II	0.196	0.187	0.199	0.209	0.206	0.175	0.214	0.191	0.200	0.178	0.161	0.167	0.232
Mn	0.003	0.003	0.003	0.003	0.003	0.002	0.004	0.003	0.003	0.002	0.002	0.003	0.002
Mg	1.791	1.806	1.781	1.779	1.792	1.813	1.791	1.814	1.814	1.823	1.860	1.828	1.761
Ca	0.002	0.002	0.002	0.002	0.002	0.006	0.002	0.001	0.001	0.002	0.004	0.001	0.002
Ni	0.007	0.008	0.001		0.000	0.003	0.007	0.008	0.007	0.007		0.007	0.001
ΣCat	2.999	3.003	2.989	2.993	2.998	2.997	3.009	3.009	3.013	3.006	3.014	3.003	2.995
Fo	90.14	90.61	89.97	89.47	89.68	91.19	89.31	90.49	90.09	91.11	92.04	91.61	88.38

subduction-related metasomatism in the mantle beneath the Styrian Basin.

2. Petrography

Peridotite xenoliths from Kapfenstein have inequigranular, protogranular textures with olivine and orthopyroxene crystals up to 5 mm. Spinel, with typical “holly-leaf” shape (Fig. 1a), is the only aluminous phase. Lherzolite 2045 is the only sample with an orthopyroxene and spinel foliation. Metasomatic textures are very rare and petrographic and textural features strongly indicate general equilibrium conditions. Glass is very rare and, when present, it is <20 µm, unsuitable for trace element analysis. Infiltration from the host basalt is not generally observed (except for sample KAP68) and contacts with the xenoliths are very sharp.

2.1. Anhydrous lherzolites

Samples KAP2, KF3, KF7 and KF9 are anhydrous lherzolites devoid of any metasomatic textures or glass. Large olivine and orthopyroxene (up to 3 mm) appear well-equilibrated with smaller clinopyroxene and spinel.

Modal contents of clinopyroxene and spinel are 14–20% and 5–8% in volume, respectively. Sample KF7 is characterized by high orthopyroxene modal content (30%vol).

2.2. Amphibole-bearing lherzolites

This group includes most of the analysed xenoliths. They contain large olivine and orthopyroxene crystals (up to 6 mm). Clinopyroxene (7–18%) is less abundant than in the anhydrous lherzolites. Apart from samples 2045, KF6 and KF8 where amphibole is rare (<1%vol) and always incipiently grown around clinopyroxene, all the other lherzolites (Be-1, Be-1A, Be-1C, KF2, KF4) contain well-equilibrated, disseminated amphibole (4–8%vol) occurring either as isolated single crystals or embedding clinopyroxene and spinel (Fig. 1a). A few samples (2045, KF4, KF6 and Be-1A) present high orthopyroxene modal contents (29–38%vol). Particularly beautiful and meaningful textures are shown by amphibole either sandwiched between spinel and clinopyroxene or surrounding spinel (Fig. 1a,b). Very small (<20 µm) glassy patches are rarely preserved in this structure.

Table 2

Major element compositions of orthopyroxenes from anhydrous lherzolites [Lh], amphibole-bearing lherzolites [Lh(a)], amphibole-bearing harzburgite [Hz(a)] and veined-lherzolite [Lh(v)] of Kapfenstein lithospheric mantle xenoliths

Sample	KAP2	KF7	BE-1	BE-1A	BE-1C	2045	KF2	KF4	KF6	KF14	KAP68	KAP1
	Lh	Lh	Lh(a)	Lh(a)	Lh(a)	Lh(a)	Lh(a)	Lh(a)	Lh(a)	Hz(a)	Hz(a)	Lh(v)
Phase	opx	opx	opx	opx	opx	opx	opx	opx	opx	opx	opx	opx
	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core
SiO ₂	55.09	54.26	54.97	54.97	55.14	55.50	55.93	55.84	53.80	55.13	57.27	54.97
TiO ₂	0.12	0.15	0.14	0.15	0.12	0.10	0.05	0.02	0.20	0.07	0.18	0.11
Al ₂ O ₃	4.76	5.41	3.88	4.02	4.20	3.75	3.41	3.62	5.45	3.28	1.40	4.47
Fe ₂ O ₃	0.25	0.49	0.14	0.11	0.20	0.07	0.41	0.33	0.69	0.50	0.06	0.27
FeO	5.81	5.53	6.07	6.36	6.39	5.94	6.23	5.59	5.60	5.25	5.18	6.03
MnO	0.14	0.16	0.14	0.14	0.12	0.18	0.19	0.15	0.15	0.16	0.12	0.16
MgO	32.98	33.08	32.89	32.64	32.83	33.48	33.68	34.02	33.25	33.96	34.84	32.99
CaO	0.88	0.89	0.86	0.85	0.92	0.53	0.77	0.77	0.77	0.76	0.72	0.76
Na ₂ O	0.16	0.12	0.06	0.09	0.08	0.04	0.13	0.07	0.09	0.09	0.09	0.11
Cr ₂ O ₃	0.42	0.50	0.53	0.63	0.55	0.30	0.43	0.40	0.48	0.57	0.60	0.44
Tot	100.60	100.59	99.69	99.96	100.56	99.89	101.23	100.81	100.47	99.77	100.46	100.34
Si	1.888	1.859	1.905	1.903	1.897	1.915	1.908	1.906	1.845	1.901	1.960	1.891
Ti	0.003	0.004	0.004	0.004	0.003	0.003	0.001	0.001	0.005	0.002	0.005	0.003
Al	0.192	0.218	0.158	0.164	0.170	0.152	0.137	0.146	0.220	0.133	0.057	0.181
Fe III	0.007	0.013	0.004	0.003	0.005	0.002	0.011	0.009	0.018	0.013	0.001	0.007
Fe II	0.167	0.158	0.176	0.184	0.184	0.171	0.178	0.160	0.160	0.151	0.148	0.173
Mn	0.004	0.005	0.004	0.004	0.004	0.005	0.005	0.004	0.004	0.005	0.003	0.005
Mg	1.684	1.689	1.698	1.684	1.683	1.721	1.712	1.731	1.699	1.745	1.777	1.691
Ca	0.032	0.033	0.032	0.032	0.034	0.020	0.028	0.028	0.028	0.028	0.026	0.028
Na	0.011	0.008	0.004	0.006	0.005	0.003	0.009	0.005	0.006	0.006	0.006	0.007
Cr	0.011	0.014	0.015	0.017	0.015	0.008	0.012	0.011	0.013	0.015	0.016	0.012
ΣCat	3.999	4.001	4.000	4.001	4.000	4.000	4.001	4.001	3.998	3.999	3.999	3.998
mg#	90.98	91.45	90.61	90.15	90.14	90.96	90.58	91.54	91.39	92.04	92.31	90.72

2.3. Amphibole-bearing harzburgites

Only one harzburgite (KAP68) is present in our collection. It has very large olivine crystals (up to 5 mm) and smaller orthopyroxene. Clinopyroxene, spinel and amphibole are all <3% in volume. With clinopyroxene abundance around 5%vol, sample KF14 is on the boundary between harzburgites and lherzolites. Because it shares many similarities with sample KAP68, it has been included in the same group. In both samples the modal abundance of amphibole is <1% and it always surrounds spinel or clinopyroxene crystals (Fig. 1c,d). A dark glassy vein with amphibole microphenocrysts, clearly texturally related to the host basalt, entirely crosses sample KAP68, without any reaction with the matrix minerals. Glassy veins and patches associated with amphibole, clinopyroxene and spinel are found in KF14. A tiny rim of clinopyroxene and glass is still preserved between spinel and amphibole, suggesting that clinopyroxene in contact with spinel was not completely exhausted by the reaction which generated amphibole (cfr. Coltorti et al., 2004a).

2.4. Composite lherzolite

KAP1 is the only composite sample (Fig. 1e). Textural features and modal mineral abundances of the

peridotite are very similar to those of the anhydrous lherzolites. The contact with the amphibole vein (up to 5 mm in thickness) is sharp, with several smaller veins intruding the peridotite. The main vein is almost completely composed of small amphibole crystals and tiny oxides concentrated in the middle of the vein. Where fluid escaping the vein came into contact with spinel in the peridotite matrix, a rim of amphibole has developed (Fig. 1f). As mentioned above, spinel plus clinopyroxene are the base on which amphibole grew.

3. Analytical methods

Major element analyses of minerals and glasses (Tables 1–5) were carried out on a Cameca SX100 electron microprobe at the Department of Lithospheric Sciences, Vienna University. The operating condition was 15 kV and 20 nA. In order to reduce alkali loss, glass analyses were performed using a defocused beam with a diameter of 5–10 μm at 15 kV and 10 nA. The error for all elements is <5%, except for Na for which it can reach 10%. Natural and synthetic standards were used for calibration, and the PAP correction (Pouchou and Pichoir, 1991) was applied to the data. Analytical conditions for Ca determination in olivine were 20 kV accelerating voltage and 40 nA beam current, with 100 s of count time

Table 3

Major element compositions of spinels from anhydrous lherzolites (Lh), amphibole-bearing lherzolites [Lh(a)], amphibole-bearing harzburgite [Hz(a)] and veined-lherzolite [Lh(v)] of Kapfenstein lithospheric mantle xenoliths

Sample	KAP2 Lh	KF7 Lh	BE-1A Lh(a)	BE-1C Lh(a)	2045 Lh(a)	KF2 Lh(a)		KF4 Lh(a)	KF6 Lh(a)	KF14 Hz(a)	KAP68 Hz(a)	KAP1 Lh(a)	
Phase	sp1	sp1	sp1	sp1	sp1	sp1	sp1	sp1	sp1	sp1	sp1	sp1	sp1
	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	In vein
TiO ₂	0.13	0.13	0.30	0.28	0.08	0.12	0.07	0.07	0.11	0.10	0.93	0.07	0.31
Al ₂ O ₃	55.96	56.42	44.08	45.54	53.10	43.25	53.10	53.58	58.71	37.16	15.54	52.72	46.72
Fe ₂ O ₃	1.92	2.80	4.90	4.09	3.10	2.27	2.22	2.06	1.68	3.82	5.36	4.87	6.64
FeO	8.65	7.65	10.13	11.11	8.71	11.63	9.97	9.24	9.25	11.38	13.58	6.80	11.52
MnO	0.03	0.08	0.08	0.05	0.08	0.13	0.08	0.10	0.08	0.14		0.07	0.14
MgO	20.70	21.47	18.69	18.43	20.08	17.43	19.84	20.24	20.79	17.20	13.52	21.18	17.87
NiO	0.37	0.39	0.29	0.33	0.34	0.35	0.30	0.36	0.37	0.25	0.18	0.38	0.25
Cr ₂ O ₃	11.89	10.83	21.06	20.66	12.45	24.35	14.99	14.88	9.22	30.39	48.65	11.31	15.15
Total	99.65	99.77	99.53	100.49	97.94	99.53	100.57	100.53	100.21	100.44	97.76	97.40	98.60
Ti	0.003	0.003	0.006	0.006	0.002	0.002	0.001	0.001	0.002	0.002	0.023	0.001	0.006
Al	1.714	1.717	1.427	1.458	1.670	1.412	1.640	1.649	1.775	1.235	0.589	1.657	1.516
FeIII	0.040	0.050	0.100	0.080	0.060	0.050	0.040	0.040	0.030	0.080	0.130	0.100	0.140
Fe II	0.190	0.170	0.230	0.250	0.190	0.270	0.220	0.200	0.200	0.270	0.370	0.150	0.270
Mn	0.001	0.002	0.002	0.001	0.002	0.003	0.002	0.002	0.002	0.003	0.000	0.002	0.003
Mg	0.802	0.826	0.765	0.746	0.799	0.719	0.775	0.788	0.795	0.723	0.648	0.841	0.733
Ni	0.008	0.008	0.006	0.007	0.007	0.008	0.006	0.008	0.008	0.006	0.005	0.008	0.006
Cr	0.244	0.221	0.457	0.444	0.263	0.533	0.311	0.307	0.187	0.677	1.237	0.238	0.330
ΣCat	3.002	2.997	2.993	2.992	2.993	2.997	2.995	2.995	2.999	2.996	3.002	2.997	3.004
mg#	80.85	82.93	76.88	74.90	80.79	72.70	77.89	79.76	79.90	72.81	63.65	84.86	73.08
cr#	12.46	11.40	24.26	23.34	13.61	27.40	15.94	15.70	9.53	35.41	67.74	12.56	17.88

on both peak and relative background positions. A pyrope-rich garnet with 5.0%wt CaO and a San Carlos olivine with 527 ppm Ca were used as primary and secondary standards, respectively. Ca content in San Carlos olivine was previously determined by INAA, isotopic dilution and microprobe techniques.

Concentrations of 28 trace elements (REE, Ba, Rb, Th, U, Nb, Ta, Sr, Zr, Hf, Ti, Y, Cr, Sc, V and Ni) of clinopyroxene and amphibole were determined in situ on >100–120 mm thick polished sections by LA-ICP-MS at the Observatoire Midi-Pyrenees (University Toulouse III). The Perkin Elmer Elan 6000 ICP-MS instrument was coupled to a Cetac LSX-200 laser ablation module that uses a 266 nm frequency-quadrupled Nd-YAG laser. A typical analysis consisted of 3 replicates of 100 readings, with each replicate representing one sweep of the mass range. The counting time for one sample was typically 160–170 s. The NIST610 glass standard was used to calibrate relative element sensitivities for the analyses of the silicates minerals (Norman et al., 1998). The calibration protocol involves standardization at the beginning, middle and end of each analytical run to correct for instrumental drift during the run. During each run NIST 612 was analysed as unknown. The accuracy and reproducibility of the analyses were given by Delpech et al. (2004). Each analysis was normalized using Ca values determined by electron microprobe. Typical theoretical detection limits range from 10–20 ppb for REE, Ba, Rb, Th, U, Nb, Ta, Sr, Zr, Hf, Y, 100 ppb for V, Sc and 2 ppm for Ti, Ni and Cr.

4. Major element phase geochemistry

4.1. Olivine

Olivine composition is quite uniform within each sample. Fo content ranges between 87.5 and 91.9, with the lowest values in olivine near the vein (KAP1) and the highest in olivine from harzburgites. Secondary olivine (ol2), analysed in reaction areas or within glassy veins, has higher Fo (90.6–92.2) and CaO (0.11–0.18% wt) contents. Olivines from anhydrous lherzolites tend to have SiO₂ and Fo contents higher than those containing disseminated amphibole (Table 1).

4.2. Orthopyroxene

Orthopyroxene compositions are also quite uniform within individual samples. The mg# [$\text{Mg}/(\text{Mg} + \text{Fe}) \times 100$] varies from 88.2 to 91.8 in lherzolites, and can be >92 in harzburgites (Table 2). However the lowest values and the largest variation in mg# are recorded in the

composite sample KAP1 where, close to the vein, mg# is 88–89, while further away from the vein it reaches 90.7. Al₂O₃ contents tend to be higher in anhydrous lherzolites compared to the amphibole-bearing ones. CaO content is always >0.7%wt (except for sample 2045), while Cr₂O₃ is always <0.6%wt, typical of orthopyroxene from spinel-bearing lherzolites (cf. Bonadiman et al., 2005). Samples KF6 and KF4 are anomalous in having the highest modal percentage of orthopyroxene (35–38%vol).

4.3. Spinel

Spinel from Kapfenstein lherzolites varies in mg# and cr# [$\text{Cr}/(\text{Cr} + \text{Al}) \times 100$] from 72.7 to 84.9 and 8.2 to 27.7 respectively, suggesting quite fertile compositions (Table 3; Fig. 2). A consistent increase in cr#, coupled with a decrease in mg#, is observed in spinels moving from anhydrous, to amphibole-poor (<1%vol) and amphibole-rich (4–8%vol) lherzolites. Spinel from anhydrous lherzolites (including the highest mg# KAP1 spinels which occur in the peridotite matrix far from the vein) have the lowest cr# (and the highest mg#). Spinel in amphibole-rich lherzolites (KF2, Be-1C, KF4) have the highest cr# coupled with the lowest mg# (Fig. 2). This trend is also observed within a single sample (KF2) where large, primary sp (high mg#, low cr#) and small, secondary sp (higher cr#, lower mg#) are associated with incipient amphibole and large amphibole crystals, respectively. Spinel in composite sample KAP1 show the widest mg# variation: much lower near the vein than far away from it. These spinels follow a trend quite different from the previous one, being characterized by lower mg# at comparable cr# (Fig. 2).

Spinel in harzburgite KAP68 is clearly different from the other samples having the lowest mg# and the highest cr#, both ratios constant at 63.6 and 67.5, respectively. Spinel from sample KF14 has mg# comparable to the most mg#-poor lherzolites, but with higher cr# (35.4–37.4).

4.4. Clinopyroxene

Three different kinds of clinopyroxene occur in Kapfenstein xenoliths: primary clinopyroxene (cpx1), secondary clinopyroxene related to orthopyroxene reaction (cpx2-O) and clinopyroxene associated with metasomatic amphibole (cpx-A) (Coltorti et al., 2004a). However, secondary clinopyroxenes occur only rarely and are usually too small to allow in situ trace element analyses. Thus only cpx1 will be considered.

Cpx1 from harzburgites (including sample KF14) have the highest mg# (93.1–93.8), SiO₂ and Cr₂O₃, as well as

Table 4
Major and trace element compositions of clinopyroxenes and amphiboles from anhydrous lherzolites (Lh), amphibole-bearing lherzolites [Lh(a)], amphibole-bearing harzburgite [(Hz(a)] and veined-lherzolite [Lh(v)] of Kapfenstein lithospheric mantle xenoliths

Sample	KF7 Lh		BE-1A Lh(a)		BE-1C Lh(a)			KF2 Lh(a)				KF4 Lh(a)					
	cpx1		cpx1		cpx1		Amph-D	cpx1		Amph-D	Amph-D	cpx1		Amph-D	Amph-D	AmphMXC	
	Core	Core	Core		Core	Rim		Core	Rim			Core	Core			Core	Rim
SiO ₂	51.44	51.58	51.00	42.98	51.25	51.60	42.61	51.78	52.49	43.28	43.38	51.88	51.98	42.83	43.22	40.37	40.35
TiO ₂	0.53	0.48	0.48	1.89	0.49	0.42	1.75	0.50	0.21	1.37	0.98	0.44	0.36	0.91	0.71	3.64	3.52
Al ₂ O ₃	7.21	7.65	6.01	13.89	5.80	5.32	13.72	7.47	6.49	14.68	14.69	7.04	6.71	15.64	15.37	15.49	15.48
Fe ₂ O ₃	1.02	0.99	0.33	2.18	0.52	0.56	2.44	0.62	0.52	2.11	2.22	0.56	0.55	2.49	2.46	1.75	1.63
FeO	2.07	2.11	3.11	2.44	2.80	2.80	2.16	2.45	2.54	2.23	2.06	2.18	2.24	1.47	1.58	5.98	6.14
MnO	0.09	0.11	0.08	0.04	0.08	0.11	0.06	0.10	0.07	0.05	0.05	0.09	0.05	0.03	0.07	0.09	0.08
MgO	15.64	15.62	15.75	17.48	16.03	16.26	17.68	14.99	15.71	17.65	17.62	15.30	15.48	17.81	17.96	15.15	15.03
CaO	19.68	18.99	20.39	10.82	20.91	20.88	10.79	19.64	19.68	10.56	10.66	19.97	19.94	10.67	10.73	10.92	11.03
Na ₂ O	2.05	2.24	1.06	3.06	1.05	1.07	3.08	2.07	1.83	3.45	3.14	1.90	1.84	3.46	3.35	2.46	2.40
K ₂ O				0.79			0.77			1.19	1.27			0.86	1.20	1.90	1.88
NiO				0.14			0.14			0.14	0.09			0.12	0.12	0.02	0.02
Cr ₂ O ₃	0.90	0.99	1.55	1.78	1.40	1.23	1.79	1.21	1.09	1.69	1.89	1.19	1.18	1.55	1.65	0.00	0.00
Total	100.63	100.76	99.76	97.49	100.33	100.25	96.99	100.83	100.63	98.40	98.05	100.55	100.33	97.84	98.42	97.77	97.55
mg#	93.09	92.95	90.0	92.74	91.07	91.19	93.58	91.60	91.68	93.38	93.84	92.60	92.49	95.57	95.30	81.87	81.35
Ba	107	108	57.7	173	115	124	179	32.4	28.7	202	203	78.5	61.6	162	181	172	161
Rb	10.2	10.1	6.68	10.4	13.0	15.7	17.1	3.11	2.04	8.80	10.42	8.64	6.76	11.8	13.79	10.5	10.0
Sr	52.4	54.6	80.5	246	79.1	80.6	180	123	155	351	263	119	117	125	138	239	194
Th	1.79	1.83	0.97	0.57	1.44	1.40	1.00	1.45	0.85	0.72	0.77	1.79	1.64	1.25	1.35		0.57
U	0.52	0.64	0.31	0.17	0.59	0.43	0.35	0.31	0.28	0.35	0.23	0.59	0.49	0.36	0.44	0.03	0.16
Nb	1.79	1.98	0.75	16.9	0.79	0.971	11.1	0.64	0.40	29.8	24.2	2.17	1.2	6.66	27.0	10.6	8.84
Ta	0.13	0.13	0.12	0.95	0.12	0.11	0.63	0.06	0.04	0.78	0.83	0.12	0.08	0.14	1.35	0.60	0.50
Zr	148	157	67.8	50.0	93.1	96.9	67.6	69.3	45.1	82.7	101.6	118	101	101	167	28.3	54.5
Hf	3.84	3.50	1.62	1.35	2.63	2.68	1.97	1.99	1.28	0.99	1.88	2.57	2.53	2.46	3.45	1.25	1.65
Y	12.2	12.2	12.1	11.5	11.0	10.5	9.63	14.1	13.0	16.3	12.5	12.5	12.8	7.75	9.15	8.54	8.05
La	6.08	6.28	5.96	6.88	6.93	7.00	6.35	7.02	6.57	10.56	9.29	8.91	8.66	6.91	8.15	2.74	3.65
Ce	11.4	11.9	14.0	15.4	14.5	14.8	14.0	13.3	14.8	24.4	21.5	18.0	16.8	14.1	16.0	8.20	9.22
Pr	1.21	1.34	1.85	2.10	1.92	1.90	1.76	1.50	1.60	3.32	2.92	2.11	1.97	1.57	1.95	1.32	1.41
Nd	5.54	4.91	10.1	9.35	8.31	7.44	8.89	5.68	6.37	14.2	12.2	8.45	7.53	7.31	8.03	7.63	7.77
Sm	1.29	1.23	2.44	2.98	2.36	2.07	1.87	1.73	1.44	3.67	4.11	1.48	1.76	1.25	1.67	2.38	2.20
Eu	0.37	0.42	0.84	0.92	0.82	0.68	0.61	0.62	0.70	1.22	1.01	0.64	0.63	0.35	0.45	0.89	0.83
Gd	1.69	1.60	2.17	2.58	2.31	2.16	2.09	2.00	1.94	3.47	2.54	1.72	1.82	1.14	1.48	2.14	1.91
Tb	0.28	0.30	0.40	0.37	0.35	0.31	0.31	0.35	0.33	0.62	0.43	0.34	0.26	0.18	0.28	0.44	0.33
Dy	1.89	1.86	2.31	2.47	2.11	2.05	1.95	2.74	2.56	3.63	2.16	2.17	1.91	1.10	1.26	2.05	1.50
Ho	0.40	0.40	0.50	0.43	0.42	0.38	0.38	0.47	0.51	0.59	0.45	0.42	0.44	0.23	0.30	0.29	0.25
Er	1.22	1.10	1.21	1.11	1.39	1.30	0.90	1.62	1.30	1.51	1.29	1.42	1.40	0.69	1.03	0.70	0.53
Tm																	
Yb	1.22	1.14	1.18	0.92	1.25	1.08	0.96	1.46	1.39	1.40	1.32	1.18	1.11	0.79	0.96	0.71	0.50
Lu	0.21	0.19	0.19	0.11	0.18	0.19	0.15	0.18	0.22	0.15	0.17	0.21	0.22	0.14	0.14		0.08
(La/Yb) _N	3.58	3.96	3.61	5.35	3.97	4.67	4.76	3.45	3.38	5.43	5.07	5.40	5.57	6.27	6.12	2.78	5.22
Ti _N /Ti*	0.51	0.48	0.52	1.79	0.52	0.51	2.27	0.66	0.26	0.97	0.89	0.61	0.49	2.12	1.27	3.81	4.01
Zr _N /Zr*	3.77	4.36	0.93	0.65	1.45	1.70	1.12	1.53	1.01	0.79	0.99	2.20	1.88	2.18	3.06	0.46	0.91

[Ti_N/Ti*], [Ti*=(Eu_N+Gd_N)/2]; [Zr_N/Zr*], [Zr*=(Nd_N+Sm_N)/2]. Normalizing values from Sun and McDonough (1989).

Sample	KF6 Lh(a)					KAP68 Hz(a)				KAP1 Lh(v)								
	cpx l	cpx l	cpx l	Amph-D	Amph-D	cpx l	cpx l	Amph-D	Amph-D	cpx l	cpx l	cpx l	cpx l	cpx l	Amph-D	Amph-V	Amph-V	Amph-V
	Core	Rim	Core				Core			Core	Rim	Core	Rim	Rim				
SiO ₂	50.47	51.38	50.84	42.60	42.60	53.40	53.33	44.77	45.18	51.98	51.81	51.21	51.97	51.78	42.96	42.63	42.58	42.61
TiO ₂	0.61	0.49	0.65	2.15	2.15	0.35	0.38	1.90	1.91	0.38	0.36	0.37	0.35	0.41	2.09	2.58	3.89	3.78
Al ₂ O ₃	7.68	6.30	7.20	15.66	15.58	2.84	3.06	10.85	10.86	6.66	6.45	7.03	6.17	6.47	15.08	13.35	14.08	14.09
Fe ₂ O ₃	0.62	0.67	0.61	2.40	2.40	0.30	0.23	2.21	1.88	0.18	0.35	0.33	0.29	0.29	2.45	1.89	1.78	1.74
FeO	2.36	2.24	2.37	1.87	1.88	2.14	2.19	1.39	1.64	2.96	3.18	2.41	3.09	3.59	2.95	3.71	4.25	4.32
MnO	0.07	0.08	0.08	0.06	0.07	0.06	0.06	0.04	0.03	0.07	0.09	0.09	0.07	0.08	0.08	0.05	0.08	0.03
MgO	15.21	16.02	15.42	17.89	17.88	16.49	16.40	18.88	18.76	15.47	15.60	15.38	15.57	15.34	16.97	17.03	16.55	16.60
CaO	21.01	21.40	20.82	11.03	11.04	20.70	20.51	10.34	10.32	20.16	20.08	19.81	19.92	20.13	10.51	10.67	10.45	10.53
Na ₂ O	1.32	1.16	1.38	3.76	3.73	1.48	1.50	3.72	3.78	1.41	1.37	1.54	1.45	1.35	2.96	2.96	2.89	2.91
K ₂ O				0.02	0.02			0.20	0.23						1.16	1.16	1.24	1.24
NiO				0.11	0.12			0.09	0.11						0.08	0.10	0.03	0.03
Cr ₂ O ₃	0.79	0.61	0.79	0.95	0.96	2.27	2.27	2.95	2.66	0.85	0.78	1.01	0.78	0.86	1.12	0.61	0.06	0.05
Total	100.14	100.35	100.15	98.50	98.43	100.02	99.92	97.34	97.36	100.13	100.07	99.18	99.66	100.30	98.41	96.74	97.88	97.93
mg#	91.99	92.72	92.06	94.46	94.43	93.21	93.03	96.03	95.32	90.30	89.74	91.92	89.98	88.39	91.11	89.11	87.40	87.26
Ba	87.9	27.6	1.66	50.3	18.9	24.3	22.7	225	144	0.01	0.03	0.03	0.07		93.7	103	251	133
Rb	8.39	2.83	0.18	5.34	2.11	2.72	0.98	7.27	5.62	0.03			0.01		3.22	3.62	9.14	4.35
Sr	39.3	29.8	28.8	59.2	70.3	93.0	69.0	135	147	36.0	36.3	37.6	50.2	101	268	266	516	352
Th	1.83	0.58	0.03	0.82	0.24	1.46	1.35	1.56	1.43	0.02	0.03	0.01	0.18	0.13	0.15	0.17	0.00	0.08
U	0.46	0.14	0.04	0.33	0.16	0.51	0.35	0.39	0.68	0.03						0.04	0.07	0.01
Nb	1.87	0.62	0.06	1.06	0.46	0.47	0.73	2.15	1.93	0.13	0.11	0.11	0.17	0.39	16.1	18.8	30.9	21.7
Ta	0.13	0.00		0.01	0.04		0.07	0.07	0.09	0.04	0.02	0.02	0.01	0.05	0.72	1.03	1.81	1.16
Zr	143	60.3	23.3	73.8	37.9	84.1	95.7	100	85.5	10.2	10.0	9.3	13.1	18.2	45.0	52.4	64.2	64.2
Hf	3.63	1.69	0.72	1.95	1.18	3.04	3.15	3.23	3.01	0.40	0.15	0.48	0.44	0.82	1.44	2.00	2.89	1.69
Y	13.0	15.2	15.1	13.8	18.3	16.8	18.0	14.3	17.6	14.5	14.7	14.0	14.8	18.0	13.7	13.2	14.4	13.5
La	5.37	1.85	0.50	2.67	0.95	6.24	6.85	7.12	6.62	0.57	0.69	0.60	1.34	3.46	4.13	3.81	7.55	5.35
Ce	10.1	4.53	2.09	5.78	3.77	6.81	7.18	8.01	6.98	1.78	1.79	1.88	3.03	10.2	11.9	11.46	27.2	14.5
Pr	1.20	0.67	0.50	0.82	0.57	0.54	0.46	0.73	0.39	0.39	0.31	0.33	0.47	1.40	2.16	1.87	3.98	2.54
Nd	4.21	4.41	3.63	3.89	4.15	4.22	4.04	3.49	4.63	2.13	1.91	1.91	2.22	7.06	12.1	10.6	21.8	13.6
Sm	1.38	1.38	1.39	1.33	1.33	1.81	1.35	0.95	2.13	0.74	1.41	0.90	0.92	1.88	3.16	3.13	5.85	4.18
Eu	0.42	0.55	0.67	0.42	0.55	0.88	0.72	0.75	0.88	0.38	0.44	0.46	0.51	1.04	0.99	1.16	2.26	1.58
Gd	1.66	2.28	1.83	1.85	2.23	3.96	3.95	3.23	2.83	1.92	1.83	1.38	1.85	2.52	3.39	3.30	4.76	3.79
Tb	0.35	0.43	0.38	0.37	0.49	0.53	0.60	0.75	0.51	0.34	0.35	0.32	0.39	0.56	0.57	0.50	0.72	0.51
Dy	2.19	2.61	2.69	2.23	3.39	3.13	3.59	2.81	3.36	2.39	2.39	2.69	2.54	3.57	3.25	3.11	3.78	2.99
Ho	0.40	0.69	0.65	0.44	0.75	0.76	0.72	0.62	0.74	0.59	0.56	0.57	0.60	0.80	0.55	0.56	0.81	0.59
Er	1.24	1.46	1.77	1.55	2.12	1.05	1.70	1.94	1.50	1.54	1.66	1.59	1.54	2.13	1.19	1.28	1.53	1.21
Tm														0.32			0.21	
Yb	1.40	1.41	1.58	1.48	2.02	0.95	1.33	0.95	1.38	1.43	1.62	1.96	1.91	1.98	0.96	0.97	1.30	0.76
Lu	0.22	0.22	0.25	0.15	0.25	0.12		0.16	0.26	0.28	0.22	0.21	0.21	0.32	0.12	0.17	0.15	0.07
(La/Yb) _N	2.75	0.94	0.23	1.29	0.34	4.69	3.71	5.37	3.44	0.28	0.31	0.22	0.50	1.25	3.10	2.82	4.17	5.03
Ti _N /Ti*	1.08	0.64	0.86	3.55	2.83	0.27	0.32	1.79	1.78	0.65	0.59	0.68	0.53	0.36	1.68	1.93	1.68	2.23
Zr _N /Zr*	4.09	1.69	0.71	2.24	1.11	2.08	2.83	3.77	1.86	0.56	0.39	0.49	0.63	0.34	0.50	0.63	0.39	0.59

Table 5

Amphibole/clinopyroxene distribution coefficients ($^{amph/cpx}D$) for amphibole-bearing lherzolites [Lh(a)] and amphibole-bearing harzburgite [Hz(a)] of Kapfenstein lithospheric mantle xenoliths

Sample	Sr	Th	U	Nb	Zr	Hf	Ti	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu
Be-1A Lh(a)	2.58	0.69	0.64	18.90	0.80	0.80	3.21	0.95	1.08	0.99	0.98	0.80	1.03	1.06	1.07	0.97	1.05	0.98	1.09	0.77	0.63
	2.92	0.61	0.38	25.41	0.78	0.79	3.81	0.93	1.06	1.11	1.12	1.07	1.47	1.21	1.24	0.99	1.15	1.03	0.87	0.85	0.60
Be-1C Lh(a)	2.28	0.69	0.59	13.99	0.73	0.75	3.18	0.88	0.92	0.96	0.92	1.07	0.79	0.75	0.91	0.86	0.93	0.91	0.65	0.76	0.82
KF2 Lh(a)	1.87	0.75	0.62	3.00	0.63	0.60	2.36	1.08	1.08	0.96	1.01	1.11	1.26	0.91	0.96	1.10	0.91	1.01	1.09	0.95	0.76
KF4 Lh(a)	1.15	0.72	0.72	6.05	1.03	0.92	1.12	0.70	0.86	0.88	0.86	0.95	1.11	0.81	0.81	0.75	0.64	0.75	0.57	0.80	0.76
	1.76	0.71	0.63	4.49	0.83	0.91	1.17	0.66	1.10	1.30	1.41	1.45	0.88	0.74	0.84	0.65	0.59	0.58	0.76	0.66	0.79
KAP68 Hz(a)	1.45	1.07	0.77	4.61	1.19	1.06	4.20	0.85	1.14	1.18	1.35	0.83	0.53	0.85	0.82	1.42	0.90	0.81	1.84	1.00	1.34
	2.13	1.06	1.98	2.63	0.89	0.95	3.99	0.98	0.97	0.97	0.84	1.15	1.57	1.22	0.72	0.85	0.94	1.04	0.88	1.04	
Mean	2.02	0.79	0.79	9.89	0.86	0.85	2.88	0.88	1.02	1.04	1.06	1.05	1.08	0.94	0.92	0.95	0.89	0.89	0.97	0.85	0.82
S.D.	0.38	0.19	0.58	1.38	0.21	0.17	1.48	0.18	0.12	0.18	0.27	0.24	0.39	0.19	0.09	0.31	0.17	0.19	0.49	0.16	0.29

Determinations were carried out only on minerals physically in contact and with homogeneous mg# and CaO distribution. See text for further explanations.

the lowest Al_2O_3 and FeO contents (Table 4; Fig. 3a). They have quite high Na_2O contents, comparable with those of the most clinopyroxene-rich lherzolites. Cpx1 in anhydrous lherzolites has some of the highest mg#. Again clinopyroxenes from composite sample KAP1 alone cover almost the whole range of mg# (88.2–91.9), taking into account clinopyroxenes near (low mg#) and further away (high mg#) from the vein. The high CaO (>19%wt) and low Cr_2O_3 (<1.6) (Fig. 3a,b) contents of cpx1 fit well within the field of clinopyroxene from spinel-bearing lherzolites (Bonadiman et al., 2005).

4.5. Amphibole

Only sample KAP1 contains amphibole in a vein (and disseminated in close proximity of it). In the other samples amphibole occurs only disseminated within the matrix, sometimes as a very tiny crystal surrounding spinel and clinopyroxene (incipient growth; Fig. 1a,b,c,d,f). Amphibole as microphenocrysts in the dark, glassy vein cutting harzburgite KAP68, and as megacrysts in the tuffaceous matrix of sample KF4 were also analysed (Table 4). All amphiboles are pargasites, with Ti content <0.5 a.f.u. (atoms per formula unit) (Leake et al., 1997). In lherzolites mg# ($\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio calculated on the basis of 23 oxygens; Leake et al., 1997) and SiO_2 contents of amphibole range from 90.5 to 96.0 and 42.2 to 43.7%wt respectively. In harzburgites, amphibole has much higher mg# (95.1–98.4) and SiO_2 (43.6–45.3%wt) contents. As in the clinopyroxenes, these amphiboles show the highest Na_2O contents (Fig. 4a). Amphibole in the vein (Amph-V) is characterized by lower mg# (87.2–89.1) and Cr_2O_3 , associated with higher TiO_2 and K_2O contents, with mg# and Cr_2O_3 increasing and TiO_2 and K_2O decreasing toward the boundary with the peridotite matrix (Fig. 4b,c,d). Amphibole in a small vein penetrating the matrix represents the extreme case where mg# and TiO_2 reach 91.6 and 1.7%wt respectively. Analyses of

the lowest Al_2O_3 and FeO contents (Table 4; Fig. 3a). They have quite high Na_2O contents, comparable with those of the most clinopyroxene-rich lherzolites. Cpx1 in anhydrous lherzolites has some of the highest mg#. Again clinopyroxenes from composite sample KAP1 alone cover almost the whole range of mg# (88.2–91.9), taking into account clinopyroxenes near (low mg#) and further away (high mg#) from the vein. The high CaO (>19%wt) and low Cr_2O_3 (<1.6) (Fig. 3a,b) contents of cpx1 fit well within the field of clinopyroxene from spinel-bearing lherzolites (Bonadiman et al., 2005).

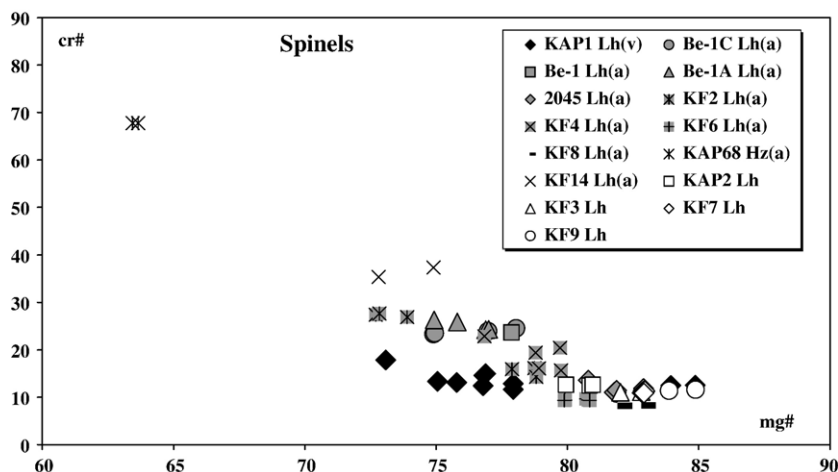


Fig. 2. cr# vs mg# in spinels from Kapfenstein lithospheric mantle xenoliths. Lh, anhydrous lherzolites; Lh(a), amphibole-bearing lherzolites; Hz(a), amphibole-bearing harzburgites; Lh(v), composite lherzolite.

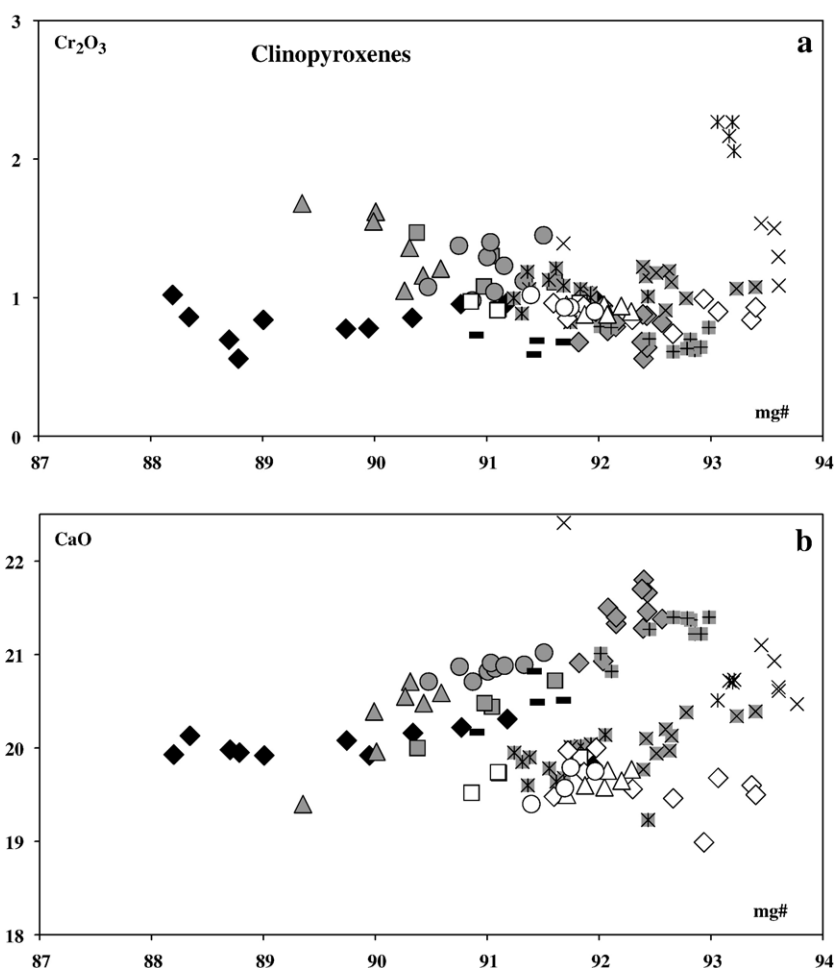


Fig. 3. Cr_2O_3 (a) and CaO (b) contents vs $\text{mg}\#$ in primary clinopyroxenes from Kapfenstein lithospheric mantle xenoliths. Symbols and abbreviations as in Fig. 2.

microphenocrysts and megacrysts are similar and have the lowest $\text{mg}\#$ (81.4–83.6) and Cr_2O_3 contents, together with the highest TiO_2 and K_2O contents (Fig. 4b,c,d).

4.6. Glass

Glass is quite rare, occurring only in harzburgites KAP68 and KF14, and in amphibole-bearing lherzolites Be-1 and Be-1C. Chemical features of a glassy vein cutting sample KAP68 are quite different from those of glass within the metasomatic textures of other samples. The former has much lower $\text{mg}\#$ (44.6–47.5) and SiO_2 (48.49–51.78) and higher TiO_2 (2.44–2.73) and K_2O (2.62–3.14) compared to the latter ($\text{mg}\#$, 61.1–73.0; SiO_2 , 56.4–62.3; TiO_2 , 0.4–2.3; K_2O , 1.2–2.2). In the discrimination diagram proposed by Coltorti et al. (2000) for identifying the metasomatic agent, the former falls in the Na-alkali-silicate field, while the latter plots in the car-

bonatite field. Alkaline magmas from the Styrian Basin (Kurat et al., 1980; Seghedi et al., 2004b) have $\text{mg}\#$ intermediate between KAP68's glass (lower values) and the other glasses. Thus, the dark, glassy vein of sample KAP68 may be the result of infiltration and fractionation from the host basalt, while the other glass occurrences have to be related to a different process, i.e. metasomatism.

5. Trace element phase geochemistry

5.1. Clinopyroxene

Although generally rather similar in major element composition, three groups of cpx1 can be distinguished based on different lithologies: i) cpx1 in anhydrous lherzolites, ii) cpx1 in amphibole-bearing lherzolites and harzburgites and iii) cpx1 in composite lherzolite (Fig. 5).

On the chondrite-normalized incompatible trace element diagram the first group has LREE varying from depleted to slightly enriched $[(La/Yb)_N, 0.27–4.35]$ with respect to Middle and Heavy REE, even within a single sample. LREE-depleted cpx1 has low Th and U contents (0.017–0.04 ppm Th; 0.009–0.04 ppm U) and Zr (and Hf) anomalies slightly below and above 1 $\{(Zr_N/Zr^*=0.65–2.74), Zr^*=[(Nd_N+Sm_N)/2]\}$, LREE-enriched cpx has high Th and U contents (0.84–2.07 ppm Th; 0.14–0.65 ppm U) and remarkable Zr (and Hf) positive anomalies $(Zr_N/Zr^*=3.77–4.36)$ (Fig. 5)(Table 4).

Clinopyroxene in amphibole-bearing lherzolites and harzburgites shows a similar compositional variability. A few samples have clinopyroxene trace element patterns very similar to those of clinopyroxenes from anhydrous lherzolite, while, at comparable REE patterns $[(La/Yb)_N=0.22–5.57]$ and negative Ti anomaly $\{(Ti_N/$

$Ti^*=0.26–0.51), Ti^*=[(Eu_N+Gd_N)/2]\}$, the vast majority of amphibole-bearing samples have lower Ba, Rb, Th, U, Nb and Ta contents as well as Sr and Zr anomalies that change from slightly negative to positive $\{(Sr_N/Sr^*=0.46–1.74), Sr^*=[(Pr_N+Nd_N)/2]; Zr_N/Zr^*=0.67–4.09)\}$ (Table 4). Cpx of sample KF8 show a LREE-depleted pattern $[(La/Yb)_N, 0.21–0.28]$, while in sample KF6 cpx1 patterns vary from LREE-depleted $[(La/Yb)_N=0.22–0.93]$ to slightly LREE-enriched $[(La/Yb)_N=1.06–2.75]$, with Sr and Zr anomalies shifting from negative to positive (Fig. 5).

The third group of cpx1 is clearly distinct, being depleted in Rb, Ba, Th, U, Nb, Ta and LREE, with $(La/Yb)_N$ ratios rather constant at about 0.3. The almost flat pattern $[(La/Yb)_N=1.25]$ displayed by one single spot may be due to a local diffusion effect caused by the LREE-enrichment near the vein (Fig. 5). Zr and Ti are

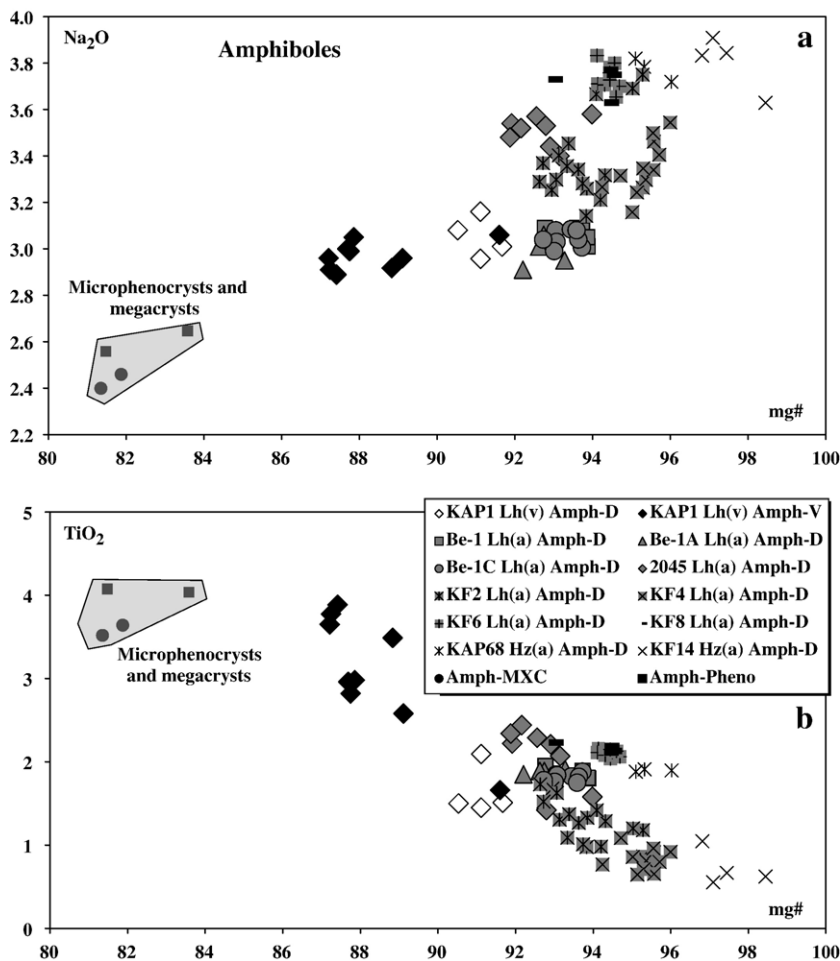


Fig. 4. Na_2O (a), TiO_2 (b), Cr_2O_3 (c) and K_2O (d) contents vs. $mg\#$ in amphiboles from Kapfenstein lithospheric mantle xenoliths. Amph-Pheno and Amph-MXC refer to microphenocrysts and megacrysts in a glassy vein cutting a peridotite and in the tuffaceous matrix respectively. Amph-D and Amph-V indicate disseminated and vein amphiboles as defined in the text. Other abbreviations as in Fig. 2.

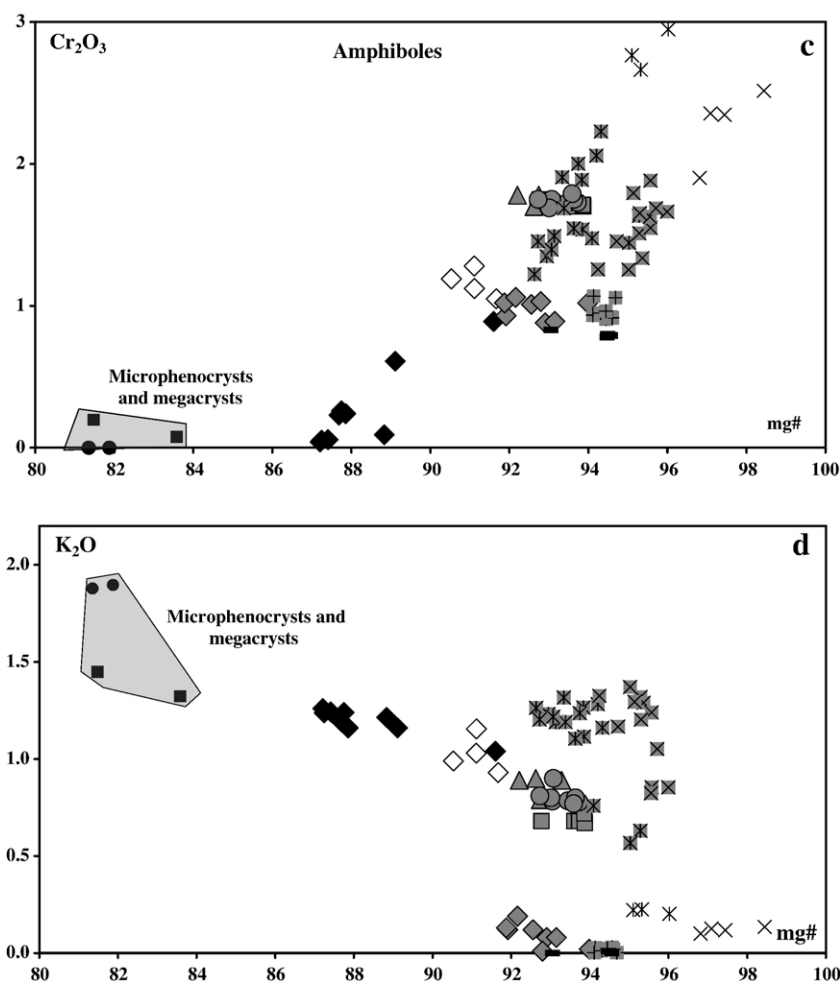


Fig. 4 (continued).

“normally” depleted with respect to the neighbouring elements ($\text{Zr}_N/\text{Zr}^*=0.34\text{--}0.63$; $\text{Ti}_N/\text{Ti}^*=0.36\text{--}0.68$). The geochemical features of this group are very similar to those of LREE-depleted cpx in anhydrous lherzolites as well as to those of the most depleted cpx1 in sample KF6 (Fig. 5).

5.2. Amphibole

On the basis of trace element composition, three groups of amphiboles can also be identified: i) vein-forming amph-V in sample KAP1, and two kinds of disseminated amphiboles (amph-D), one characterized by ii) enriched incompatible trace element patterns and the other by iii) depleted incompatible trace element patterns (Fig. 6). Trace element patterns of megacrysts are also reported for comparison.

Chondrite-normalized incompatible trace element patterns of Amph-V show remarkable depletions in Th and U and enrichment in Nb, Ta, Sr and Ti. $(\text{La}/\text{Yb})_N$ ranges from 2.82 to 5.03 and Zr has a negative anomaly ($\text{Zr}_N/\text{Zr}^*=0.39\text{--}0.63$) (Table 4). These patterns, together with those reported for Amph-V by Zanetti et al. (1995), are very similar to those of the megacrysts (Fig. 6).

The incompatible trace element enriched amphiboles form most of the amph-D in the xenoliths. On the whole their trace element abundances are rather homogeneous, although within each individual sample some differences can be pointed out. With respect to amph-V they have similar Rb, Ba, Nb, Ta, Sr, LREE, Yb and Lu contents, but higher Th, U, Zr, and lower Ti and HREE (except for Yb and Lu) amounts. As with the cpx1 in amphibole-bearing lherzolites, in these amphiboles Zr anomalies vary from slightly negative to positive (Zr_N/Zr^*

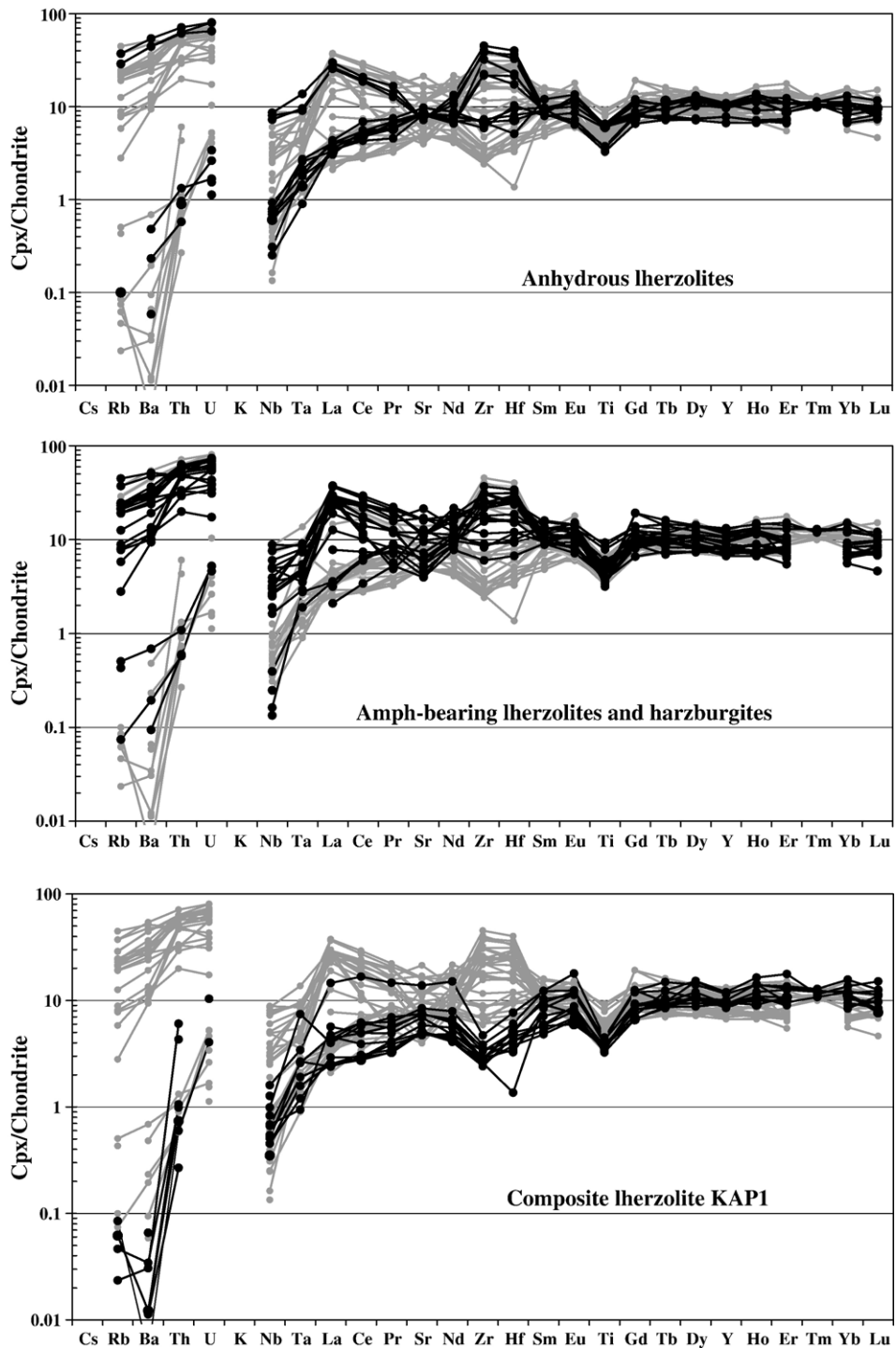


Fig. 5. Chondrite-normalized incompatible trace element diagram for clinopyroxenes from Kapfenstein lithospheric mantle xenoliths. Normalizing values from Sun and McDonough (1989).

$Zr^*=0.54\text{--}3.77$ (Table 4). In fact a strict correspondence within each sample between Zr-rich or Zr-poor amphibole and clinopyroxene can be observed.

Completely different patterns are seen in amph-D in samples KF6 and KF8, which are the only two samples that contain the third group of amphiboles. They are

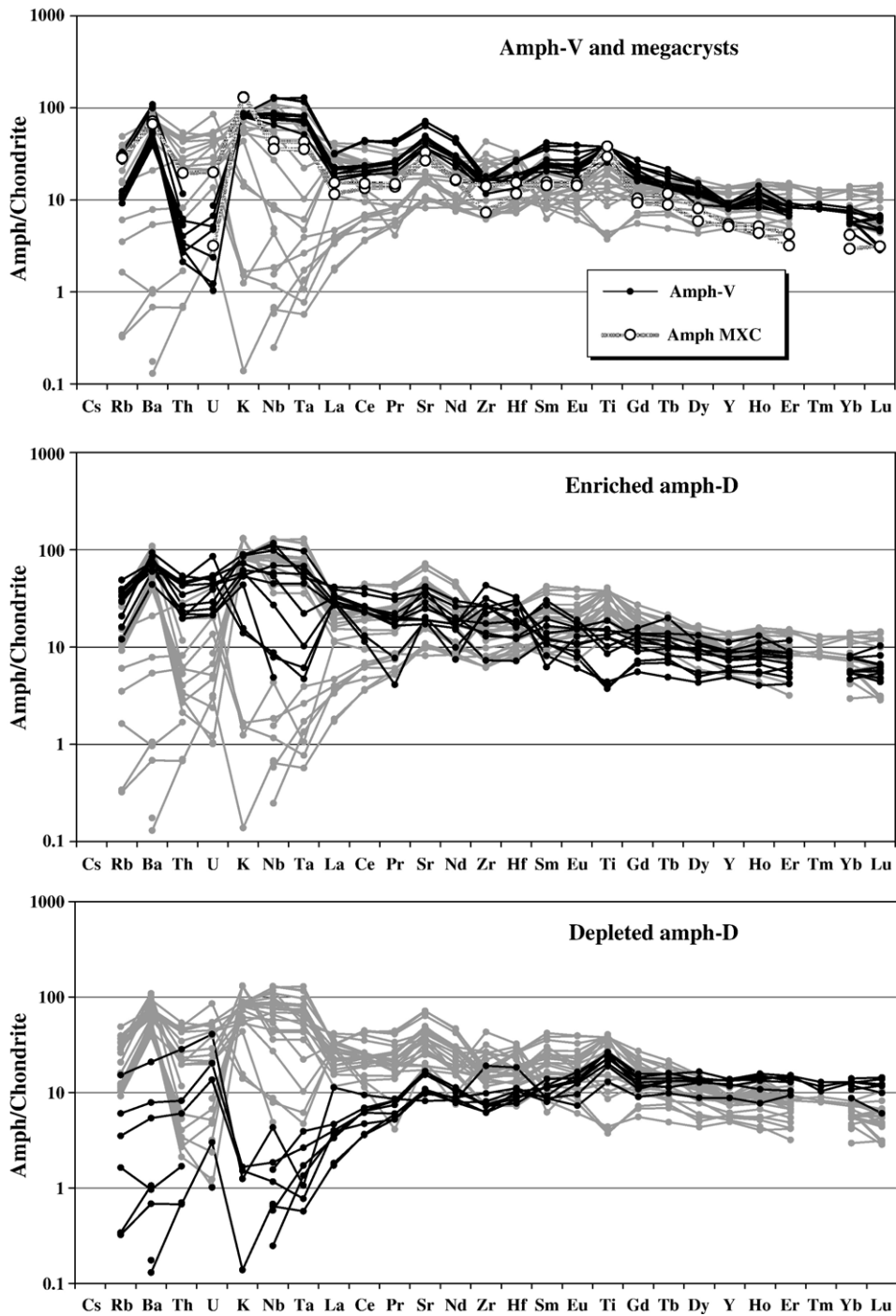


Fig. 6. Chondrite-normalized incompatible trace element diagram for amphiboles from Kapfenstein lithospheric mantle xenoliths. Abbreviations as in Fig. 4. Normalizing values from Sun and McDonough (1989).

strongly depleted in LILE, LREE, Nb and Ta with $(La/Yb)_N$ ranging from 0.13 to 1.3 and Yb at about $12 \times Ch$. Slight positive Sr and Ti anomalies can also be observed (Fig. 6).

6. P – T conditions

Within each sample both cpx1 and orthopyroxene have homogeneous major element compositions,

particularly $\text{mg\#}$ and, together with ol1 , they show mutual equilibrium relationships, as indicated by both petrographic features and similarity with the Fe/Mg exchange equilibria of Brey and Köhler (1990). Thus estimates of T – P conditions of the protogranular assemblage can be obtained. Temperatures were calculated using the two-pyroxene geothermometer of Brey and Köhler (1990), assuming an initial P of 1.5 GPa. Although no great variations were observed between core and rim of crystals, core analyses were used to avoid Fe/Mg variation due to heating from the host basalts or from veins cutting the xenolith. As expected from the homogeneous mineral compositions, T estimates are very constant, standard deviation for all data varies between 2.2 and 25.4 °C.

Pressures were estimated using the Ca distribution in olivine (Köhler and Brey, 1990), using the T obtained from the geothermometer of Brey and Köhler (1990). In order to reduce the error in P estimates, Ca determination in olivine was performed with particular accuracy (see Analytical methods). The calculated T – P values are shown in Fig. 7, together with the P – T estimations obtained for the same xenolith suite by Kurat et al. (1991), Vaselli et al. (1996), Falus et al. (2000), Embey-Isztin et al. (2001). The Styrian Basin geotherm is steeper than both the shield and Perşani Mountains geotherms (Lankreijer et al., 1997; Sachsenhofer et al., 1997). There is a good agreement between our data and those previously reported. Most lherzolites and harz-

burgite plot on the estimated Styrian Basin geotherm, while a few anhydrous and amph-bearing lherzolites do not follow the curve, indicating higher temperature (or lower pressure) than expected. The similarity between P – T conditions obtained on both anhydrous and amphibole-bearing lherzolites, as well as the comparable Fe/Mg opx/cpx distribution in the two lithologies, support the use of Brey and Köhler (1990) geothermometer also in the presence of amphibole (Roach, 2004). The lowest P value (0.7 GPa) is recorded by sample KF14, where a very narrow plagioclase rim exists around spinel, suggesting a subsolidus re-equilibration below the spinel–plagioclase transition. Although plagioclase was not observed in composite lherzolite KAP1, the presence of the big amphibole vein is consistent with rather shallow depth of provenance (1 GPa).

7. $\text{amph/cpx } D$

Amphibole/clinopyroxene partition coefficients were determined only on amph/cpx crystals in contact, characterized by major element compositional homogeneity within each crystal and constant $\text{mg\#}$ and CaO distribution. In this way carefully selected D values were obtained for each sample (Table 5). Textural and geochemical equilibrium conditions were not attained in composite lherzolite KAP1 and amphibole-bearing lherzolite KF6, thus these samples are not reported in Table 5.

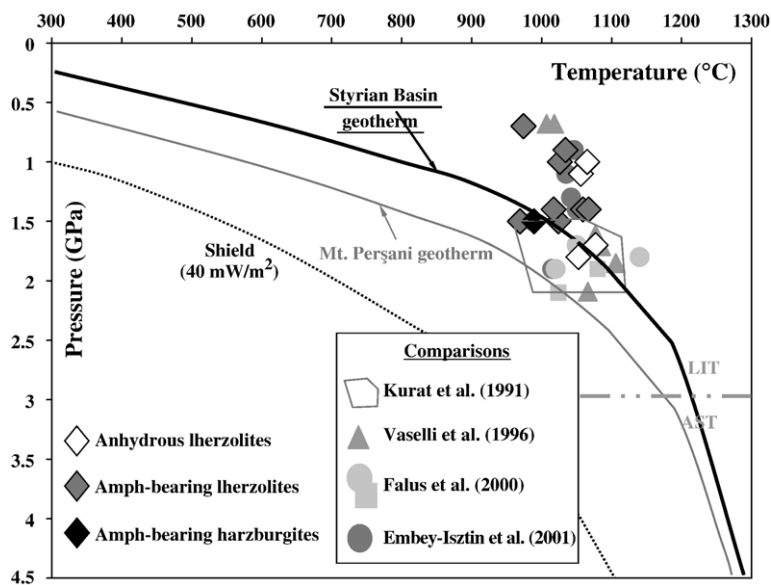


Fig. 7. Orthopyroxene–clinopyroxene thermobarometric estimates for Kapfenstein mantle xenoliths (Brey and Köhler, 1990; Köhler and Brey, 1990). Styrian Basin and Mt. Persani geotherms are from Sachsenhofer et al. (1997) and Lankreijer et al. (1997) respectively. Lithosphere/Asthenosphere (LIT–AST) boundary is from Horváth (1993).

Amph/cpx REE partitioning varies between 1.01 (± 0.1) for La to 0.73 (± 0.09) for Lu, in good agreement with natural and experimental data of Adam and Green (1994), Witt-Eickschen and Harte (1994) and Chazot et al. (1996). The latter authors in particular report slightly higher values for the whole spectrum of REE, with $^{amph/cpx}D_{HREE}$ varying from slight below to higher than 1.

Kapfenstein clinopyroxenes and associated amphiboles have the same geochemical affinity for Th, U and Zr, as shown by the quite similar $^{amph/cpx}D_{Th,U,Zr}$ values (Table 5) and also suggested by the lattice strain theory (Blundy and Wood, 2003). Diopsidic clinopyroxenes from Kapfenstein are peculiar for their high Zr, Th and U contents, resulting in $^{amph/cpx}D$ for these elements < 1 (Table 5). The high contents of these elements indicate that the reacting fluids should have been quite enriched in Zr, Th and U, lending support to the idea that a melt instead of a volatile-rich fluid was the metasomatizing agent.

8. Discussion

8.1. Evolutionary model

Based on the petrographic and geochemical observations, the following specific features of the Kapfenstein lithospheric mantle can be summarized, allowing to draw some conclusions:

- i) Composite xenolith KAP1: a strong similarity exists between amphibole from the large vein in this sample and the amphibole megacrysts from the same area, which are believed to be a product of alkaline magma fractionation (Zanetti et al., 1995; Vaselli et al., 1996). Amph-V trace element patterns do not match those of clinopyroxene in the matrix (Fig. 8a). Clinopyroxene displays LREE-depleted patterns (plus negative Zr and Ti anomalies) while amph-V is slightly LREE-enriched, which is not what would be expected from the distribution

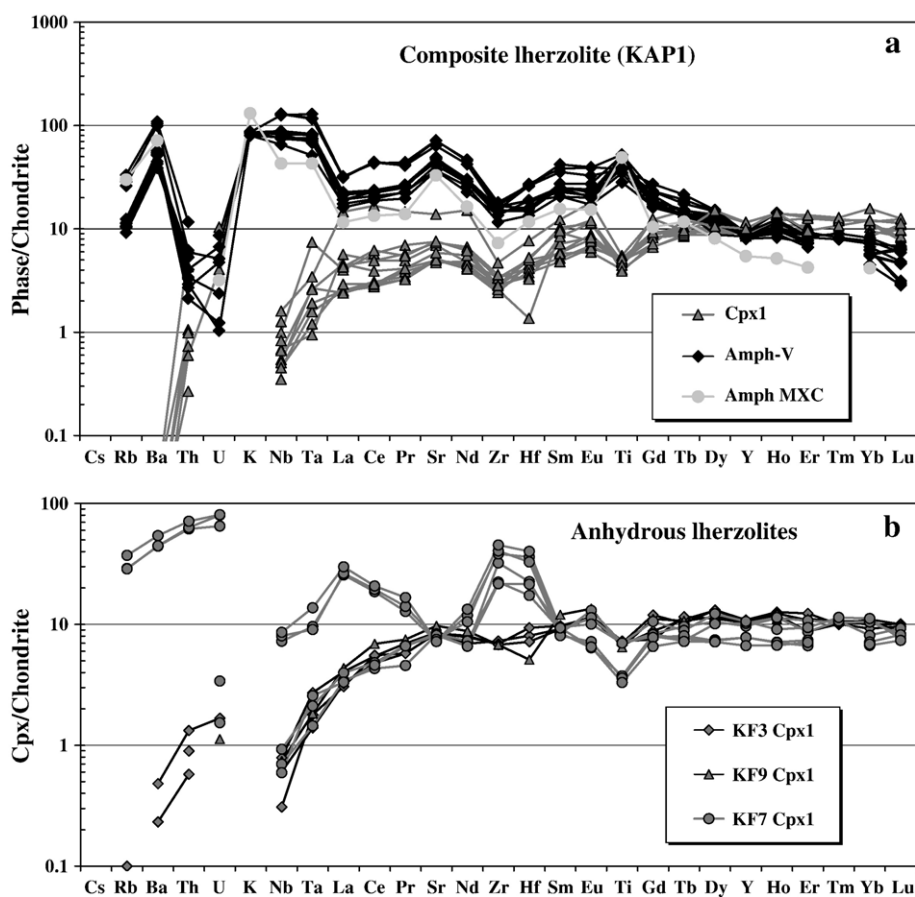


Fig. 8. Chondrite-normalized incompatible trace element diagrams for clinopyroxenes and amphiboles from Kapfenstein lithospheric mantle xenoliths. Abbreviations as in Figs. 2 and 4. Normalizing values from Sun and McDonough (1989).

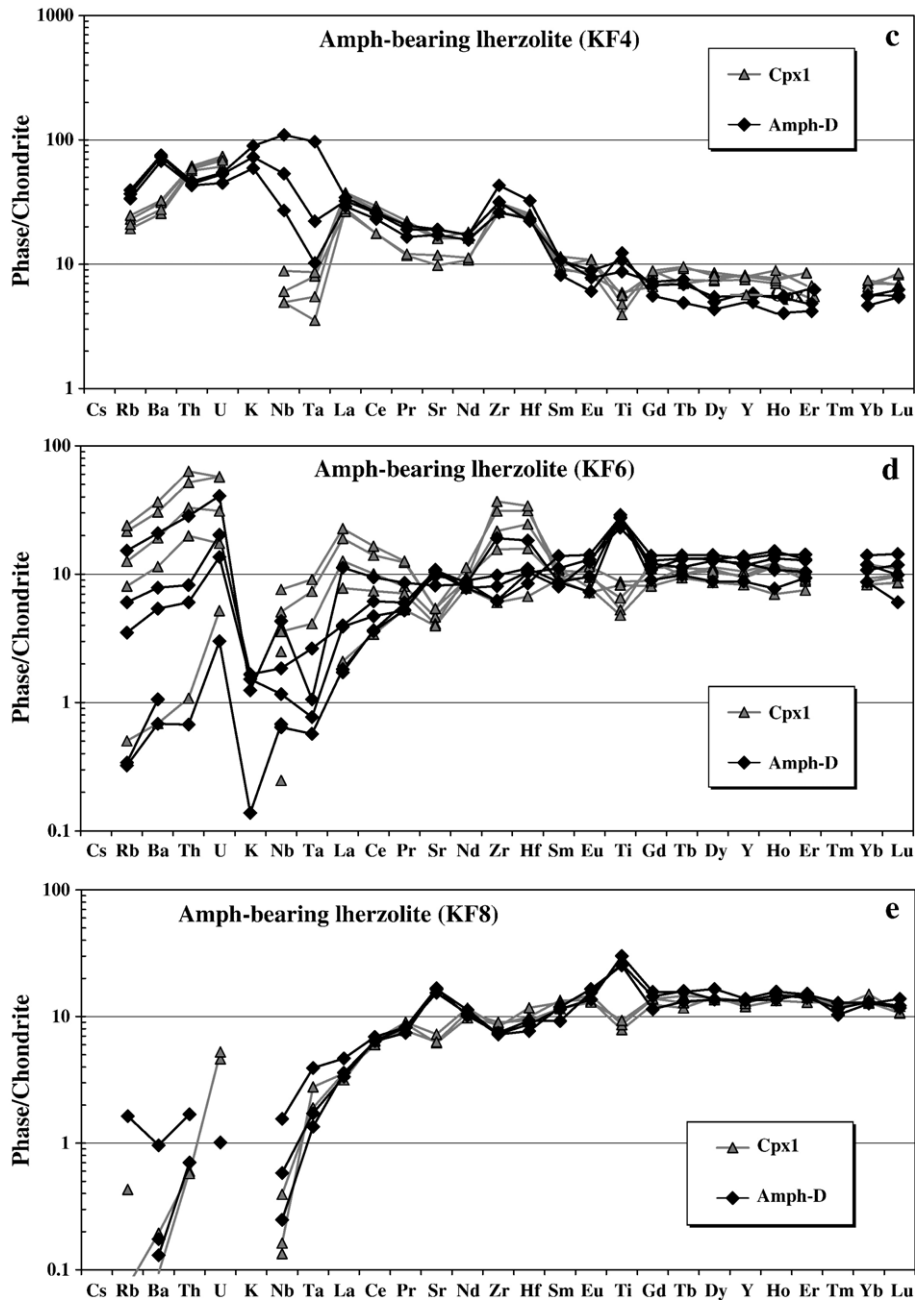


Fig. 8 (continued).

coefficients ($^{amph/cpx}D_{LREE} \approx 1$, Adam and Green, 1994; Witt-Eickschen and Harte, 1994; Chazot et al., 1996). Cpx in the matrix is very similar to those analyzed in anhydrous samples (Figs. 5 and 8b), suggesting that the original protolith underwent partial melting in the spinel facies (Beccaluva et al., 2001; Bonadiman et al., 2005), prior to being cut by the vein (KAP1 only). The decrease of $mg\#$ in

olivine, orthopyroxene, clinopyroxene and spinel approaching the vein is a further indication that this vein was formed by the late passage of magma fracturing the peridotite.

- ii) The coexistence of LREE-depleted and LREE-enriched clinopyroxene (Fig. 8b) in anhydrous lherzolite (sample KF7) is evidence that cpx enrichment predated amphibole formation. Thus,

metasomatic fluids enriched in these elements would have infiltrated the peridotite before the onset of amphibole formation. The infiltrating capability of these fluids was very limited, speaking in favour of a rather viscous metasomatizing agent or a volatile-rich fluid. This allowed the preservation of some depleted portion of the pre-metasomatic lithosphere.

- iii) Most samples contain disseminated amphibole, as isolated crystals or more often associated with sp and cpx. In texturally and geochemically well-equilibrated samples, amphibole trace element abundances parallel both LREE-depleted and LREE-enriched cpx (Fig. 8c,d,e). Amphiboles are enriched, and positive Zr and Hf anomalies are present, only when they coexist with enriched clinopyroxene (Fig. 8c,d), as also observed in amphibole from Kamchatka (Kepezhinskas et al., 1996). These facts coherently indicate that amphibole grew at the expense of sp and cpx.
- iv) Sample KF6 deserves a particular attention. As in anhydrous sample KF7, it bears both LREE-depleted and LREE-enriched cpx, but in this sample they coexist with LREE-depleted or slightly LREE-enriched amphibole (Fig. 8d). Amphibole is scarce (<1%vol), incipiently growing around clinopyroxene and with lower Rb, Ba, Nb, Ta and LREE contents than clinopyroxene (Fig. 8d). This would be possible only if amphibole started growing after clinopyroxene, trying to equilibrate with its overall geochemical budget.

Following this line of reasoning the lithospheric mantle below the Styrian Basin first underwent a limited partial melting episode in the spinel stability field, as recorded by the LREE-depleted (with weak negative Zr and Ti anomalies) cpx. Successively a metasomatic event enriched some portions of the lithosphere generating the Zr (and Hf, plus Th, U)-rich cpx. A small quantity of disseminated amphibole was formed after cpx as a result of a “sterile” (at least for trace elements) metasomatic event. The final process was an alkaline magmatism, which generated the amphibole vein, with clearly distinct geochemical budget.

No time constraints between the various episodes are available. However if we take into account samples KF6 (amphibole-bearing) and KF7 (anhydrous), where disequilibrium between the various clinopyroxenes is still present, the following evolution can be sketched out. The depletion event may have occurred well in the past, but the Zr-rich clinopyroxene-forming metasomatic event and the amphibole-forming one should have taken place close to one

other. If the first metasomatic event occurred a long time ago, or if a large time span had passed between this event and the next one, incompatible elements would have diffused and LREE-depleted clinopyroxene would not have been preserved in the sample. Similarly, if the subsequent “sterile” metasomatic event occurred a long time ago, all amphiboles would have re-equilibrated with the clinopyroxene, thus they would be LREE-enriched.

8.2. Nature of the metasomatic agents

The rarity of glass in these xenoliths strongly limits the possibility of inferring the nature of the metasomatic agent. According to the glass discrimination diagram proposed by Coltorti et al. (2000), this metasomatic agent should have been Na- or Ca-rich or both. Carbonatite metasomatism could be considered, as proposed by Demény et al. (2004) for a carbonate glass occurrence in amphibole-bearing xenoliths from Szentbékáll (Lake Balaton). However carbonatite metasomatism would fail to account for the high Zr and Hf contents recorded by clinopyroxene, as well as for the rather low Nb contents of amphibole. This metasomatism would produce Zr-poor cpx and Nb-rich amphibole, which is exactly the contrary of what it is observed in cpx and in many amphibole from Kapfenstein. It is well known that primary carbonatite melts are always characterized by selective depletion of Zr and enrichment of Nb (Hauri et al., 1993; Coltorti et al., 1999; Powell et al., 2004).

In the post-collisional alkaline magmatism of the Carpathian–Pannonian region, Seghedi et al. (2004b) recognized several asthenospheric and lithospheric components, some of which were significantly modified by subduction-related fluids. Trace element patterns of some basalts from the Styrian basin resemble those of “calc-alkaline, adakite-like magmas” from South Harghita (Transylvanian Basin) discussed by Seghedi et al. (2004b). These components detected in the Styrian basaltic magmas strongly support that the lithospheric mantle beneath the area may have experienced subduction-related metasomatic enrichment. Slab dehydration alone however will not be able to produce the enrichments in Th and Zr (and Hf) observed in Kapfenstein cpx, since these elements are unlikely to be mobilized by volatile-rich fluid (Hawkesworth et al., 1997). As a consequence, the metasomatizing fluid responsible for these enrichment was more likely to have been a melt. The most likely product of a MORB-like crust melting would be a SiO₂-, Na₂O-, Al₂O₃-rich magma, which could be termed “adakite” (without entering the problem of nomenclature in much detail) such as those found in Kamchatka (Kepezhinskas et al.,

1995), Aleutians (Yogodzinski et al., 1995) and the Austral Andes (Stern and Kilian, 1996; Kilian and Stern, 2002). This melt migrating through the mantle column above the subducting slab certainly changes its chemical and physical characteristics by continuous interaction with the peridotite matrix. As a result this latter increases its orthopyroxene modal contents (as observed in few Kapfenstein xenoliths with opx up to 38%), while most of the additional chemical budget will be accommodated in clinopyroxene up to onset of amphibole crystallization. Amphibole formation is strongly constrained by volatile and/or TiO_2 contents, which in turn may depend on T – P melting condition of the slab (Rapp et al., 1999; Tiepolo et al., 2001). According to the experimental work of Rapp et al. (1999) an adakite with strong positive Zr (and Hf) anomalies can be produced by melting a hydrous oceanic crust at 3.8 GPa. More recently

Pertermann et al. (2004) indicated that the presence of Zr anomalies (both positive or negative) in a liquid produced by melting of eclogite will largely depend on the cpx/garnet ratios in the residuum. In any case the SiO_2 -rich nature of the melt would lead to an increase in viscosity and polymerization degree, thus also limiting its migration capability.

Zr-(and Hf) enriched clinopyroxenes are not commonly found in mantle xenoliths, especially in spinel-bearing peridotites, or even in mafic lavas. Two occurrences were described by Kilian et al. (2002) for clinopyroxenes in mantle xenoliths from Southern Argentina and by Kovács et al. (2004) for clinopyroxenes in Type II xenoliths from Nograd–Gomor volcanic field (Hungary–Slovakia boundary) (Fig. 9a). Kilian et al. (2002) found a strong difference between Zr-depleted core and Zr-enriched rim of clinopyroxene in spinel-bearing xenoliths from Pali Aike, invoking

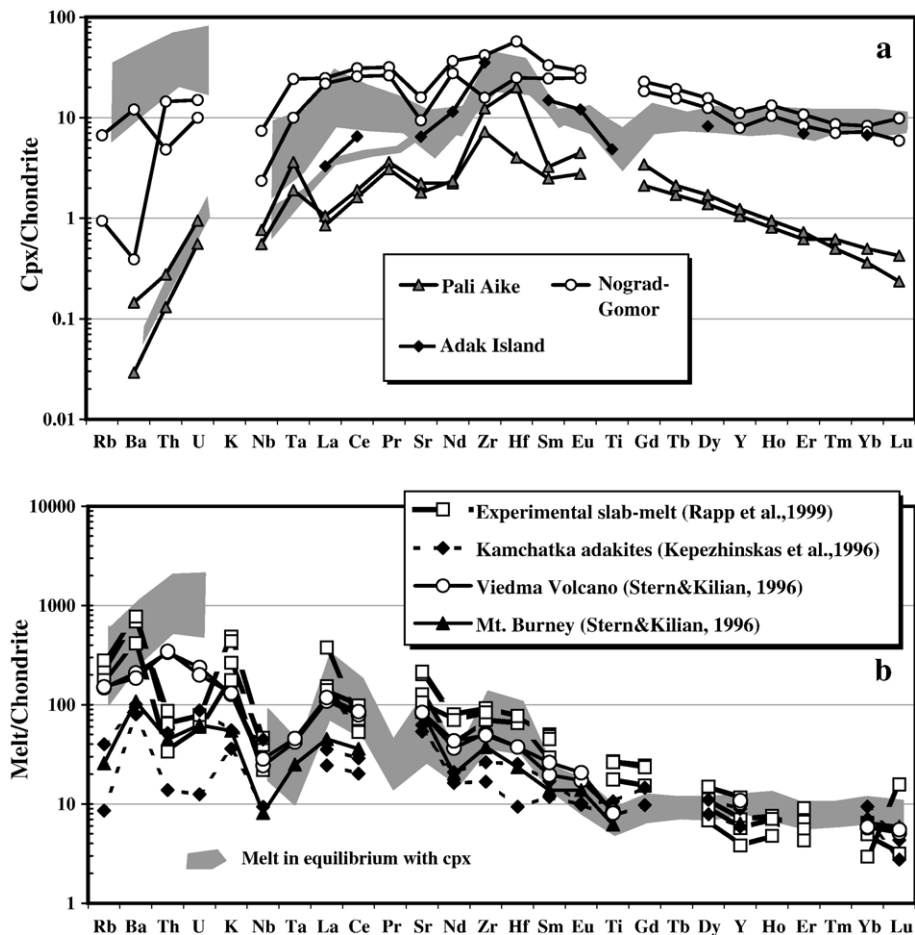


Fig. 9. a) Chondrite-normalized incompatible trace element patterns of clinopyroxene from anhydrous lherzolite, KF7 (gray field) compared with clinopyroxenes from Adak Island adakite (phenocryst), from clinopyroxenite xenolith from Nograd–Gomor volcanic field and from garnet–spinel-bearing peridotite of Southern Patagonia. b) Calculated melts (gray field) in equilibrium with Kapfenstein clinopyroxenes compared with experimental and natural adakites.

an HFSE-rich LILE-poor metasomatism recently affecting the shallower spinel-(and garnet-) bearing harzburgitic mantle of this region. Two hypotheses were put forward in order to explain this peculiar metasomatism: i) low degree melt, whose nature, however, was not addressed and ii) fluids derived from an upwelling depleted asthenosphere containing residual HFSE-rich slab components.

Kovács et al. (2004) found in Nograd–Gomor volcanic field clinopyroxene veins that formed first as magmatic cumulates from a basaltic melt (whose nature was not further specified), and were later metasomatized by an adakite melt as deduced from the amphibole composition. These clinopyroxenes have very high Zr contents (up to $40 \times \text{Ch}$) and the amphibole/clinopyroxene textural relationships are comparable with those of clinopyroxenes from Kapfenstein lherzolites. The inferred geotectonic setting for the Hungarian/Slovakian volcanic field was described as a retreating fore-arc, where mixing between slab-derived fluids and asthenospheric melt is most likely to occur.

Some adakitic lavas from the Andes and Kamchatka volcanoes show positive Zr anomalies (Kepezhinskis et al., 1996; Stern and Kilian, 1996; Kilian and Stern, 2002), similar, although less pronounced, to those found in experimental adakite/mantle interaction (Rapp et al., 1999) (Fig. 9b). Although quite variable in their range of incompatible trace elements, some cpx phenocrysts of adakitic lavas from the Aleutians (Yogodzinski and Kelemen, 1998) appear also to match quite well the pattern of Kapfenstein cpx (Fig. 9a). As a corollary the trace element contents of calculated melts (D after Basaltic andesites and Andesites from GERM data set: <http://earthref.org/GERM/main.htm>) in equilibrium with the Zr-enriched Kapfenstein cpx overlap quite well the compositional range of adakites, particularly regarding the Zr anomaly (Fig. 9b). Viedma volcano is peculiar being the only case where melt bears a Th content comparable to the inferred Kapfenstein metasomatizing agent. Stern and Kilian (1996) invoked the involvement of a variable, but significant, amount of subducted sediment for the generation of these peculiar lavas.

8.3. Amphibole generation

Amphibole is commonly found in experimentally-produced metasomatized peridotite that has interacted with a SiO_2 -rich slab-derived melt, with a melt/rock ratio < 1 (Sen and Dunn, 1994; Rapp et al., 1999), but, petrographic and geochemical evidence from Kapfenstein xenoliths clearly indicate that this phase was formed after cpx. This suggests that the overall physico-chemical conditions (water activity and/or melt/rock ratio) for the

formation of this volatile-bearing phase were not initially appropriate. Opx (and perhaps cpx) formation after reaction with the incoming melt, or changes in the melting condition of the downgoing slab, could have driven the overall composition and/or the melt/rock ratio toward volatile-saturated fluids, triggering amphibole crystallization. In both cases a substantial compositional change is not observed between cpx and amphib-D. It is doubtful if we may consider the event responsible for depleted amphib-D formation as a new, separate metasomatic event or as part of the same petrologic process which had already generated the enriched cpx. In any case the main geochemical features of the system remained constant. It was characterized by low Nb, Ta and Ti contents as expected in this kind of metasomatism, considering that rutile is commonly present in eclogite residua (Zack et al., 2002).

Petrographic and geochemical features support the idea that no genetic relationships exist between Kapfenstein amphib-V and amphib-D. In sample KAP1 Amph-D near the vein has a composition identical, in both major and trace elements, to that of Amph-V and no chemical fractionation due to percolation has been observed (Fig. 4a). On the other hand melt percolation from the thick vein is unable to explain both the large variation in incompatible element contents between the two types of amphiboles and the high Zr/Nb ratios recorded in Kapfenstein amphib-D (and clinopyroxenes). In numerical and experimental modelling, open-system melt migration by reactive porous flow would lead to crystallization of mg#-rich amphibole significantly enriched in Nb with respect to Zr, provided that the interstitial melt is progressively depleted in Ti by dissolution and mineral-forming reactions (Vernières et al., 1997; Tiepolo et al., 2001; Ionov et al., 2002).

A comparable situation to that of Kapfenstein was analyzed by Moine et al. (2001) for amphib-V and amphib-D from Kerguelen mantle xenoliths, where several analyses of disseminated amphiboles in a dunitic matrix at variable distances from a vein are reported. They show a strong Ti fractionation as a function of the percolation capability, but the overall variation in Nb and Zr contents is less than three times the values of the amphibole in the thick veins (Fig. 10). If we compare the Nb and Zr contents of Kapfenstein amphib-D and amphib-V, a difference of more than two order of magnitude can be observed (Fig. 6). Moreover Zr/Nb ratios vary between ca. 2.7 for amphib-V and 76.5 for amphib-D ($\text{Zr/Nb}_{\text{Amph-V}} = 1.9\text{--}3.2$; $\text{Zr/Nb}_{\text{Amph-D}} = 3.6\text{--}461$), thus increasing away from the vein. Irrespective of the vein distance, Kerguelen amphiboles maintain almost constant Zr/Nb ratios similar to those of amphibole from the Kapfenstein vein, but quite different from the great majority of Kapfenstein amphib-D (Fig. 10; Coltorti et al., 2004b).

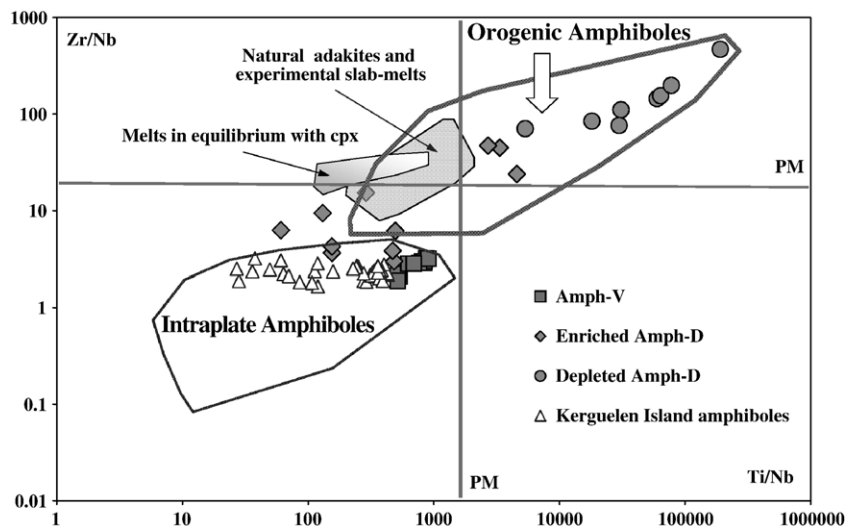


Fig. 10. Zr/Nb vs Ti/Nb ratios of Kapfenstein amphiboles. Analyses of vein and disseminated amphiboles (not distinguished) from Kerguelen mantle xenoliths are reported for comparison. Field of natural and experimental adakites is reported together with the field of melt calculated in equilibrium with Kapfenstein clinopyroxenes. Fields for intraplate and orogenic amphiboles are from Coltorti et al. (2004b).

Nb in particular can be used to discriminate between amphibole generated from intraplate metasomatism and amphibole generated from orogenic metasomatism. Kapfenstein amphibole has a Nb content of 0.16–31 ppm, straddling the fields of amphibole in xenoliths from alkaline within-plate magmas such as Antarctica (52–106 ppm; Coltorti et al., 2004b) and that of amphibole in xenoliths from calc-alkaline s.l. convergent magmas such as Japan (0.04–11 ppm; Johnson et al., 1996). As a consequence we can put forward the idea that geochemical features recorded by Kapfenstein amphiboles mark the transition between the end of the low Nb slab-derived melt (proto-adakite?) metasomatism responsible for the Zr-rich Nb-poor amphibole (and cpx) formation and the beginning of high-Nb alkaline intraplate metasomatism responsible for the vein formation (Fig. 10).

On the other hand the event responsible for the generation of amphibole in the large vein, the megacrysts and the Nb-enriched amph-D and, eventually, the intraplate alkaline magmas which brought the xenoliths to the surface speaks in favour of i) an involvement of differently enriched portion of the lithosphere or ii) an asthenospheric uprising which would have occurred between the Zr-rich cpx-forming and the Nb-rich amph-V forming events.

9. Conclusion

The petrographic and geochemical study of anhydrous and amphibole-bearing mantle peridotites from Kapfenstein allows the identification of two different

kinds of metasomatism which affected the lithospheric mantle beneath the Styrian basin.

The first event, which accordingly to Vaselli et al. (1996) occurred in slightly depleted lherzolites, is responsible for the genesis of LREE-(plus Th, U, Zr, Hf) enriched clinopyroxene and was caused by a slab melt-related (proto-adakite?) metasomatizing agent. These geochemical features can be obtained by partial melting of oceanic crust leaving an eclogitic residuum. The same metasomatic event was also responsible for the depleted amph-D formation, which grew at the expense of primary spinel and clinopyroxene, due to variation in f_{H_2O} and/or melt/rock ratios.

Enriched Amph-D are, however, characterized by progressive enrichment in LILE and Nb (and Ta), supporting the idea that a new metasomatic event was responsible for their generation. The same geochemical signature can be recognized in the amph-V which constitute the large vein cutting the slightly depleted lherzolite, which in turn resemble megacrysts and microphenocrysts from the host alkaline basalt. These facts lend support to the existence of a relationships between intraplate alkaline magmatism and metasomatism. Thus the style of metasomatism changed from a low Nb slab-derived melt (proto-adakite?) and high-Nb alkaline intraplate metasomatic agents. In this context it is matter of considerable debate if the Zr-cpx enrichment was acquired by reaction with melt derived from an oceanic crust or from eclogitic portions which were left behind by previous subduction events and scavenged by an asthenospheric uprising.

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