Composition and evolution of lithosphere beneath the Carpathian–Pannonian Region: a review

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Abstract

Our knowledge of the lithosphere beneath the Carpathian–Pannonian Region (CPR) has been greatly improved through petrologic, geochemical and isotopic studies of upper mantle xenoliths hosted by Neogene–Quaternary alkali basalts. These basalts occur at the edge of the Intra-Carpathian Basin System (Styrian Basin, Nógrád-Gömörf and Eastern Transylvanian Basin) and its central portion (Little Hungarian Plain, Bakony-Balaton Highland).

The xenoliths are mostly spinel lherzolites, accompanied by subordinate pyroxenites, websterites, wehrlites, harzburgites and dunites. The peridotites represent residual mantle material showing textural and geochemical evidence for a complex history of melting and recrystallization, irrespective of location within the region. The lithospheric mantle is more deformed in the center of the studied area than towards the edges. The deformation may be attributed to a combination of extension and asthenospheric upwelling in the late Tertiary, which strongly affected the central part of CPR subcontinental lithosphere.

The peridotite xenoliths studied show bulk compositions in the following range: 35–48 wt.% MgO, 0.5–4.0 wt.% CaO and 0.2–4.5 wt.% Al₂O₃ with no significant differences in regard to their geographical location. On the other hand, mineral compositions, particularly of clinopyroxene, vary according to xenolith texture. Clinopyroxenes from less deformed xenoliths show higher contents of ‘basaltic’ major elements compared to the more deformed xenoliths. However, clinopyroxenes in more deformed xenoliths are relatively enriched in strongly incompatible trace elements such as light rare earth elements (LREE).

Modal metasomatic products occur as both hydrous phases, including pargasitic and kearsutitic amphiboles and minor phlogopitic micas, and anhydrous phases — mostly clinopyroxene and orthopyroxene. Vein material is dominated by the two latter phases but may also include amphibole. Amphibole mostly occurs as interstitial phases, however, and is more common than phlogopite. Most metasomatized peridotites show chemical and (sometimes) textural evidence for re-equilibration between metasomatic and non-metasomatic phases. However, amphiboles in pyroxenites are sometimes enriched in K, Fe and LREE. The presence of partially crystallized melt pockets (related to amphiboles and clinopyroxenes) in both peridotites and pyroxenites is an indication of decompression melting and, rarely, incipient partial melting triggered by migrating hydrous melts or fluids. Metasomatic contaminants may be ascribed to contemporaneous subduction beneath the Carpathian–Pannonian Region between the Eocene and Miocene.

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Sulfide inclusions are more abundant in protogranular and porphyroclastic xenoliths relative to equigranular types. In mantle lithologies, sulfide bleb compositions vary between pentlandite and pyrrhotite correlating with the chemistry and texture of the host xenoliths. While sulfides in peridotites are relatively rich in Ni, those in clinopyroxene-rich xenoliths are notably Fe-rich.© 2004 Elsevier B.V. All rights reserved.

Keywords: Carpathian–Pannonian Region; Upper mantle xenoliths; Lithosphere; Deformation; Sulfide inclusions; Melt pockets; Metasomatism

1. Introduction and geodynamic setting

The history of shallow subcontinental lithospheric mantle, its geochemical mass balances and physical state, can be constrained by studies of upper mantle xenoliths commonly hosted in alkali basalts. The spatial–temporal pattern of volcanic activity in the Carpathian–Pannonian Region (CPR) (Fig. 1a) is closely related to geodynamic evolution, particularly the subduction of the European Plate beneath the ALCAPA and Tisza–Dacia blocks, and the subsequent extension and inversion events (Fodor et al., 1999; Csontos et al., 2002). These effects were instrumental in producing Early Miocene acidic calc-alkaline ignimbrites and tuff deposits, Middle Miocene to Recent calc-alkaline volcanic formations, and Late Miocene to Recent alkali basalts (Szabó et al., 1992).

Knowledge of the lithosphere beneath the region has been further improved by petrographic, geochemical and isotope geochemical studies of upper mantle xenoliths entrained in Neogene–Quaternary alkali basalts (Embey-Isztin et al., 1989; Kurat et al., 1991; Downes et al., 1992; Szabó and Taylor, 1994; Szabó et al., 1995a; Vaselli et al., 1995, 1996; Rosenbaum et al., 1997; Chalot-Prat and Boullier, 1997; Chalot-Prat and Arnold, 1999; Dobosi et al., 1999; Falus et al., 2000; Embey-Isztin et al., 2001; Bali et al., 2002) and bear fundamentally on geo-dynamic evolution of the Intra-Carpathian Basin System (Szabó et al., 1992; Embey-Isztin et al., 1993).

The Pannonian Basin (Fig. 1a) is a Mediterranean-type back-arc system that opened in response to lithospheric stretching behind the Carpathian arc during two extensional episodes: (1) Early to Middle: a Miocene passive rifting phase driven by subduction rollback (Royden et al., 1983), and (2) a Late Miocene syn- to post-rift phase accompanied by asthenospheric upwelling and active thinning of the mantle lithosphere. The second of these dominated the evolution of central parts of the basin (δ=4–8), while both western and eastern margins of the basin were subject to compressional regimes (Fig. 1a,b) (Huismans et al., 2001, additional references therein). The Neogene–Quaternary alkali basalts, sampling the upper mantle and lower crust, erupted in the central (Little Hungarian Plain, Bakony-Balaton Highland), western and northern marginal regions (Styrian Basin and Nógrád-Gömör, respectively) of the Pannonian Basin. Similar alkali basalt also occurs at the Eastern Transylvanian Basin within the CPR (Fig. 1a) and yield a unique opportunity to give an insight into the nature and evolution of the lithosphere by study of the xenoliths and to constrain such mantle processes as partial melting, deformation and mantle metasomatism in the different portions of the region which processes must have been related to the formation of the Intra-Carpathian Basin System (we use the term Intra-Carpathian Basin System in sense of Csontos 1995).

The purpose of this contribution is twofold: (1) to summarize the most significant lithologic, textural and geochemical knowledge of the subcontinental lithospheric mantle beneath the region, and (2) to show the possible relation between the formation and evolution of the Intra-Carpathian Basin System and the systematic geochemical and textural variability observed in the xenoliths using previous studies, but also incorporating results of our current researches, i.e., deformation analysis and detailed study of melt pockets and sulfide blebs of the upper mantle xenoliths.

2. Mantle petrology and deformation

Based on studies of upper mantle xenoliths hosted in the Neogene–Quaternary alkali basalts from the CPR (e.g., Embey-Isztin et al., 1989; Kurat et al., 1991; Downes et al., 1992; Szabó and Taylor, 1994; Szabó et al., 1995a; Vaselli et al., 1995, 1996; Chalot-
Fig. 1. (a) Lithospheric thickness of the Carpathian–Pannonian Region after Lenkey (1999). Calk-alkaline volcanic fields and major upper mantle xenolith localities in the Plio-Pleistocene alkali basaltic occurrences are also indicated: SBVF—Styrian Basin Volcanic Field; LHPV—Little Hungarian Plain Volcanic Field; BBHVF—Bakony-Balaton Highland Volcanic Field; NGVF— Nógrád-Gömör Volcanic Field; ETBVF—Eastern Transylvanian Basin Volcanic Field. (b) Schematic W–E cross section of the area studied through alkali basaltic occurrences of SBVF, BBHVF and ETBVF (Szabó et al., 1995b).
Prat and Boulier, 1997; Bali et al., 2002), the lithospheric mantle lithologically is relatively heterogeneous because spinel lherzolites, harzburgites and dunite are all present and there is a peculiar abundance of wehrlites, websterites, clinopyroxenites (Fig. 2). Breakdown products of garnet-bearing mantle fragments have been found in pyroxenite xenoliths (Török, 1995) and some peridotite xenoliths, too (Falus et al., 2000). The orthopyroxene/clinopyroxene ratio of the CPR mantle xenoliths shows a great variability (between 0 and 32) compared to the subcontinental lithospheric mantle rocks around the world, which generally exhibit values around 2 or slightly higher (Downes et al., 1992) (Fig. 2). The very high ratios can be observed not only in pyroxene-rich rock types (i.e., websterites) but also in clinopyroxene-rich lherzolites and clinopyroxene-bearing dunites particularly in the Styrian Basin (e.g., Bali et al., submitted for publication).

The peridotite (basically spinel lherzolite) xenoliths, representing residual material of the mantle with complex history, show variable textural features strongly related to the locations within the CPR. The xenoliths from the eastern and western portions of the CPR are characterized by the dominance of protogranular and protogranular to porphyroclastic textures (after Mercier and Nicolas, 1975), whereas in the central part of the region more deformed and recrystallized xenoliths (equigranular and secondary recrystallized or poikilitic as Embey-Isztin et al., 1989 called the latter one) are also present in considerable abundance (e.g., Kurat et al., 1991; Embey-Isztin et al., 1989; Szabó et al., 1995b). The Nógrád-Gömör Volcanic Field (NGVF) located at the northern edge of the Pannonian Basin, however, represents a wide variety of upper mantle xenolith textures ranging from the less protogranular and protogranular to porphyroclastic textural types at the northern part of the volcanic field to porphyroelastic, equigranular and secondary recrystallized textures towards the southern part of the xenolith occurrences (Szabó and Taylor, 1994).

Significant correlation was found between textural types and equilibrium temperatures, estimated from the major element content, of the CPR xenoliths (Szabó et al., 1995b). Mantle xenoliths with protogranular textures always show the highest equilibrium temperatures (1150–1050 °C), except for the ETBVF suite which displays slightly lower temperatures (1050–1000 °C). Whereas porphyroelastic, equigranular and protogranular to porphyroclastic textures (after Mercier and Nicolas, 1975), whereas in the central part of the region more deformed and recrystallized xenoliths (equigranular and secondary recrystallized or poikilitic as Embey-Isztin et al., 1989 called the latter one) are also present in considerable abundance (e.g., Kurat et al., 1991; Embey-Isztin et al., 1989; Szabó et al., 1995b). The Nógrád-Gömör Volcanic Field (NGVF) located at the northern edge of the Pannonian Basin, however, represents a wide variety of upper mantle xenolith textures ranging from the less protogranular and protogranular to porphyroclastic textural types at the northern part of the volcanic field to porphyroelastic, equigranular and secondary recrystallized textures towards the southern part of the xenolith occurrences (Szabó and Taylor, 1994).

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nular and secondary recrystallized samples (if present) show lower equilibrium temperatures (ranging from 1080 in porphyroclastic to 850 °C in some poikilitic samples; Szabó et al., 1995b; Embey-Isztin et al., 2001).

Xenoliths from all the five Neogene–Quaternary major volcanic fields (i.e., xenolith localities) were selected for careful textural and deformation analysis in order to describe the behavior of the lithospheric mantle beneath the region during the formation of the whole Intra-Carpathian Basin System (Falus et al., 2000; Falus and Szabó, 2002). Textural patterns recognized in the xenoliths from SBVF display minor to moderate deformation and recrystallization producing dominantly protogranular, porphyroclastic textures also recognized earlier (Kurat et al., 1991; Vaselli et al., 1995). The often-observed tilt walls in olivine and orthopyroxene porphyroclasts clearly indicate that the deformation occurred in the dislocation creep regime (Falus, 2004). Some intensively deformed xenoliths are clearly observed from the ETBVF (Vaselli et al., 1996). Moreover, some of the xenoliths display strong mylonitic deformation (Fig. 3a), which is a unique feature in the CPR (Falus, 2004). Similar textural feature has been quite rarely observed in xenoliths derived from the mantle worldwide (e.g., Pike and Schwartzmann, 1977). Nevertheless, the extent of deformation in the eastern

Fig. 3. Photomicrographs of upper mantle xenoliths from the CPR showing characteristic textural features. (a) Peridotite from ETBVF displaying mylonitic deformation. Shearing parallel to horizontal axis of the image. Cross-polarized light. (b) Peridotite from the SBVF. Pyroxene-spinel clusters as breakdown products of garnet olivine reaction. Plain-polarized light. Dashed line showing outline of the cluster. (c) Peridotite from BBHVVF. Moderate elongation subparallel to horizontal axis of the image. Cross-polarized light. LPO pattern showing moderate to strong preferred orientation—[100][010] slip. Horizontal lines on stereograms indicate lineation. (d) Peridotite from BBHVVF. Uniform elongation of grains from bottom left to top right of the image. Cross-polarized light. LPO pattern shows strong preferred orientation—[100][010] slip. Horizontal line on stereograms indicates lineation. Abbreviations: ol—olivine; opx—orthopyroxene; cpx—clinopyroxene; sp—spinel; mp—melt pocket; mx—matrix.
and western margins of the basin system was low enough to preserve the products of garnet breakdown due to decompression (Fig. 3b) in both regions (Falus et al., 2000). These textures were formed in the dislocation creep regime indicated by the moderate to strong lattice preferred orientation (LPO) (Falus and Szabó, 2002). We suggest that the same type of deformation took place in the upper mantle beneath the central part of the Pannonian Basin as indicated by porphyroclastic to equigranular xenoliths from the LHPVF and BBHV (Embey-Isztin et al., 1989; Downes et al., 1992; Szabó et al., 1995a) displaying moderate (Fig. 3c) to strong LPO (Fig. 3d). This deformation, however, was partly overprinted due to annealing and static recrystallization (Falus, 2004). The marginal lithospheric sections could have avoided recrystallization due to their marginal position, thicker lithosphere (Fig. 1a,b) and the cooling effect of the suspected subducted slab in the North and East (Bielik et al., 1991; Tomek and Hall, 1993).

The high abundance of statically recrystallized equigranular and secondary recrystallized xenoliths in the BBHV, and some of the LHPVF and South NGVF, recognized also earlier (Embey-Isztin et al., 1989; 2001; Downes et al., 1992; Szabó and Taylor, 1994; Szabó et al., 1995a), clearly indicates a strong deformation and subsequent annealing process in the upper mantle beneath the central part of the CPR. This latter thermally activated process (Lloyd et al., 1997) clearly suggests the anomalously high position of the asthenosphere (Fig. 1a,b) and the cooling effect of the suspected subducted slab in the North and East (Bielik et al., 1991; Tomek and Hall, 1993).

Nevertheless, mineral composition in the CPR xenoliths, particularly clinopyroxene, varies according to the xenolith textures as pointed out by Downes (1990) and Szabó et al. (1995b). Less deformed xenoliths have clinopyroxene with high amount of basaltic major elements (Al, Ti, Na and Fe) compared to more deformed samples. However, clinopyroxenes in the more deformed and more intensively recrystallized xenoliths show higher content of strongly incompatible trace elements such as light rare earth elements. This feature can rather be explained by the influence of an incompatible element-rich fluid phase impregnated the preexisting deformed peridotitic assemblage, which provided a more permeable pathway for the migrating fluids than the undeformed peridotite (Downes, 1990) and resulted only in cryptic metasomatism and contemporaneous annealing. However, depletion in basaltic major elements may also be related to fluid/melt migration and reaction with the peridotitic wall-rock as Kelemen et al. (1992) pointed out. This would also explain the observed decoupling between major and

### 3. Major, trace element and radiogenic isotope geochemistry of peridotite assemblages

The peridotite xenoliths from the alkali basalts of the CPR have a bulk compositions ranging from 35 to 48 wt.% MgO, 0.5 to 4.0 wt.% CaO, 0.2 to 4.5 wt.% Al$_2$O$_3$, and 0.01 to 0.24 wt.% TiO$_2$. There are no significant chemical differences of xenoliths among the major localities although, the compositional range of the NGVF covers the highest MgO-bearing xenoliths, whereas ranges of the SBVF and ETBV xenoliths involve samples containing the lowest MgO content. Xenoliths from the BBHV and LHPVF show a transitional character (Fig. 4). Concentration of basaltic elements, representing Al$_2$O$_3$ and TiO$_2$, and of CaO displays a negative correlation with MgO (Fig. 4) as Downes and Vaselli (1995) have already noted. These chemical features of the CPR xenoliths are in agreement with xenoliths from other localities (e.g., Rhenish Massive, Massif Central) and with alpine massive peridotites (e.g., Lherz) (Bodinier et al., 1988; Downes et al., 1991; Wilson and Downes, 1991). It is suggested that gradual depletion in basaltic elements is connected at first consideration to partial melting event(s).

Rare orthopyroxene porphyroclasts in equigranular xenoliths display lobated grain boundaries. These porphyroclasts display remarkable zonation in Al- and Na-contents decreasing towards the rims, whereas Ca displays considerable increase towards the rims. Similar orthopyroxene porphyroclasts were described from the Oman ophiolite (Dijkstra et al., 2002). This feature is suggested to represent reaction of these orthopyroxenes with migrating fluids, suggesting that annealing and recrystallization were not in every case an isochemical process, but also involved migrating fluids/melts.
trace elements world wide (Frey and Green, 1974; Wilshire and Shervais, 1975).

The Sr and Nd isotopic compositions of separated clinopyroxenes of the CPR peridotite xenoliths are shown in Fig. 5. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ values range from 0.7016 to 0.7048 and 0.5126 to 0.5136, respectively, and show negative correlations. The highest $^{143}\text{Nd}/^{144}\text{Nd}$ and lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values can usually be observed in the SBVF and ETBVF xenoliths (Vaselli et al., 1995; 1996; Bali et al., submitted for publication). Whereas, the clinopyroxenes from xenoliths of the central part of the Pannonian Basin (BBHVF and LHPVF) and Nógrád-Gömör (northern Pannonian Basin) have low $^{143}\text{Nd}/^{144}\text{Nd}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ values (Downes et al., 1992; Szabó and Vaselli, unpublished). It is also clear that the radiogenic isotopic behavior of the BBHVF xenoliths show strong correlation with textural types; the less deformed xenoliths display the most depleted isotopic character, whereas the deformed samples have the strongest enrichment in radiogenic Sr. The enrichment of radiogenic isotopes in the central segment of the CPR could be related to reaction of peridotites with percolating melts/fluids (Downes et al., 1992; Downes and Vaselli, 1995) causing cryptic metasomatism, mentioned above. The origin of these melts/fluids can be related by either asthenospheric melts similar to the host basalt or to subduction related calc-alkaline melts in case of those samples displaying strongly radiogenic

Fig. 4. Harker diagrams of bulk compositions of CPR xenoliths for TiO$_2$, Al$_2$O$_3$, CaO vs. MgO. Data source for SBVF: Kurat et al. (1991), Vaselli et al. (1995) and Bali et al. (submitted for publication); for LHPVF: Embey-Isztin et al. (1989), Downes et al. (1992) and Szabó et al. (1995a); for BBHVF: Embey-Isztin et al. (1989) and Downes et al. (1992); for NGVF: Szabó and Taylor (1994); for ETBVF: Vaselli et al. (1995). For comparison, the field of the European subcontinental lithosphere mantle (Downes, 2001) is also shown.
4. The modification of dry peridotitic material by modal metasomatism

Besides the dry olivine-rich peridotitic assemblage, xenoliths showing enrichment in both anhydrous phases (as clin- and orthopyroxenes) and/or hydrous minerals (such as amphiboles and phlogopites) are also present. Such clinopyroxenite and composite (clinopyroxenite/peridotite) xenoliths occur in all localities. Although most of the pyroxenite xenoliths from the CPR have igneous textures and do not reflect deformation (Embey-Isztin et al., 1990; Kovács et al., this volume), some of the rocks derived from the ETBVF do display textural evidence for stress-induced recrystallization. Undulatory extinction and subgrain development are frequently identified features (Szász, unpublished).

Chemical composition of clinopyroxene-rich xenoliths generally shows enrichment in basaltic and light rare earth elements. These rock fragments are the products of asthenosphere-derived mafic melts crystallized as pyroxenite cumulates either in the lithospheric mantle or lower crust (e.g., Dobosi et al., 2003; Kovács et al., this volume) similar to those studied in the East Eifel (Sachs and Hansteen, 2000) and Penghu Islands xenoliths (Ho et al., 2000). In several peridotite xenoliths from the BBHVVF not only clinopyroxenite but websterite veins can also be observed, which are interpreted as reaction products of mafic melts and wall-rock peridotites. This mafic melt could be similar to those that produced the clinopyroxene salvages (Bali et al., submitted for publication).

In contrast with the clinopyroxene-rich bands, the orthopyroxene-enriched rocks (i.e., orthopyroxene-rich websterites and orthopyroxenites), occurring rarely in the BBHVVF (Bali, 2004; submitted for publication) and LHPVF (Szabó et al., 1995a,b), were produced by the infiltration of Si-rich silicate melt or fluid. This melt/fluid transported high amount of incompatible trace elements and reacted with the strongly depleted peridotitic assemblage suggested by the U-shaped chondrite normalized REE-patterns of the clinopyroxenes (Bali, 2004; Bali et al., submitted for publication). Based on the Sr–Pb-isotopic composition of the separated clinopyroxenes of these xenoliths, the results indicate that these rocks were derived from asthenospheric sources with similar Sr–Nd isotope compositions (Downes et al., 1992; Rosenbaum et al., 1997).

Fig. 5. The Sr and Nd isotopic compositions of separated clinopyroxenes of the CPR xenoliths. Data source for SBVF: Vaselli et al. (1995) and Bali et al. (submitted for publication); for LHPVF: Downes et al. (1992); BBHVVF: Downes et al. (1992); for NGVF: Szabó and Vaselli (unpublished); for ETBVF: Vaselli et al. (1995). For comparison, the isotopic compositions of the host basalts (Embey-Isztin et al., 1993), MORB and bulk earth (Zindler and Hart, 1986) are also shown.
orthopyroxene-rich rocks, the reagent Si-rich melt/fluid might have been released from subducted slab.

Hydrous phases as pargasitic and kearsutitic amphiboles and phlogopitic micas also occur as modal metasomatic minerals in both peridotite and pyroxenite xenoliths from the CPR. Amphiboles, occurring as interstitial phases, veins and selvages, are more common than phlogopites. In spite of the significant textural variation of amphiboles, they display moderate variation in major element composition. The majority of amphiboles from the NGVF, LHPVF, SBVF and ETBVF peridotites are pargasites, whereas BBHVF amphiboles show wide compositional range (Fig. 6). Amphiboles in clinopyroxene-rich xenoliths and amphibole megacrysts were also plotted and it is clearly revealed that amphibole megacrysts display both higher Fe\(^{3+}\)/[Fe\(^{3+}\)+Al(VI)] ratio and Ti-content than amphiboles in pyroxene-rich xenoliths and veins (Fig. 6). The occurrence of amphiboles in the SBVF and ETBVF shows weak preference to textural types, presumably because of the low variability of textures in these regions. Nevertheless, amphiboles in the xenoliths from the central part of the basin show strong preference to the most deformed and recrystallized rocks. They are absent from protogranular xenoliths. Presence or absence of amphiboles is independent from both texture and chemistry of clinopyroxene xenoliths in the NGVF (Kovacs et al., this volume) and in the BBHVF (Bali, 2004).

Considering the trace elements in amphiboles, large differences can be observed in all localities. At the SBVF mostly interstitial amphiboles have been found in peridotite xenoliths, which show the widest compositions, ranging from LREE-depleted to LREE-enriched primitive mantle normalized patterns. In the case of the ETBVF, interstitial amphiboles from peridotite xenoliths also display a wide compositional

![Fig. 6. Fe\(^{3+}\)/[Fe\(^{3+}\)+Al(VI)] vs. Ti for amphiboles in upper mantle xenoliths and also for amphibole veins and megacrysts from the CPR. Data source for SBVF: Vaselli et al. (1996) and Bali et al. (submitted for publication); for LHPVF: Szabó et al. (1995a); for BBHVF: Embey-Izsztin (1976), Bali et al. (2002), Dobosi et al. (2003) and Bali (2004); for NGVF: Szabó and Taylor (1994) and Kovács et al. (this volume); for ETBVF: Zanetti et al. (1995) and Vaselli et al. (1995). The fields of pargasite, Mg-hastingsite and kaersutite are taken after Leake (1978). Values of Fe\(^{3+}\) were calculated using equation of Droop (1987). Amphiboles define well-expelled fields according to their occurrence (i.e., peridotite, clinopyroxene-rich xenoliths and megacrysts).](image-url)
range with the lowest REE-contents, whereas amphiboles from amphibole-rich veins have the most enriched compositions in LREEs and amphiboles from relatively common clinopyroxenite xenoliths show a moderately enriched REE pattern. Interstitial amphiboles are frequent phases in the NGVF peridotite xenoliths. They show a relatively wide compositional range with a slight depletion in LREEs, whereas amphiboles, occurring often in clinopyroxenite xenoliths, show the same REE pattern as those ones which are the most REE-enriched in the NGVF peridotite xenoliths. Amphiboles from the central part of the Pannonian Basin (BBHVF, LHPVF), occurring as very rare interstitial phases in peridotites xenoliths, have a flat REE-pattern. Amphiboles in the clinopyroxene-rich veins also show flat or n-shape REE distribution (Fig. 7). Based on major- and trace-element characteristics of these amphiboles, occurring either as interstitial phase in peridotites or as constituent in veins or clinopyroxenite xenoliths, the

![Diagram of Amphiboles in Xenoliths](image_url)

**Fig. 7.** Primitive mantle normalized (Sun and McDonough, 1989) rare earth element patterns of amphiboles in xenoliths from the CPR. Amphiboles in peridotite xenoliths display wider compositional range and relatively lower abundance of either light or heavy rare earth elements compared to amphiboles in veins and clinopyroxene-rich xenoliths (data from Kurat et al., 1991; Szabó and Taylor 1994; Szabó et al., 1995a,b; Zanetti et al., 1995; Vaselli et al. 1995, 1996; Dobosi et al., 2003; Kovács et al., this volume; Bali, 2004).

![Diagram of Partition Coefficients](image_url)

**Fig. 8.** Amphibole/clinopyroxene partition coefficients using composition of the coexisting minerals. Data source for SBVF: Vaselli et al. (1996) and Bali et al. (submitted for publication); for LHPVF: Szabó et al. (1995a); for ETBVF: Vaselli et al. (1995).
metasomatic agents that produced them could have been volatile-bearing silicate melt which originated from either subducted slab or asthenospheric mantle (Szabó and Taylor, 1994; Kovács et al., this volume).

However, in several cases, textural equilibrium cannot be assumed as the amphiboles consume the surrounding mantle phases; the majority of the hydrous phases are chemically in equilibrium with the anhydrous mantle minerals in the peridotites as suggested by the calculated partition coefficients (e.g., Embey-Isztin, 1976; Szabó and Taylor, 1994; Szabó et al., 1995a; Vaselli et al., 1995; 1996; Bali et al., 2002; Bali et al., submitted for publication, Kovacs et al., this volume). Only three xenoliths in the suites studied, occurring as clinopyroxene-rich veins from ETBVF and SBVF (Vaselli et al., 1995; 1996; Bali et al., submitted for publication), show disequilibrium (Fig. 8). This means that either they could not reach the chemical equilibrium with the depleted clinopyroxene from the peridotitic wall-rock or they formed further from the vein conduit, which transferred metasomatic agents as Tiepolo et al. (2001) and Ionov et al. (2002) concluded studying peridotite xenoliths and clinopyroxene veins in them from Spitsbergen.

Melt pockets in peridotite xenoliths are often related to melting and breakdown of metasomatic amphiboles. These amphiboles often went through mantle processes as they became ‘source materials’ for the subsequent silicate melt pocket formation, which were reported in several xenolith locations in the central part of the CPR (Szabó et al., 1995a, 1996; Embey-Isztin and Scharbert, 2000; Demény et al., 2000; Bali et al., 2002), although Schiano and Bourdon (1999) summarized that the interstitial silicate melt pockets can be considered as open systems and their phases preserve only the last equilibrium state. Consequently, study of the melt pockets provides direct insight into the melting and crystallization processes, as well as mechanism of mixing and migration of melts in the mantle. This way, we can obtain more information on the spatial particularities in thermal evolution of the subcontinental lithospheric mantle of the Pannonian Basin system.

In the LHPVF, BBHVF and NGVF melt pockets can be considered to be common although minor constituents of mantle xenoliths containing assemblages of glass, ±clinopyroxene, ±olivine, ±spinel, ±plagioclase phenocrysts, and ±carbonate, ±sulfide, ±apatite. Their size corresponds to those of the mantle minerals (Fig. 9a,b). They occur solely in deformed and recrystallized xenoliths. Detailed microprobe and trace element studies revealed that the melting of mantle amphibole (and coexisting clinopyroxene) played a significant role in the formation of the melt pockets even in those cases when the amphibole was completely missing in the assemblage of the studied xenoliths (Fig. 10).

Fig. 9. Photomicrographs of silicate melt pockets in upper mantle xenoliths from the CPR. The photos were taken under plane-polarized light. (a) Melt pocket, occurring interstitial to olivine (ol) and orthopyroxene (opx), containing resorbed pargasitic amphibole (amp), glass (gl) and newly formed clinopyroxene and spinel in protogranular BBHVF peridotite. (b) Melt pocket (mp) occurring interstitial to olivine (ol) and orthopyroxene (opx) close to the host basalt in secondary recrystallized NGVF dunite. Melt pocket consists of newly formed fine-grained clinopyroxene, spinel and plagioclase.
Fig. 10. Al₂O₃, CaO, FeOₓ, MgO, Na₂O vs. MgO variation diagrams of bulk compositions of melt pockets from the BBHV and NGVF xenoliths. Data source for BBHV: Bali et al. (2002); for NGVF: Szabó et al. (1996). For comparison, composition of average BBHV pargasitic amphibole (Bali et al., 2002), NGVF mantle clinopyroxene (Szabó and Taylor, 1994), BBHV alkali basalt (Embey-Isztin et al., 1993), NGVF alkali basalt (Szabó, unpublished) and NGVF andesite (Szabó, unpublished) is also shown.
Furthermore, in case of few xenoliths from both the BBHVF and NGVF, external melts/fluids should be also assumed as the bulk composition of the melt pockets strongly differ from the mantle minerals (Szaboé et al., 1996, Bali et al., 2002). The trace element composition of the BBHVF melt pockets further shows strong enrichment in highly incompatible elements displaying similar primitive mantle normalized patterns to the calc-alkaline andesites of the CPR. This suggests that the external melt/fluid phase incorporated into the composition of those melt pockets was released from subducted oceanic slab (Bali et al., 2003).

5. Significance of sulfide inclusions and chalcophile elements in mantle processes

Recent studies showed that knowledge of distribution of chalcophile [Cu and platinum group elements (PGEs)] provides important contribution to the understanding of mantle process such as partial melting (Frey et al., 1985; Peach et al., 1990; Fleet et al., 1996; Gueddari et al., 1996; Gaetani and Grove, 1997; Handler and Bennet, 1999; Rehkamper et al., 1999; Ripley et al., 2002). Distribution of these elements is basically controlled by sulfide inclusions in the lithospheric mantle during partial melting (Fleet et al., 1996; Handler and Bennet, 1999; Alard et al., 2000; Burton et al., 2000; Lorand and Alard, 2001).

Consequently, a synthesis of petrographical and geochemical results of sulfide blebs in the CPR xenoliths reported by Szabó and Bodnar (1995); Falus (2000); Zajacz and Szabó (2003) and Török et al. (2003) provides a profound insight into the evolution of the mantle beneath the area studied. Four different types of sulfide inclusions can be distinguished in the CPR peridotite xenoliths: (1) Single, isolated, spherical primary inclusions, which are enclosed in orthopyroxene, clinoxyroxene and rarely olivine (Fig. 11b,c,d). Their grain size ranges between 10 and 120 μm. The majority of the studied sulfide inclusions in the CPR peridotites belong to this group. (2) Interstitial polygonal sulfide grains to the mantle silicates with curvilinear or linear boundaries, which indicate textural equilibrium with their environments (Fig. 11a). The size of these sulfide grains ranges from 50 to 220 μm. Interstitial sulfide grains can be found dominantly in protogranular and protogranular to porphyroclastic xenoliths in the CPR. (3) Large (up to 300 μm) isometric primary sulfide blebs or elongated sulfide pods intergrown with hydrous minerals such as amphibole or rarely phlogopite that were found in modally metasomatized SBVF and NGVF xenoliths. (4) Tiny (<15 μm) spherical or negative crystal-shaped sulfide blebs, occurring along healed fractures in primary mantle minerals as secondary inclusions.

Deformation and recrystallization of the mantle rocks play important role in the sulfide abundance in mantle peridotites. A clear relation between the degree of deformation and sulfide abundance has been found in the NGVF xenoliths (Szabó and Bodnar, 1995), where protogranular to porphyroclastic peridotites contain the highest modes of sulfides (~0.5 vol.% and the recrystallized equigranular samples have the lowest sulfide contents (~0.02 vol.%). This relation is less evident in the xenoliths from BBHVF because only strongly deformed peridotites (characteristic for this region as described above) were studied (<0.05 vol.%). Furthermore, xenoliths, derived from the Styrian and Eastern Transylvanian Basins all have protogranular and protogranular to porphyroclastic textures and are characterized by very low sulfide content (<0.01 vol.%) (Falus, 2000).

The enclosed and interstitial sulfide grains (Fig. 11a–d) interpreted as primary inclusions consist of Ni-poor monosulfide solid solution (mss), and pentlandite or Ni-rich mss, and a Cu-bearing phase: chalcopyrite or intermediate solid solution (iss). Bulk composition of primary sulfide inclusions (Fig. 12) shows a wide range of Ni+Co content between 12 and 32 wt.%, and Cu content between 0.1 and 7.9 wt.%; however, some sulfide blebs from ETBV are extremely high Cu-content up to 14.7 wt.%. The bulk Cu content of sulfide blebs shows negative correlation with the degree of depletion of the host xenolith represented by the mg# of clinopyroxenes (Fig. 13). We believe that behavior of copper during melting in the mantle is controlled by sulfide inclusions. This behavior could be a straight consequence of its high partition coefficient for sulfide/silicate melt (ranging from order of 10^2 to 10^3) depending on the sulfur fugacity (Frey et al., 1985; Peach et al., 1990; Gueddari et al., 1996; Ripley et al., 2002) and the high incompatibility of Cu in rock forming silicate and oxide phases. The texture of
xenoliths studied also correlate with the Cu content of the sulfide inclusions showing a profound Cu depletion in the more deformed samples (Fig. 13). The negative correlation between the bulk Cu content of sulfide inclusions and mg# of coexisting clinopyroxenes is a clear evidence for the incompatible behavior of copper in the subcontinental lithospheric mantle. Based on experimental works (Fleet and Pan, 1994; Li et al., 1996), partial melting of sulfide produces liquid phase enriched in Cu and solid mss phase depleted in copper. This leads us to suggest that partial melting of sulfide inclusions and mobilization of the low viscosity sulfide melt fraction (Gaetani and Grove, 1999) could occur during deformation and partial melting processes. This supposition is also confirmed by the systematic difference in sulfide abundance of different textural types of xenoliths showing lower sulfide content in the more deformed samples. This also suggests that higher degree of deformation in the lithospheric mantle corresponds to stronger depletion (or higher degree of partial melting) in the studied mantle segment as we discussed above relying on previous studies (Downes, 1990; Downes and Vaselli, 1995; Szabó et al., 1995b).

Ni is also a sensitive element during partial melting of sulfides and may be enriched in the sulfide melt, but it was taken out of consideration because of the Ni equilibrium distribution between olivine and sulfide.

Fig. 11. Photomicrographs of different textural types of sulfide inclusions. The photos were taken under reflected light: (a) two-phase sulfide inclusion composed of pentlandite (pn) and chalcopyrite in olivine of protogranular to porphyroclastic spinel lherzolite from the NGVF; (b) sulfide inclusion composed of chalcopyrite, monosulfide solid solution (mss), and pentlandite enclosed in olivine of protogranular to porphyroclastic spinel lherzolite from the NGVF; (c) enclosed sulfide inclusion composed of chalcopyrite and pentlandite in clinopyroxene of porphyroclastic spinel lherzolite xenolith from the SBVF; (d) enclosed multiphase sulfide inclusion in spinel of porphyroclastic spinel lherzolite from the ETBVVF. Pentlandite occurs as exsolved lamellae in the monosulfide solid solution. Chalcopyrite occurs at the outer edges of the inclusion.
which is able to modify the Ni content of sulfide inclusions (Fleet and MacRae, 1988; Fleet and Stone, 1990).

6. Concluding remarks

Previous studies of the CPR have established that the Intra-Carpathian Basin System evolved in two stages during the Miocene, involving: passive rifting as a response to subduction rollback, and subsequent active rifting and lithosphere thinning in the central part of the basin. On the basis of the evidence from basalt-hosted xenoliths, we can offer several additional conclusions regarding the evolution of subcontinental lithosphere in the Intra-Carpathian Basin System:

1. A significant correlation exists between dominant xenolith textural types and their geographic locations. Basically undeformed (protogranular) or only slightly deformed (protogranular to porphyroclastic) xenoliths occur at the margins of the basin system and lack any lattice-preferred orientation. Statically recrystallized, annealed

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Fig. 12. Bulk chemical composition of sulfide blebs from different locations of the CPR upper mantle xenoliths plotted in the Cu–Fe–(Ni–Co)–S system (Kullerud et al., 1969). Data source for SBVF, BBHVF and ETBVF: Falus (2000); for LHPVF: Szabó (unpublished); for NGVF: Szabó and Bodnar (1995). For comparison, clinopyroxene-rich NGVF xenoliths are also shown (Zajacz and Szabó, 2003).

Fig. 13. Mg# of clinopyroxenes vs. bulk Cu content of sulfide inclusions enclosed in silicate phases of different textural types of upper mantle xenoliths of the CPR. Data source for SBVF: Vaselli et al. (1996), Bali et al. (submitted for publication); for LHPVF: Szabó et al. (1995a), Falus (2000) and Szabó (unpublished); for BBHVF: Falus (2000) and Bali et al. (2002); for NGVF: Szabó and Taylor (1994), and Szabó and Bodnar (1995); for ETBVF: Vaselli et al. (1995) and Falus (2000).
(equigranular, secondary recrystallized) xenoliths occur more frequently towards the center of the basin, show moderate to strong lattice-preferred orientation, and systematic correlation between geochemical character and texture. Compared to undeformed samples, annealed samples are relatively depleted in ‘basaltic’ major elements, whereas trace elements and radiogenic isotopes are relatively enriched in equigranular and recrystallized samples. Bulk Cu contents and the abundance of sulfide blebs in upper mantle xenoliths also correlate with inferred partial melt degree and deformation state of the mantle. Sulfides in the equigranular and recrystallized samples (depleted in basaltic major elements) show relatively low bulk Cu contents.

(2) The widespread occurrence of modal amphibole in CPR xenoliths indicates that subcontinental lithospheric mantle in the region was pervasively metasomatized. Xenolithic amphiboles from the central portion of the Pannonian Basin show a marked tendency to deformed textural types, suggesting relationship of metasomatic processes to basin formation. While it has been assumed that metasomatic agents affecting the region mainly comprise percolating basaltic melts, the geochemical data suggest that at least some derive from subducting slabs associated with the Carpathian arc-trench rollback system.

(3) Silicate melt pockets were observed in xenoliths from the central and northern part of the CPR. These features and their geographic confinement are attributed to two possible factors:

(a) The interaction of migrating slab-derived melts or fluids with pre-existing amphiboles and clinopyroxenes to produce new, metasomatically induced melt fractions;

(b) Decompression melting of amphibole-dominated assemblages, prevalent in central parts of the basin where melt pockets are more abundant and ratios of amphibole to melt pocket abundance in xenoliths are lower. This type of process is consistent with the notion of mantle upwelling beneath the central part of the Pannonian Basin causing decompression and reheating during the second, syn-rift stage of basin evolution.

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