MITT.ÖSTERR.MINER.GES. 150 (2005)

MANTLE XENOLITHS IN NEOGENE VOLCANIC ROCKS OF THE STYRIAN BASIN

by

A. Mogessie[1], I. Fritz[2], K. Ettinger[1] & A. Proyer[1]

[1]Institut für Erdwissenschaften, Bereich Mineralogie und Petrologie
Universität Graz, Universitätsplatz 2, 8010 Graz, Austria
[2]Landesmuseum Joanneum, Abteilung für Geologie und Paläontologie
Raubergasse 10, 8010 Graz, Austria

Volcanism in the Styrian Basin

The historical term "Styrian Volcanic Arc" for the volcanic province that extends from Pohorje in Slovenia, through SE Austria and into the Balaton area of Hungary (Fig. 1), was criticised by EMBEY-ISZTIN et al. (1989, 1990) because (i) it contradicts the modern concept of plate tectonics in that the alkali basaltic volcanoes are non-orogenic and unrelated to any subduction zone, (ii) geophysical evidence points to the presence of a mantle diapir below the Pannonian area and the alkali basalts and tuffs of Styria, Burgenland, Kisalföld and the Balaton regions are therefore most likely to have been generated by partial melting in the rising diapir, and (iii) the centre of the volcanic activity is in the Balaton area rather than Styria. It was therefore proposed that this term be replaced by the genetically neutral term ***Transdanubian Volcanic Region (TVR)***.

The volcanic rocks in the area comprise dacites, andesites, trachyandesites, trachytes, basalts, alkali basalts, basanites and nephelinites (HERITSCH, 1967). Lava compositions vary with both their spatial and their temporal distributions. The older Miocene (~ 17–15 Ma) volcanic activity is confined to the southern part of the volcanic region and is characterized by andesitic and trachytic lavas, whereas the younger Pliocene to Pleistocene (4–1 Ma) volcanics are of alkali-basaltic composition (HERITSCH, 1967; KOLLMANN, 1965). The main extension-related eruption provinces are in the Styrian basin and Burgenland (Eastern Austria), Balaton (Western Hungary), northern Hungary, southern Slovakia, and in the Eastern Translyvanian Basin of Romania (Fig. 1). As summarised by VASELLI et al., (1996a) the Plio-Pleistocene alkali basalt eruptions in this ***Carpatho-Pannonian Region (CPR)*** occurred subsequent to the subduction-related calc-alkaline volcanism that formed the Carpathian arc (SZABO et al., 1992). Both types of magmatic activity penetrated different tectonic microplates, which form a mosaic beneath the CPR (CSANTOS et al., 1992).

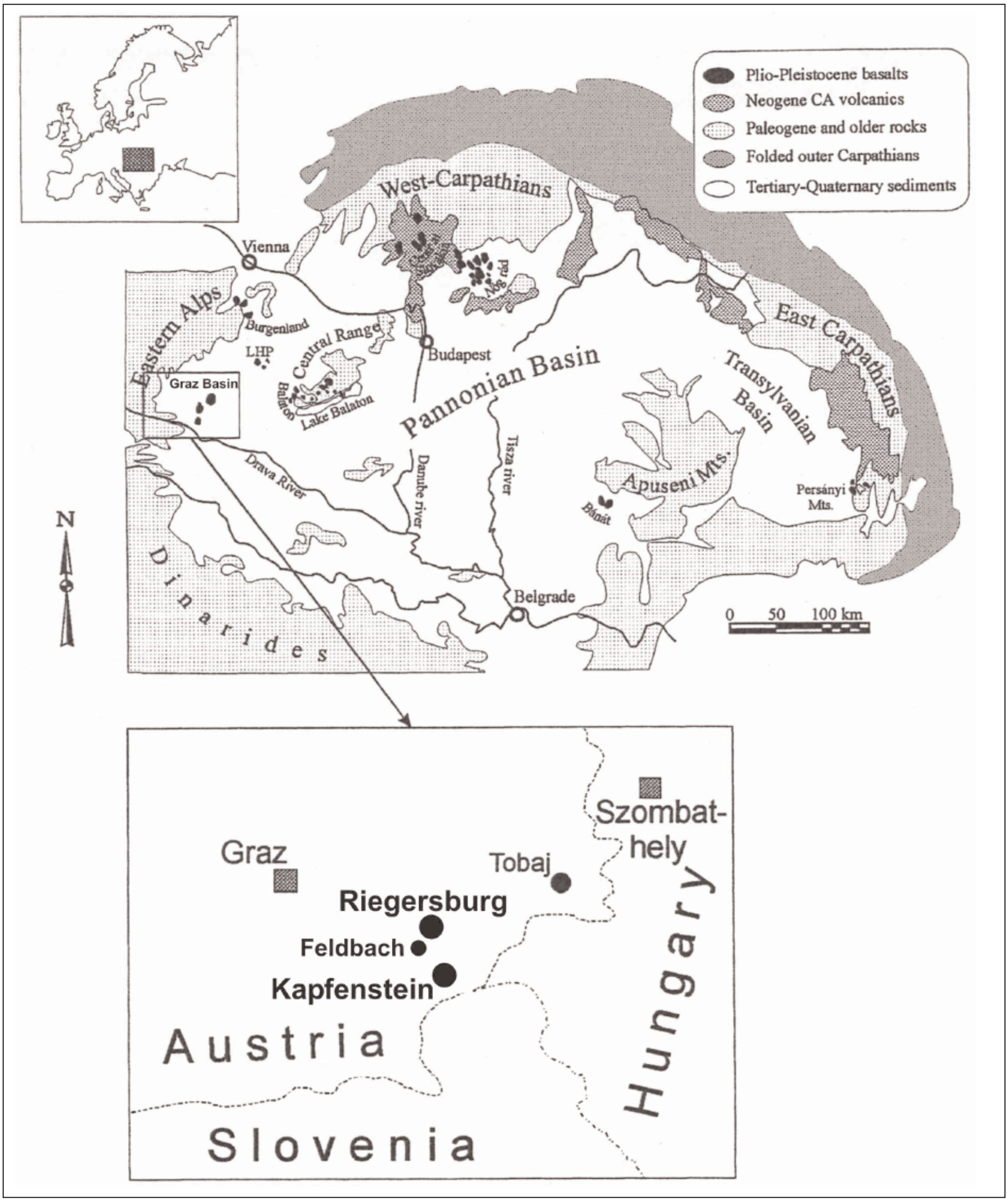

Fig. 1

Geological sketch map of the Pannonian Basin and the upper mantle xenolith localities of the Graz Basin, eastern Austria (adopted from DOBOSI et al., 1999).

Sedimentation of the Eastern Styrian Basin probably started in the Ottnangium and is documented since the Karpatium (Fig. 2). At the end of the Karpatium the first phase of volcanic activity produced acid to intermediate K-bearing magmas, commonly latitic, (e. g. Ilz-Walkersdorf, Gleichenberg-Mitterlabill-Perbersdorf, Weitendorf-Wundschuh). Radiometric age dating suggests that this phase goes back as far as the Lower Badenium and was followed by a second

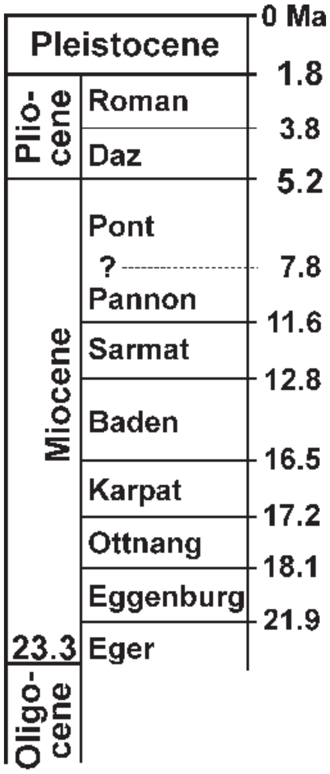

Fig. 2
A simplified geological timescale.

eruptive phase of Lower Pannonium age which has only been documented in Burgenland, at Pauliberg and Oberpullendorf (BALOGH et al., 1994). The sedimentary environment during this activity was mainly of limnic-fluvial character and only rarely marine, with deposits of a braided river system including vast flood plains and large areas of still water (according to the facies model of KOVAR-EDER & KRAINER, 1990).

The Plio-Pleistocene (4–1 Ma) volcanism is mainly basaltic and shows both effusive and explosive characteristics. The effusive deposits in Klöch and Hochstraden are interpreted as superficial lava sheets (WINKLER, 1913), while the basalt of the Steinberg (near Feldbach) is partly subvolcanic (MURBAN, 1939). In addition to these effusive manifestations of the volcanism in Eastern Styria there was also substantial explosive activity, documented by numerous tuff deposits. About 30 - 40 tuff volcanoes are known (KOLLMANN, 1965), most of them linked to explosion pipes. The diameter of these diatremes tapers off at depth, as documented by refraction-seismic studies in both the basaltic tuff area of Altenmarkt near Riegersburg and at the southern end of the basaltic tuff in Stadtbergen, near Fürstenfeld (KOLLMANN, 1965). Because of their strong resistance to weathering compared to the surrounding clastic sediments, which are generally unconsolidated, the volcaniclastics form prominent topographic highs (e. g. Riegersburg, Kapfensteiner Kogel, Kindsbergkogel & Seindl). Among these volcanoes are several tuff cones, which contain a wide variety of xenoliths of both crustal and upper mantle origin.

Location 1: Different types of pyroclastic rocks form the volcanic hills of the Riegersburg – Altenmarkt locality (FRITZ, 1994). The rock on which the Riegersburg castle is built (Fig. 3, photo a) shows many signs of a phreatomagmatic eruption mechanism (FRITZ, 1996). The low vesicularity of the juvenile components, the high frequency and great number of eruptions are just as characteristic of phreatomagmatic eruptions as the low-angle cross-stratification which can be detected in some places.

In the volcanic areas of Altenmarkt, near Riegersburg, (see Table 1 for representative analysis) clear layers of (ash) lapilli tuffs, the formation of which can be largely attributed to fall out deposits, are exposed in an old quarry, (Fig. 3). In some areas bomb sag structures can be found, indicating "wet" conditions of formation. Well layered fine grained sediments provide evidence of the presence of a maar lake at the end of the volcanic activities in Altenmarkt.

The mantle xenoliths embedded in the host basalt of this area are usually rather small (up to a few centimetres), some of them nicely preserved in the building stones used for the pavements, walls and doorways of the castle. In some cases gabbroid inclusions in basaltic bombs are documented (Photo b). However, most of the xenoliths found in this locality are of crustal origin, very prominently exposed along the footpath up to the Riegersburg.

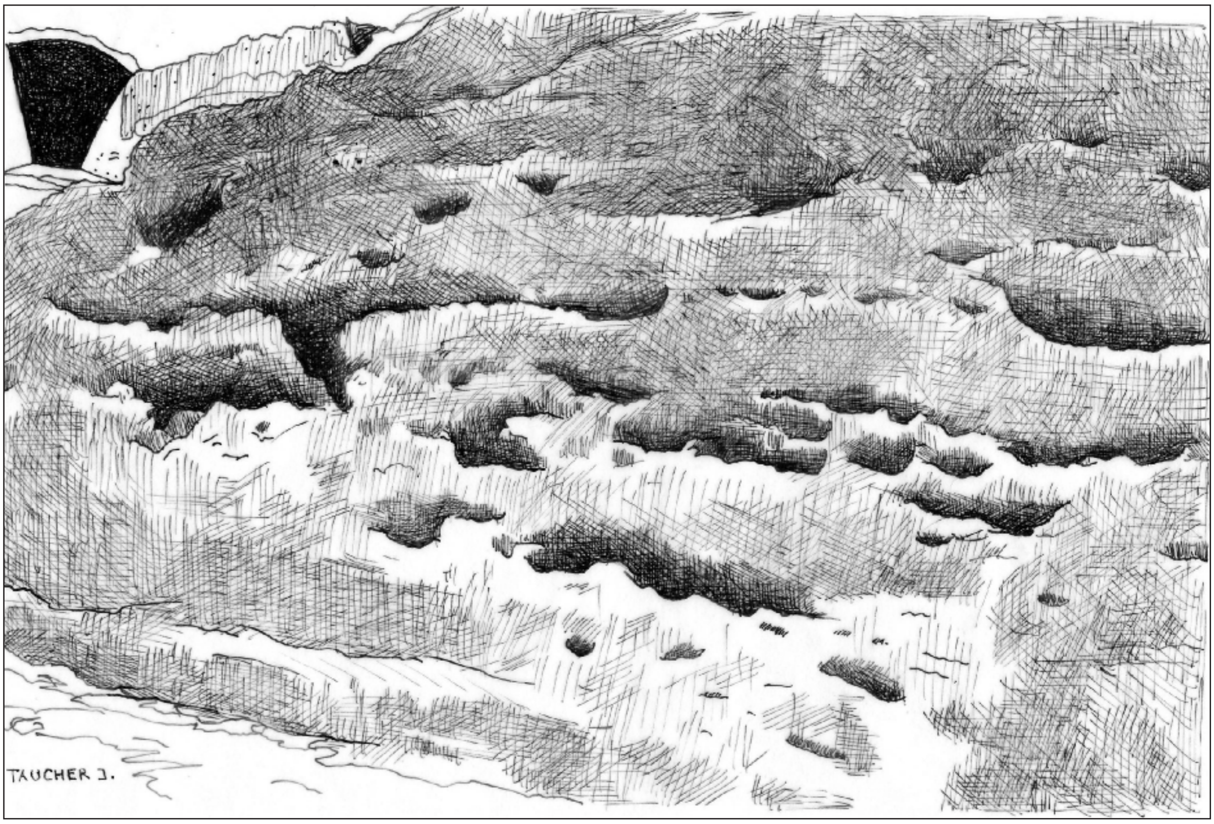

Photo a

Riegersburg castle with a drawing of the volcanic outcrop (by contemporary styrian artist Josef Taucher).

	Kapfenstein					Riegersburg
	Websterite	Harzburgite	Lherzolite	Hbl-Lherzolite	Basanite	Basanite
SiO_2	47.49	41.92	42.78	43.21	45.41	46.35
TiO_2	0.47	0.008	0.03	0.08	1.95	1.82
Al_2O_3	12.85	0.96	1.55	2.74	14.39	14.04
Cr_2O_3	0.184	0.183	0.303	0.396	0.038	-
FeO_t	7.49	8.57	8.09	9.57	9.7	10.85
MnO	0.165	0.125	0.133	0.164	0.197	0.17
MgO	19.9	46.26	43.28	39.8	8.28	8.3
CaO	9.93	0.59	1.75	2.01	9.44	9.67
Na_2O	0.961	0.081	0.127	0.469	4.14	3.2
K_2O	0.005	0.005	0.017	0.029	2.18	2.27
Total	99.44	98.7	98.06	98.46	95.73	96.67
Mg/(Mg+Fe)	82.6	90.6	90.5	88.1	60.3	43.34
Co	53.3	125.	113.	109.	36.5	NA
Ni	560.	2750.	2270.	2010.	190.	NA
Rb	0.24	-	-	-	82.7	NA
Sr	18.6	-	-	-	1100.	NA
Ba	9.	-	-	-	924.	NA
La	0.44	0.19	0.25	0.78	68.5	NA
Ce	1.77	-	-	2.5	124.5	NA
Sm	1.15	0.033	0.088	0.28	8.8	NA
Eu	0.45	0.017	0.037	0.11	2.79	NA
Tb	0.4	-	-	-	1.07	NA
Dy	3.	-	-	-	5.71	NA
Yb	1.83	0.09	0.16	0.25	2.37	NA
Lu	0.29	0.015	-	0.036	0.33	NA

Table 1

Major (wt.%) and trace element (ppm) contents of host basanite and ultramafic xenoliths from Kapfenstein, Austria.

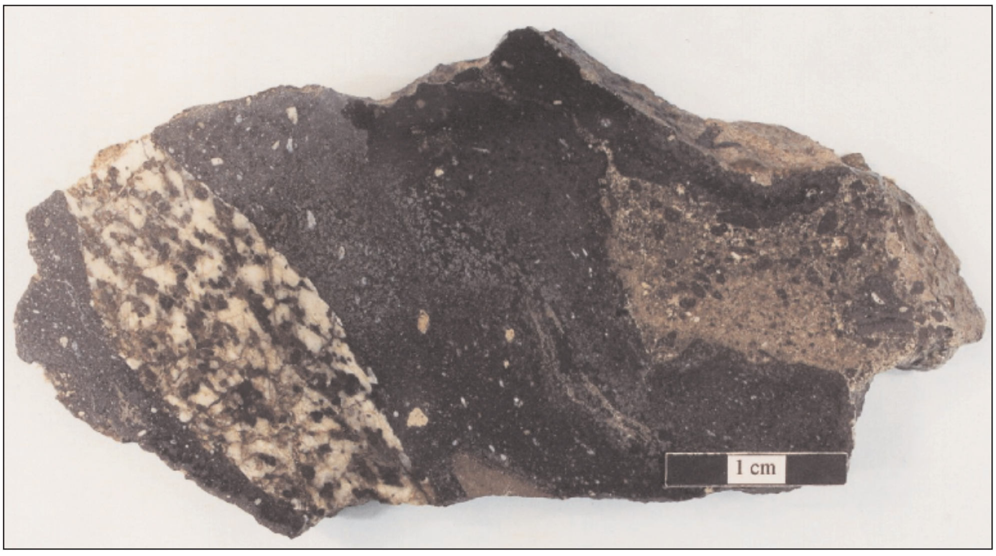

Photo b
Gabbro xenolith in a basaltic tuff.

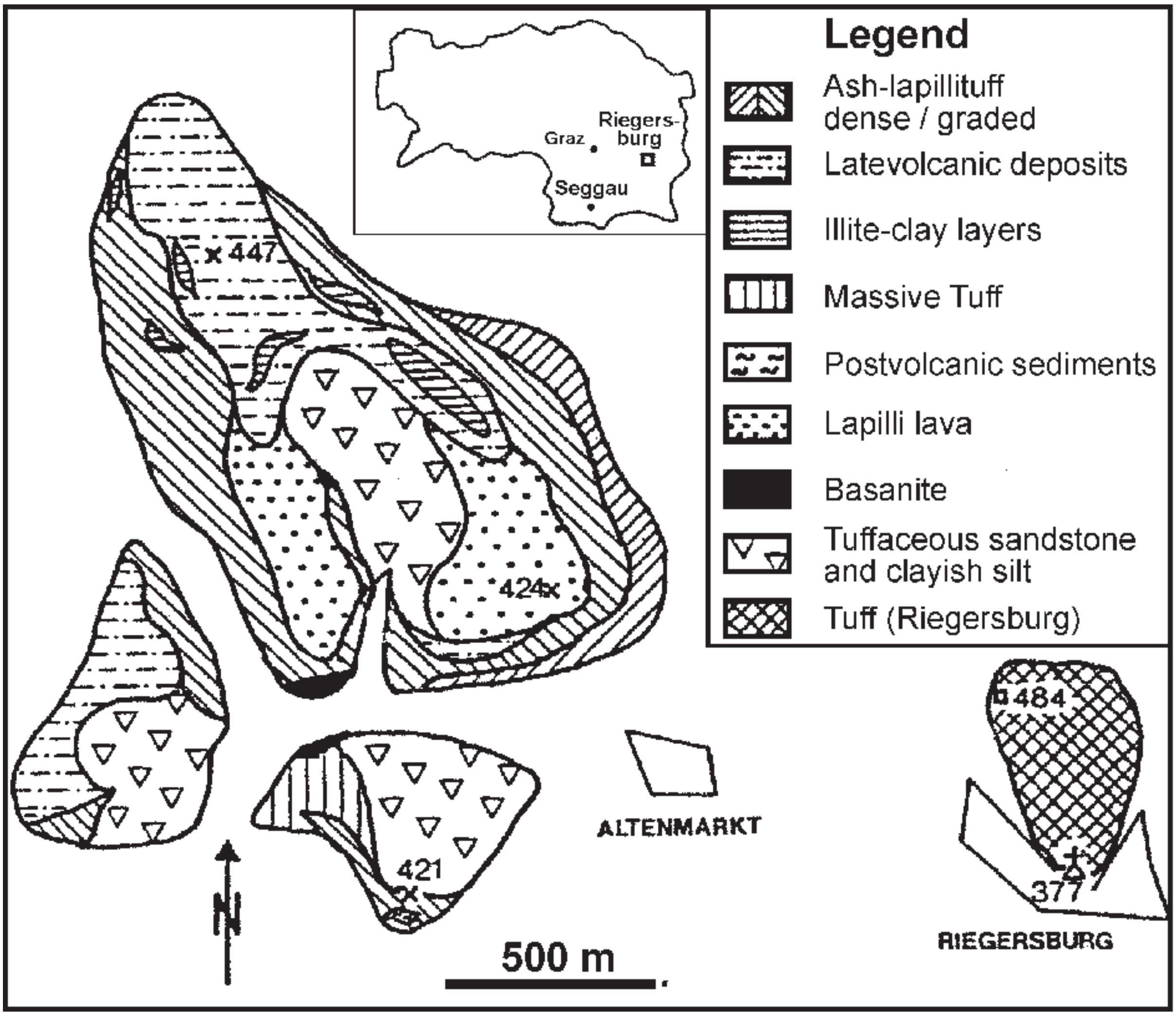

Fig. 3
Simplified geological map from Altenmarkt near Riegersburg.

Ultramafic mantle xenoliths from Kapfenstein, Eastern Styria, Austria

Location 2: The prominent hill of Kapfenstein, adorned with yet another castle, is also a volcanic edifice of the second, younger phase of volcanism in the Styrian basin (Fig.1, photo c), with tuff cones and a wide variety of xenoliths of both crustal and upper mantle origin. A considerable number of ultramafic mantle xenoliths of variable composition (see below) have been found and investigated from this site. They occur embedded in mainly porphyroclastic sediments that also contain a high percentage of crustal xenoliths, including large rounded pebbles from river beds. The various features of the volcano-sedimentary environment are described and are visible in exposures along the “Geotrail”. Mantle xenoliths can be found at a few locations along the trail and in exposures immediately beneath the castle.

Photo c
Kapfenstein castle (seen from the south).

Kapfenstein was recognized early as a locality for mantle xenoliths and has subsequently became a classical one (SIGMUND, 1899, SCHADLER, 1913, SCHOCKLITSCH, 1933). Analytical data on xenoliths from Kapfenstein have been reported by SCHADLER (1913), ROSS et al, (1954); KURAT (1971), KURAT et al., (1976, 1977a, 1980, 1991), VASELLI et al., (1996a), DOBOSI et al., (1999) and SCHNEIDER, (2004). Based on analytical data, KURAT (1971) ascertained the upper mantle origin of these rocks. In addition, KURAT et al., (1977b, 1980, 1991), VASELLI et al. (1996a) reported extensive geochemical data of these xenoliths with the objective of characterizing the upper mantle below Kapfenstein and to shed light on the genesis of these rocks.

Petrographic descriptions of the xenoliths and the host rocks (from KURAT et al., 1980)

Host basanite: This is a vesicular vitrophyric rock with abundant phenocrysts of augite and plagioclase; common are xenoliths of olivine, orthopyroxene, clonopyroxene, and spinel which obviously have been derived from peridotite inclusions; interstitial glass is very alkali-rich and bears variable amounts of small plagioclase laths and titanian magnetite.

Ultramafic xenoliths: Rocks are almost exclusively members of the spinel-lherzolite-harzburgite-dunite suite with spinel-lherzolite being by far the most abundant rock type. Some of the characteristic ultramafic xenoliths are described below:

Garnet-spinel-websterite: This rock consists of clinopyroxene (60 vol.%), orthopyroxene (30 vol.%), 5–10% spinel and minor amounts of garnet and opaques. Texture is granoblastic and clinopyroxenes show extensive exsolutions of orthopyroxene, spinel and garnet. All the garnet present has apparently exsolved from clinopyroxene.

Hornblende-spinel lherzolite: This is a typical equigranular granoblastic rock with dispersed greenish-brown titanium pargasites. Close to the hornblendite contact there are large sheets of phlogopite and a zone of large clinopyroxene crystals.

Hornblendite: consists almost exclusively of coarse grained (ca. 1 cm) titanium pargasite which has a tendency to form equilibrium triple points. Sulfides (now oxidized) are generally present as droplike inclusions within large amphibole crystals. Olivine (round inclusions in amphibole) and phlogopite (intergranular) are rare and irregularly distributed.
Amphibole lherzolite: medium grained; typical equigranular granoblastic; green spinel; clinopyroxenes have sometimes orthopyroxene exsolution lamellae; brown titanium pargasite is located around spinel grains. The overall mineral chemistries are indistinguishable from normal amphibole-free lherzolites. The amphibole has low K-content suggesting that it was formed late by H_2O-metasomatism.
Coarse grained lherzolite: This is part of the normal dunite-lherzolite series. Spinels are brown and both clino- and orthopyroxenes have exsolution lamellae. The rock is slightly deformed and some small scale fine-grained recrystallization have developed at grain boundaries.
Coarse-grained harzburgite: is part of the normal dunite-lherzolite series with dark brownish-red spinels and ganoblastic texture.

Modal mineral composition

Based on electron microprobe analyses of minerals and bulk analyses of rocks the modal contents of olivine, orthopyroxene, clinopyroxene, amphibole and spinel in the Kapfenstein xenoliths were calculated (KURAT et al., 1980). The harzburgite xenolith consists of 83.4 vol.% olivine, 13.7 vol.% orthopyroxene, 2.2 vol.% clinopyroxene and 0.6 vol.% spinel; whereas the different types of lherzolites (described above) contain 57.2 – 76.4 vol.% olivine; 14.4 – 30.2 vol.% orthopyroxene, 7.9 – 14.2 vol.% clinopyroxene; 1.2 – 4.2 vol. % spinel and in the amphibole-bearing lherzolites, 0.8 – 6.6 vol.% amphibole.

Chemical composition of the host rock and xenoliths

Basanite: The Kapfenstein basanite is very similar in composition to several nepheline basanite lavas from the Styrian volcanic arc. Major and trace element contents are presented in Table 1 (taken from KURAT et al., 1980). The La/Yb ratio for the Kapfenstein basanite is very high (Fig. 4). This is due to stronger enrichment of light rare earth elements (LREE) relative to the heavy rare earth elements (HREE). Since the Mg/(Mg+Fe) ratio of the Kapfenstein basanite (0.63) and its Ni and Co content are high, the strong LREE enrichment cannot be attributed to fractional crystallization but rather indicate a primitive liquid derived by a small degree of partial melting of the upper mantle rocks (KURAT et al., 1980). The high degree of REE fractionation clearly places the site of melt generation into the deeper parts of the upper mantle where garnet peridotites are stable (KAY & GAST, 1973).

	Kapfenstein	Gerce	Szentbekalla	Szigliget	Bondorohegy
Total sample/N/	38	112	138	113	85
Protogranular & protogranular-porphyritoclastic	100	10	67	31	31
Porphyroclastic	-	81	-	-	-
Equigranular	-	5	14	65	25
Granoblastic tabular	-	-	-	-	37
Poikilitic	-	4	19	4	7

Table 2

Percentage abundance of xenolith textural types of the Transdanubian Volcanic Region (after KURAT et al., 1991).

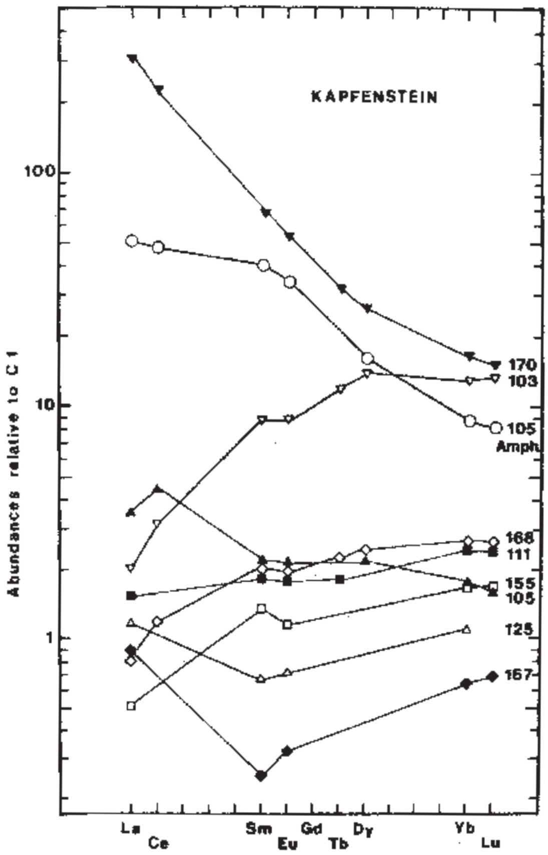

Fig. 4
REE pattern (normalized to C1) of samples from Kapfenstein, Austria (from KURAT et al., 1980). 170: host basanite; 103: websterite; 168, 111, 155, 105 and 125: lherzolites; 167: harzburgite.

Spinel-lherzolite-harzburgite main series: The major element composition of spinel lherzolite and harzburgite xenoliths from all over the world is similar (MAALØE & AOKI, 1971) and varies in between narrow limits. Comparison of the lherzolite suite from Kapfenstein with data for xenoliths from other localities reveals some remarkable features of the Kapfenstein samples:

i) Most Kapfenstein samples have extremely low K contents (ca. 10 ppm). Based on the low concentration of K in the xenoliths even minor contaminations of the Kapfenstein xenoliths by the host basanite is improbable.

ii) Spinel lherzolite has the lowest Mg/(Mg+Fe) ratio and the highest Al and Ca contents of the Kapfenstein main lherzolite series. Its CaO content (3.04 %) is among the highest reported so far from lherzolites (KURAT et al., 1980). Except for a depletion of highly incompatible elements, this xenolith closely approaches the composition of postulated primordial mantle material (RINGWOOD, 1975; PALME et al., 1978).

Textures of xenoliths in the TVR

It has been widely recognized that textures of peridotite xenoliths in alkali basalts, lamprophyres, and kimberlites directly reflect the structural state of the upper mantle as well as ancient tectonic events and deformations (e.g. WITT & SECK, 1987 among others). Protogranular rocks are essentially undeformed, porphyroblastic, and equigranular; fluidal and disrupted textures represent progressively deformed states of the upper mantle (MERCIER & NICOLAS, 1975; HARTE, 1977). If one considers the geographic distribution and abundances of texture types across the TVR (Table 2) it becomes clear that this distribution is not random and shows characteristics similar to those noticed in the Massif Central by COISY (1977). In the external region of the TVR (below Kapfenstein) the upper mantle is essentially undeformed or only slightly deformed (dominance of protogranular textures), whereas in the internal region (Balaton, Hungary) both deformed (equigranular) and undeformed (protogranular) xenoliths occur. Porphyroclastic textures predominate in areas situated between the external and internal regions. Thus, the textures of upper mantle xenoliths from inside and outside the TVR seem to support the diapir model of EMBEY-ISZTIN et al. (1989, 1990).

Mineral chemistry of Kapfenstein ultramafic Xenoliths

The chemical variability of the rock-forming minerals corresponds to that observed in peridotite xenoliths from many other localities. Thus, the composition of olivine varies between Fo 89-92.5, NiO between 0.3-0.4 wt.%, CaO 0.03-0.08 wt.%. Most orthopyroxenes of Kapfenstein xenoliths have CaO contents between 0.6-0.9 wt.%. The composition of spinels exhibits the greatest chemical range (Cr-number 6-59; mg-number 57-78). Amphiboles have generally pargasitic compositions and appear to be equilibrated with the coexisting phases except in some samples where amphibole compositions vary from grain to grain and with distance from the hornblendite vein.

In Figs 5, 6 & 7 some mineral chemical data for olivines, spinels, and clinopyroxenes respectively from Kapfenstein are compared with those from other TVR localities. The frequency distribution of Fo-contents (Fig. 5) shows a regular unimodal pattern with a pronounced peak in the case of Kapfenstein xenoliths but a flat distribution pattern for the rocks of other TVR occurrences. The mg-cr diagrams (Fig. 6) show that the compositional variability of spinels falls within the limits for xenolith spinels of world-wide occurrences as given by IRVINE (1967), however, the higher proportion of medium and high Cr spinels in the Hungarian xenoliths is evident. In contrast, the Kapfenstein peridotite xenoliths show a unimodal distribution with a predominance of low Cr spinels. In the Cr_2O_3-Al_2O_3 plot for clinopyroxenes (Fig. 7) the majority of the Kapfenstein xenoliths clusters between the lines representing $Al_2O_3 : Cr_2O_3$ ratios between 5 and 10, whereas the respective values are between 2 and 10 for xenoliths of other TVR localities. All these data indicate that the Kapfenstein xenoliths are much less fractionated than all other TVR xenoliths. Apparently, the undeformed xenoliths from Kapfenstein are mainly primitive and unfractionated.

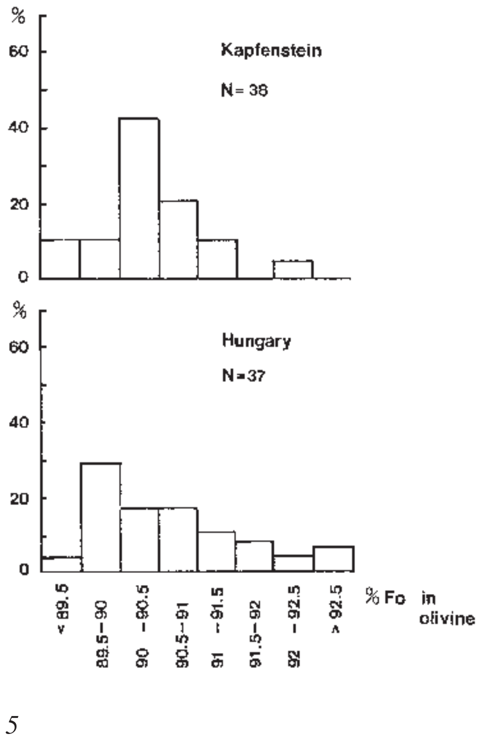

Fig. 5
Frequency distribution of molecular Fo-contents of xenolithic olivine from Kapfenstein and from Hungarian TVR localities (from KURAT et al., 1991).

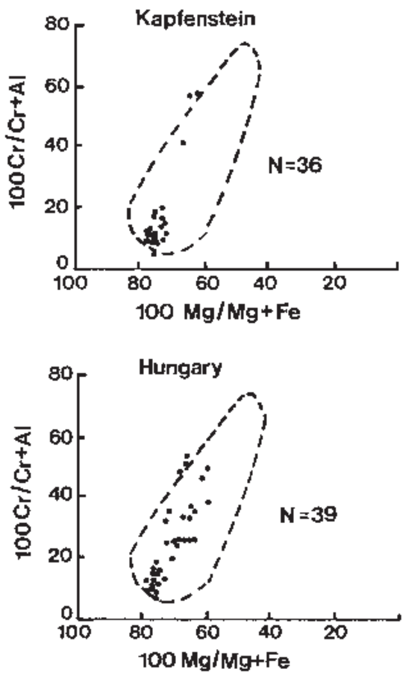

Fig. 6
Cr-number vs. mg-number in spinels from Kapfenstein and from other TVR localities (from KURAT et al., 1991).

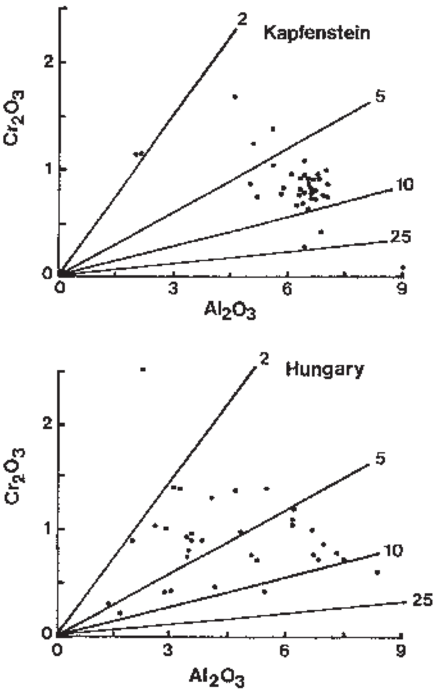

Fig. 7
Weight percent Cr_2O_3 vs. Al_2O_3 in clinopyroxenes from Kapfenstein and other TVR localities. Straight lines indicate different Al_2O_3/Cr_2O_3 ratios (from KURAT et al., 1991).

Crystallization temperature and pressure of the ultramafic xenoliths in the TVR

The frequency distribution of equilibrium temperatures (Fig. 8) also exhibits striking differences. Kapfenstein xenoliths show a very regular pattern and a maximum at the interval of 1000 – 1050°C using WELLS (1977) geothermometer. In contrast, the pattern is flat for the other samples. The P-T equilibrium (Fig. 9) conditions (VASELLI et al., 1996a) as derived by the single-pyroxene thermobarometry of MERCIER (1980) shows that the Hungarian xenoliths differ from the Kapfenstein xenoliths by a wider range in both P and T. While most equilibrium conditions for Kapfenstein xenoliths cluster between 15 and 20 kb at temperatures mostly about 150°C above the geotherm, those for the Hungarian xenoliths spread over a much wider P-T range.

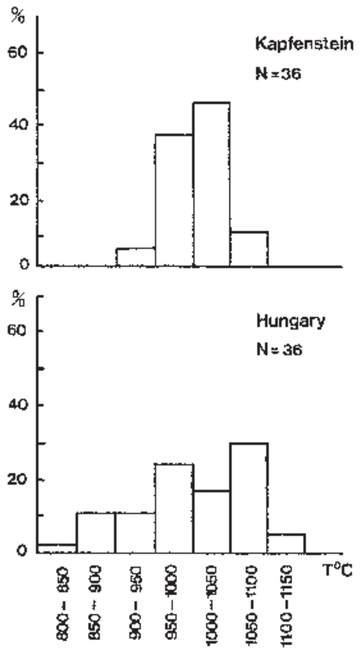

Fig. 8
Frequency distribution of equilibrium temperatures for Kapfenstein and for Hungarian TVR peridotite xenoliths (from KURAT et al., 1991).

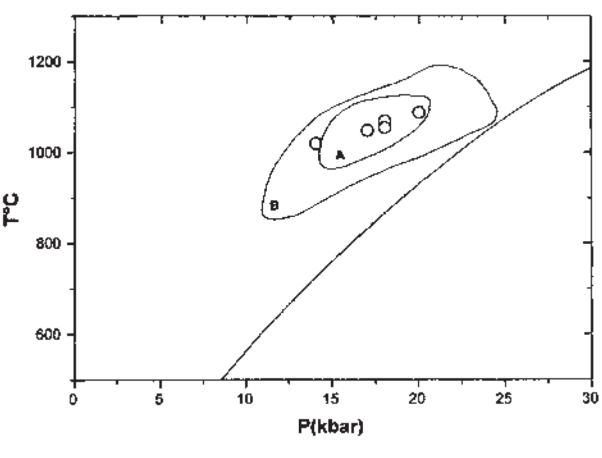

Fig. 9
Equilibrium P-T conditions for spinel-lherzolite xenoliths from Kapfenstein. Line indicates the oceanic geotherm of CLARKE & RINGWOOD (1964). A and B fields indicate ultramafic xenoliths from Kapfenstein and Central Hungary, respectively (from KURAT et al., 1991 and VASELLI et al., 1996a).

Petrogenesis

Petrological analyses of several ultramafic xenoliths from Kapfenstein, Austria, suggest that the upper mantle below Kapfenstein has been sampled by the basanite lava ca 50-80 km depth (KURAT et al., 1980). In spite of the large ca.30 km sampling profile, the upper mantle below Kapfenstein appears to be of rather monotonous composition with lherzolite being by far the most common rock type. Furthermore, these lherzolites generally show little variation in mineral composition which implies little variation in bulk composition for a large proportion of lherzolite samples. The overall range of modal composition reaches from lherzolite to dunite and is characterized by continuously changing mineral compositions. The most apparent variables are the Fe/Mg ratio of the silicates and the Cr content of spinel. The Cr content of spinels tends to systematically increase with decreasing Fe/Mg ratio of the silicates. Within these suite of rocks ranging from high $(Fe/Mg)_{ol}$ and low $(Cr/Al)_{sp}$ to low $(Fe/Mg)_{ol}$ and high $(Cr/Al)_{sp}$, bulk major, minor and trace element contents vary similarly in a regular manner. According to KURAT et al., (1980) this rock suite represents a residual sequence formed by different degrees of partial melting in the upper mantle ranging from a "primitive" lherzolite to a highly depleted harzburgite. Only very few samples bear evidence for local inhomogeneities as well as evidence for mobilization processes taking place within the upper mantle:

- i) the hornblendite represents a wet alkali-basaltic mobilisate which crystallized within the upper mantle. This basaltic mobilisate not only formed the hornblendite but also caused
- ii) a basalt metasomatism of a normal lherzolite which led to formation of the amphibolite lherzolite.
- iii) two amphibole-lherzolites give evidence for H_2O metasomatism taking place within the upper mantle. The overall bulk and mineral compositions of these rocks fit perfectly the normal lherzolite-dunite sequence. Amphibole in these samples has been formed by reaction of spinel with clinopyroxene and water.
  No contamination of these samples by larger amounts of incompatible elements is detectable. Thus, addition of solely water to normal lherzolite, causing formation of amphibole characteristically poor in K, is responsible for the formation of these rocks.
- iv) the garnet-spinel websterite sample provides evidence for the formation and trapping of tholeiitic liquids within the upper mantle below Kapfenstein.

Investigations of trace element distributions between different minerals not only revealed that the lherzolite-dunite series is indeed a depletion series but also showed that several trace element distribution coefficients are strongly dependent on equilibration temperature. The bulk composition of Kapfenstein xenoliths varies from depleted mantle harzburgites to scarcely depleted spinel lherzolites, and geochemically and isotopically they are rather heterogeneous. Geochemical and textural similarities to xenoliths from the Persani Mts (Eastern Transylvanian Basin, Romania) suggest similar deformation, depletion and enrichment processes in the mantle underlying these two areas. The Styrian Basin is on the westernmost edge of the diapiric upwelling which geophysical investigations indicate is centered in the Balaton region of the TVR.

Thus it is not surprising that the deformation and geochemical signatures of the Styrian Basin lithospheric mantle resemble those found in the easternmost edge at Persani Mts. (VASELLI et al., 1996a).

A metasomatic process that has taken place in the upper mantle beneath Southeastern Austria has been discussed by DOBOSI et al., (1999). Based on a LA-ICP-MS study of the different mineral phases of the ultramafic xenoliths, these authors derived a non-equilibrium trace element distribution between clinopyroxenes and concluded that a metasomatic event took place shortly before the rocks were delivered to the Earth´s surface. Thus, metasomatism and volcanic activity seem to be related and a consequence of the rising diapir underneath the Pannonian Basin. Several metasomatic events, probably related to fluids dominated by CO_2, water, or both were taking place. However, the intensity of that activity was generally low, as was the tectonic activity in the border zone of the Pannonian Basin.

References

BALOGH, K., EBNER, F. & RAVASZ, Cs. Mit Beiträgen von HERRMANN, P., LOBITZER, H. & SOLTI, G. (1994): K/Ar-Alter tertiärer Vulkanite der südöstlichen Steiermark und des südlichen Burgenlands. - Jubiläumsschr. 20 Jahre Geol. Zusammenarbeit Österreich-Ungarn, Teil 2, 55-72.

COISY, P. (1977): Structure et chimisme des peridotites en enclaves dans les basaltes du Massif Central. Modeles geodynamiques du manteau suprieur. Univ. Nantes, unpublished thesis, 115pp.

CSANTOS, L., NAGYMAROSY, A., HORVATH, F., KOVAC, M. (1992): Tertiary evolution in the Intra-Carpathian area: a model. - Tectonophysics, 208, 221-241.

DOBOSI, G., KURAT, G., JENNER, G. A. & BRANDSTÄTTER, F. (1999): Cryptic metasomatism in the upper mantle beneath Southeastern Austria: a laser ablation microprobe-ICP-MS study. - Mineralogy and Petrology, 67, 143-161.

EMBEY-ISZTIN, A., SCHARBERT, H. G., DIETRICH, H., POULTIDIS, H. (1989): Petrology and geochemistry of peridotite xenoliths in alkali basalts from the Trans-danubian Volcanic Region. - J. Petrol., 30, 79-105.

EMBEY, ISZTIN, A., SCHARBERT, H. G., DIETRICH, H. & POULTIDIS, H. (1990): Mafic granulite and clinopyroxenite xenoliths from the Transdanubian Volcanic Region (Hungary): implications for the deep structure of the Pannonian Basin. - Min Mag., 54, 463-483.

FRITZ, I.(1994): Gesteinsvariationen in einem Vulkangebiet der Oststeiermark am Beispiel Altenmarkt bei Riegersburg. - Matrixx, Mineralogische Nachrichten aus Österreich, 3, 73-81.

FRITZ, I. (1996): Notes on the Plio-/Pleistocene volcanism of the Styrian Basin. - Mitt. Ges. Geol. Bergbaustud. Österr., 41, 87-100.

HARTE, B. (1977): Rock nomenclature with particular relation to deformation and recrystallization textures in olivine-bearing xenoliths. - J. Geol., 85, 279-288.

HERITSCH, F (1967): Über die Magmenentfaltung des steierischen Vulkanbogens. - Contrib. Mineral. Petrol. 15, 330-334.

IRVINE, T. N. (1967): Chromian spinel as petrochemical indicator. Part 2. Petrologic applications. - Can J Earth Sci, 4, 71-103.
KAY, R. W. & GAST, P. W. (1973): The rare-earth content and origin of alkali-rich basalts. - J. Geol., 81, 653-682.
KOLLMANN, K., (1965): Jungtertiär im Steirischen Becken. - Mitt.Geol.Ges., 57, 479-632.
KOVAR-EDER, J. & KRAINER, B.(1990): Faziesentwicklung und Florenabfolge des Aufschlusses Wörth bei Kirchberg/Raab (Pannon, Steirisches Becken). - Ann.Naturhist. Mus.Wien, 91, A, 7-38.
KURAT, G. (1971): Granat-Spinel-Websterit und Lherzolit aus dem Basalttuff von Kapfenstein, Steiermark. - Tschermaks Mineral. Petrog. Mitt., 16, 192-214.
KURAT, G., KARCHER, A. & SCHARBERT, H. G. (1976): Petrologie des oberen Erdmantels unterhalb von Kapfenstein, Steiermark. - Fortschr. Mineral., 54, 53-54.
KURAT, G., KARCHER, A. & SCHARBERT, H. G. (1977a): The earth´s upper mantle below Kapfenstein (Eastern Styria, Austria). - Min. Soc. Bull., 34, 6.
KURAT, G., PALME, H. & SPETTEL, B. (1977b): Zur Geochemie des Erdmantels unterhalb von Kapfenstein, Steiermark. - Fortschr. Mineral., 55, 170-171.
KURAT, G., PALME, H., SPETTEL, B., BADDENHAUSEN, H., HOFMEISTER, H., PALME, C., & WÄNKE, H. (1980): Geochemistry of ultramafic xenoliths from Kapfenstein, Austria: evidence for variety of upper mantle processes. - Geochemica et Cosmochemica Acta, Vol. 44, 45-60.
KURAT, G., EMBEY-ISZTIN., A., KRACHER, A. & SCHARBERT, H. G. (1991): The upper mantle beneath Kapfenstein and the Transdanubian Volcanic Region, E Austria and W Hungary: A Comparison. - Mineralogy and Petrology, 44, 21-38.
MAALØE, A. & AOKI, K. (1977): The major element composition of the upper mantle estimated from the composition of lherzolites. - Contrib. Mineral. Petrol., 63, 163-173.
MERCIER, J-C. (1980): Single-pyroxene thermobarometery. - Tectonophysics. 70, 1-37.
MERCIER, J-C. & NICOLAS, A. (1975): Textures and fabrics of upper mantle peridotites as illustrated by xenoliths from basalts. - J. Petrol, 16, 454-487.
MURBAN, K.(1939): Die vulkanischen Durchbr¸che in der Umgebung von Feldbach. - Mitt. Abt. Bergb., Geol. u. Paläont. Landesmus. Joanneum, 3, Graz.
PALME, H, BADDHAUSEN, H., BLUM, K., CENDALES, M., DREIBUS, G., HOFMEISTER, H., PALME, C., SPETTEL, B., VILSCEK, E., WÄNKE, H., & KURAT, G. (1978): New data on lunar samples and achondrites and a comparison of the least fractionated samples from the earth, the moon and the eucrite parent body. - Proc. Lunar Sci. Conf. 9th, 25-57.
RINGWOOD, A. E. (1975): Composition and Petrology of the Earth´s mantle. 618 pp., McGraw-Hill.
ROSS, C. S., FORSTER, M. D. & MYERS, A. T. (1954): Origin of dunites and of olivine-rich inclusions in basaltic rocks. - Am. Mineral., 39,693-737.
SCHADLER, J. (1913): Zur Kenntnis der Einschlüsse in den südsteierischen Basalttuffen und ihre Mineralien. - Tschermaks Mineral Petrog. Mitt., 32, 485-511.
SCHNEIDER, I. (2004): Krusten und mantelxenolithe des Steierischen Vulkangebietes – Petrographie und Geochemie. Bakkalaureates-Projektarbeit, Universität Graz, pp.51.
SCHOKLITSCH, K.(1933): Beiträge zur Kenntnis der oststeirischen Basalte 2. Teil. - Cbl. Mineral.Geol.Paläont.Abt. A, 1933, 348-159, Stuttgart.

SIGMUND, A. (1899): Die Basalte der Steiermark. 6. Die Basalttuffe. - Tschermaks Mineral. Petrog. Mitt., 18, 377-407.
SZABO, C. S., HARANGGI, S.Z. & CSANTOS, L. (1992): Review of Neogene and quaternary volcanism of the Carpathian Pannonian Region. - Tectonophysics, 208, 243-256.
VASELLI, O., DOWNES, H., THIRWALL, M. F., VANNUCCI, R. & CORADOSSI, N. (1996a): Spinel-peridotite xenoliths from Kapfenstein (Graz Basin, Eastern Austria): a geochemical and petrological study. - Mineral.Petrol., 57, 23-50, Wien.
WELLS, P. (1977): Pyroxene thermometery in simple and complex systems. - Contrib Mineral Petrol, 62, 129-139.
WINKLER, A.(1913): Das Eruptivgebiet von Gleichenberg in Oststeiermark. I. Der Werdegang der Geologischen Forschung im Eruptivgebiet. II. Der geologische Bau der Region um St.Anna, Hochstraden, Klöch. - Jb.Geol.R.A., 53, 403-502.
WITT, G. & SECK, H. A. (1987): Temperature history of sheared mantle xenoliths from the West Eifel/West Germany: Evidence for mantle diaprism beneath the Rhenish Massif. - J. Petrol 28, 475-493.