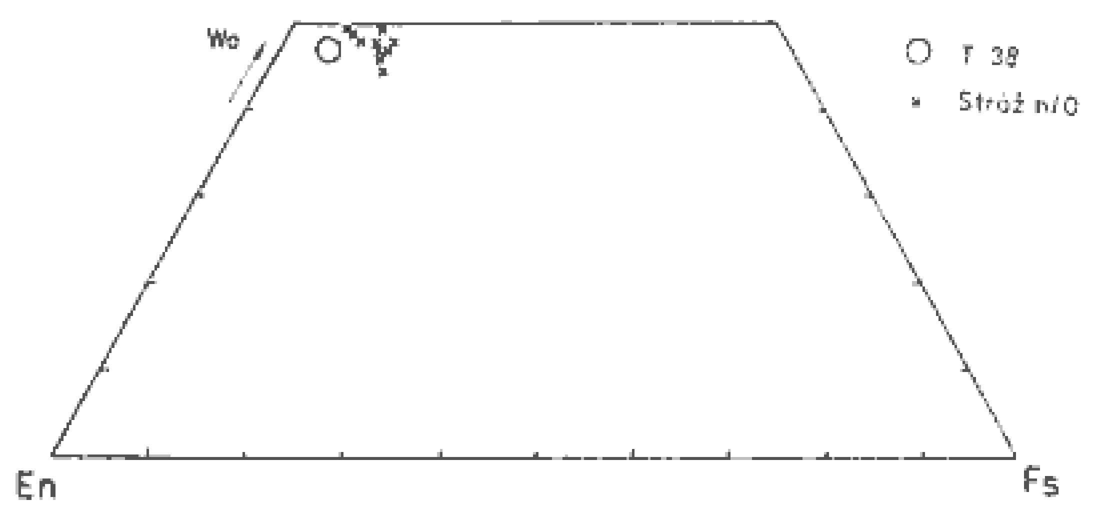

Fig. 5.4 *Chemical composition of pyroxenes, pyroxene-bearing granulites. Circle - field of the T38 borehole sample, cross - Stráž nad Ohří sample.*

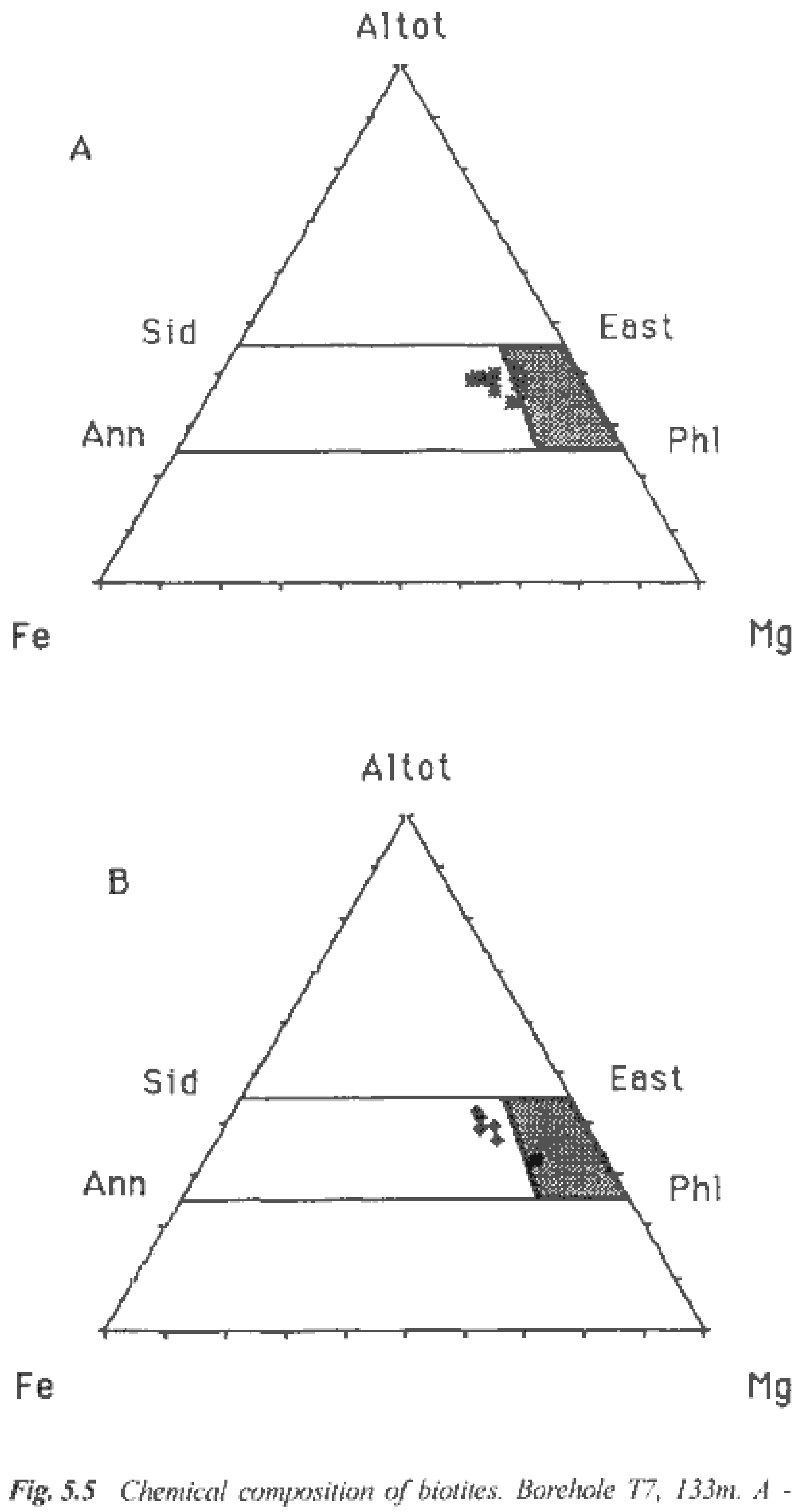

Fig. 5.5 *Chemical composition of biotites. Borehole T7, 133m. A - biotites at garnet rim, B - biotite inclusions in garnet.*

blende, actinolite, ferroan pargasitic hornblende, or edenite (after classification of Leake 1978).

Biotite

Biotites are generally strongly pleochroic, commonly with reddish tint reflecting high Ti content; many samples contain high amount of eastonite component, too.

Biotites in the foliation and static flakes in the matrix of metapelitic assemblages have high Mg/Mg+Fe ratios (0.63-0.83) and high TiO_2 contents (3.3-5wt%). Biotites adjacent to garnets and kyanites differ in lower TiO_2 contents (2.5-2.8wt%), and higher Al contents. Biotite inclusions in garnets are of two types: Ti-rich and Al-rich, respectively. Biotites from basic amphibole-bearing rocks have Mg# = 0.65-0.7, but low Ti contents (below 2wt%).

Muscovite

Muscovite in the rock foliation is phengitic, containing up to 3.34 Si p.f.u.. In the RPZ borehole felsic rocks, Si contents varies even within one muscovite grain (total range 3.13-3.21 p.f.u.). Muscovite grains associated with Ky have max. 3.15 p.f.u. Si. Fine-grained products of Ky breakdown contain as much as 3.1 p.f.u. Si. Muscovite forms even complete fine-grained pseudomorphoses esp. in felsic rocks, in some cases it recrystallizes in larger flakes.

6. Mantle assemblages

Investigated samples (courtesy dr. Fiala and own sampling) come from a 228m continuous ultrabasic rock sequence crossed by T7 borehole. Mineralogy, mineral chemistry and whole-rock chemistry of these rocks, described as wehrlites, dunites and eclogites, were studied by Fiala (1965), Rost & Grigel (1969), Kopecký & Paděra (1974) and Fiala & Paděra (1977, 1984).

The ultrabasic body from the T7 borehole is stratified, with predominant garnet lherzolites interlayered with dunites with or without garnet. The boundaries between lherzolites and dunites are sharp, the layer thickness ranges from a few centimeters to several tenths of meters (Kopecký & Paděra 1974). The least abundant rock type is garnet pyroxenite, that occurs in the lherzolites as small lenses, inclusions and layers of cm, and rarely dm size. The exception is a thicker body at a depth of 408-415 m.

6.1 Mineralogy and petrology

a) Lherzolites and dunites

Rock textures are characterized by generally completely recrystallized, rather homogeneous fine-grained (0.1-0.4mm) matrix, surrounding large garnet porphyroclasts. Large Opx, resp. Cpx and Ol porphyroclasts occur exceptionally, associated with garnets, resp. as inclusions in garnets in dunitic compositions. Deformation is concentrated in narrow zones with mylonitic texture (elongation of Sp grains) and pronounced serpentinization. Coronitic textures have been preserved in domains of low strain.

The mineral assemblage of the lherzolites is olivine, clinopyroxene, orthopyroxene, garnet, and serpentine, with minor phlogopite, magnetite, talc, chlorite, amphibole and calcite.

Dunites differ from the studied lherzolites by their lower contents of garnet (even missing) and pyroxenes. In contrast to lherzolites, spinel is rather abundant in these rocks. It occurs not only in the matrix, but also develops in kelyphitic coronas around garnets, which are absent in lherzolites.

Olivine

Olivine is the major phase of the matrix of the two rock types. In lherzolites, it occurs just in form of fine-grained (O.1 mm) neoblasts of homogeneous composition (Fo_{90}). In dunites, olivine porphyroclasts either in matrix (less commonly forming clusters) or included in large garnets are also present. The inclusions are generally completely serpentinized. The composition of neoblasts and inclusion in garnet is similar (Fo_{92}, Fiala & Paděra 1977; FP77).

Symplectite (coronas)

Coronas consisting of garnet II, spinel and clinopyroxene II can be observed around some garnet porphyroclasts exclusively in dunites (described by FP77). The outer rim of the symplectites is formed by orthopyroxene, generally coarser-grained than the orthopyroxene neoblasts in the matrix, the inner zone by fine-grained filamental intergrowth of pyroxene and spinel. More common are symplectites in which spinel dominates over pyroxenes, without any new garnet. Another, rarer type of symplectite has a dark brown colour, and presumably consists of a fine-grained pyroxene. At places, garnets are completely consumed by symplectites.

In lherzolites, garnets are commonly rimmed by a continuous corona of chlorite, with pyroxene relicts, talc and amphibole at the outer side, at places relatively abundant.

Pyroxene

Clinopyroxene and orthopyroxene neoblasts (in the ratio cca 2:1) occur randomly in the lherzolite matrix, and have the composition of jadeitic diopside (X_{Mg} = 0.76-0.81, Jd = 15-17 mol%) and enstatite (En = 87-88 mol%), respectively. The cores of clinopyroxene grains are in some cases slightly depleted in Ca with respect to the rims. Jd contents in cores and rims are rather constant.

In dunites, pyroxenes are also involved in symplectites as described above. Clinopyroxenes from symplectite are slightly enriched in Al and depleted in Fe compared to the matrix ones; their composition corresponds to endiopside (wet anal. of FP 77). Orthopyroxenes from matrix and from symplectite differ only slightly in composition (i.e. Mg/Mg+Fe) and are close to enstatite. Compared to the lherzolites, clinopyroxene neoblasts are enriched in Cr ± Ca and depleted in Fe, Al and Na. Lherzolite Opx is somewhat richer in Fe and poorer in Mg (FP77).

Orthopyroxene porphyroclasts (up to 1.5 cm in size) are associated with some garnets in dunites. A larger clinopyroxene grain containing exsolution lamellae of spinel was found as an inclusion in garnet. In the matrix, rare grains of green Cr-diopside occur.

Garnet

In lherzolites, deep red garnet porphyroclasts (up to 4mm in size) are pyrope - almandine - grossular solid solutions (69-72 mol% Prp, 17-19 mol% Alm, 3-5 mol% Grs, up to 1mol% Sps). The Cr_2O_3 contents is 2.0-2.6% (2-4% according to wet chemical analyses in Fiala 1965). They are zoned, with homogeneous cores and a slight increase in Fe+Mn and decrease in Mg+Ca at the narrow rim (Fig. 6.1). Orange-red garnets (up to 2 cm) described by Fiala (1965) are according to him relatively depleted in Cr (ca 1 wt % Cr_2O_3).

In dunites, garnet occurs as large (up to 2 cm) porphyroclasts. Small garnet II is associated with spinel and pyroxene in symplectite surrounding these porphyroclasts. These garnets are depleted in Cr and enriched in Al and Fe relative to the large ones - their composition is according to Fiala & Paděra (1977) similar to those of lherzolites. Garnets from lherzolites analysed during this work, however, are poorer in Cr compared to these GrtII. The above authors did not observe any chemical zonation in garnets.

Spinel

In lherzolites, minor spinel occurs just in the rock matrix, forming either isometric oval grains or elongated grains in zones of higher deformation.

In dunites, spinel grains occur in symplectites as well as in the matrix. Their size increases with increasing distance from the large garnet, and reaches up to few mm in matrix. At the same time, their composition changes, becoming lower in Cr, Ca and Fe^{2+} and higher in Mg and Fe^{3+}. Al and Ti values fluctuate. All spinels are ternary solid solutions of $MgCr_2O_4$-$FeCr_2O_4$ (chromite) and $MgAl_2O_4$ (spinel)(anal. in FP77).

Chlorite, amphibole, talc, and phlogopite

occur in minor amounts, largely at garnet rims (especially in lherzolites). Chlorite, amphibole and talc represent products of pyroxene breakdown reactions. Greenish colour of talc/chlorite observed in dunites reflects higher Cr-contents.

Serpentine

is very abundant, forming a dense network in the rocks.

Magnetite and ilmenite

are accessories.

b) Garnet pyroxenite

Apart from bimineral (Grt-Cpx) assemblages that contain only minor amounts of biotite or amphibole, rocks with significant amounts of phlogopite and amphibole were observed (see also Fiala & Paděra 1977, Kopecký & Sattran 1962). Common accessories are kyanite, zoisite, rutile, ilmenite and chlorite.

The rocks are heteroblastic, with large garnet porphyroblasts (up to 1.5mm) surrounded by a medium to coarse-grained matrix consisting mainly of clinopyroxene; phlogopite and amphibole form larger crystals. The minerals display no preferred orientation. The rocks bear signs of heterogeneous rather brittle deformation, resulting in fine-grained recrystallization in more strained zones and development of generally subparallel fractures in garnet, or even garnet disintegration.

Following description refers mainly to a bi-mineral rock sample, with minor amounts of biotite and amphibole (depth 404m).

Clinopyroxene

All the clinopyroxenes have quite uniform omphacitic composition, with X_{Mg} = 0.53-0.58 and X_{Jd} = 0.28-0.33 (Fig. 6.1). One inclusion of clinopyroxene in garnet shows compositional zoning with slight Fe depletion and Mg enrichment of the rim. Grains in the matrix are unzoned. As the only difference in composition, Fiala & Paděra (1984) mention higher Na contents in the matrix clinopyroxenes than in the clinopyroxene inclusions in garnet.

Garnet

Garnets contain 42-53 mol% Prp, 24-30 mol% Alm and 22-30 mol% Grs (this work, Fig. 6.2). X_{Sps} does not exceed 0.9 mol%. Compositional zoning of garnets is characterized by an increase in MgO from core to rim, and its decrease close to the rim, compensated by FeO. The Ca profile is rather flat (Fig. 6.3).

Garnets contain inclusions of rutile, clinopyroxene and phlogopite; Fiala & Paděra (1984) describe also amphibole and zoisite, usually concentrated in the garnet cores.

Amphibole, biotite, chlorite, zoisite

Analysed amphibole (this work, and Fiala & Paděra 1984) is pargasitic hornblende (according to the classification of Leake 1978). Composition of chlorites corresponds to penninite and talc-chlorite (classification of Hey 1954).

Biotite composition corresponds to phlogopite.

Zoisite occurring in minor amounts in the matrix and included in garnet contains only small Fe admixture (Fiala & Paděra 1984).

6.2 Paragenetic evolution

a) Garnet lherzolite and dunite

Presence of successive equilibrium assemblages and reaction textures are consistent with the polyphase evolution of the rocks. The early stage of the evolution is marked by the mineral assemblage

olivine I + orthopyroxene I + clinopyroxene I ± spinel I

the relics of which were observed exceptionally in dunitic rocks (Sp as exsolutions in pyroxene) (stage I).

The mineral assemblage of the stage II

olivine II + orthopyroxene II + clinopyroxene II + garnet I

is characteristic of lherzolitic compositions, where no early minerals neither newly formed symplectites are present. However, garnet and spinel, respectively spinel-bearing coronas developed in dunitic rocks, which reflects a change in P-T conditions. Cr-rich garnet breakdown according to the reaction

Cr-Grt I + Ol II = Grt II + Cr-Spl II + Cpx III + Opx III (13)

gave rise to the stage III assemblage

olivine III + orthopyroxene III + clinopyroxene III + garnet II + spinel II,

and successive reaction

Grt II + Ol III = Cpx IV + Opx IV + Spl III (14)

to the stage IV one:

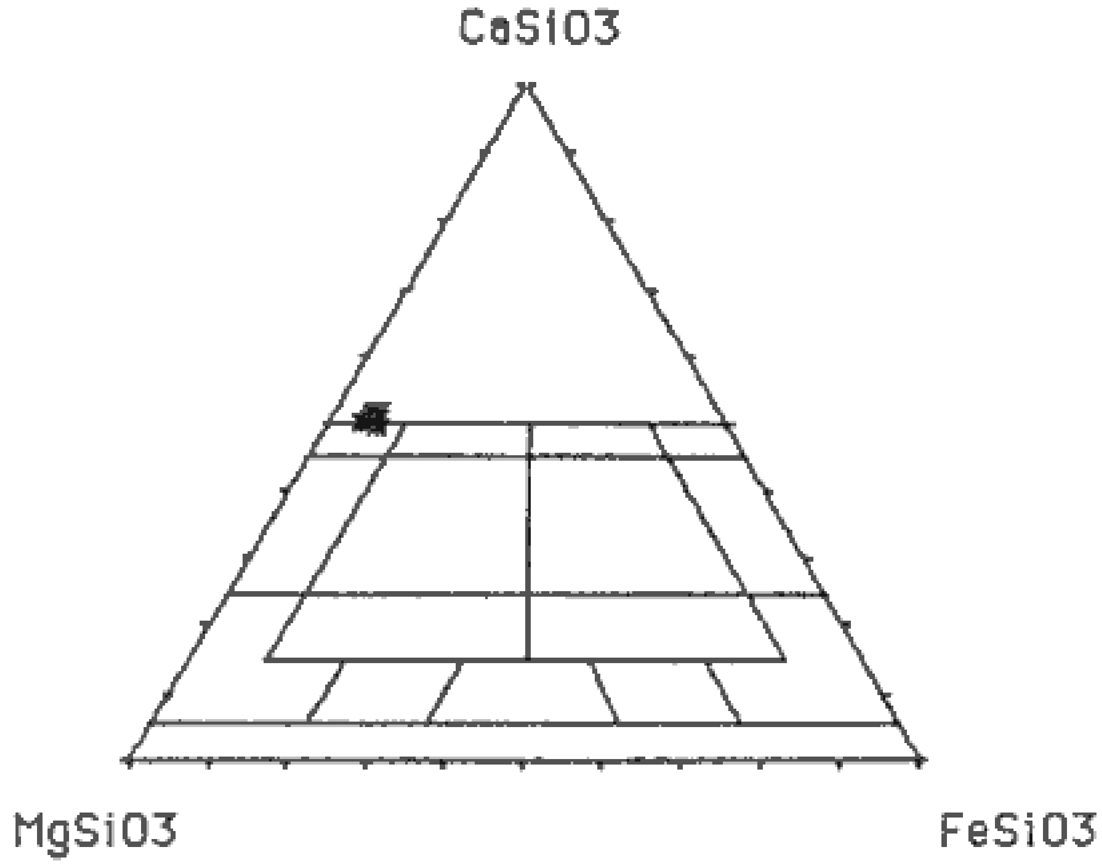

Fig. 6.1 Chemical composition of pyroxene, garnet pyroxenite. Borehole T7, 404m.

olivine IV + orthopyroxene IV + clinopyroxene IV + spinel III.

The further rock evolution can be traced based on hydration reactions, which document the retrograde metamorphic conditions accompanied by increase of water activity.

Chlorite coronas around garnets reflect reaction

Opx + Grt + H_2O *= Chl (+ Cpx)* (15)

or

Opx + Spl + Ol + H_2O *= Chl* (16)

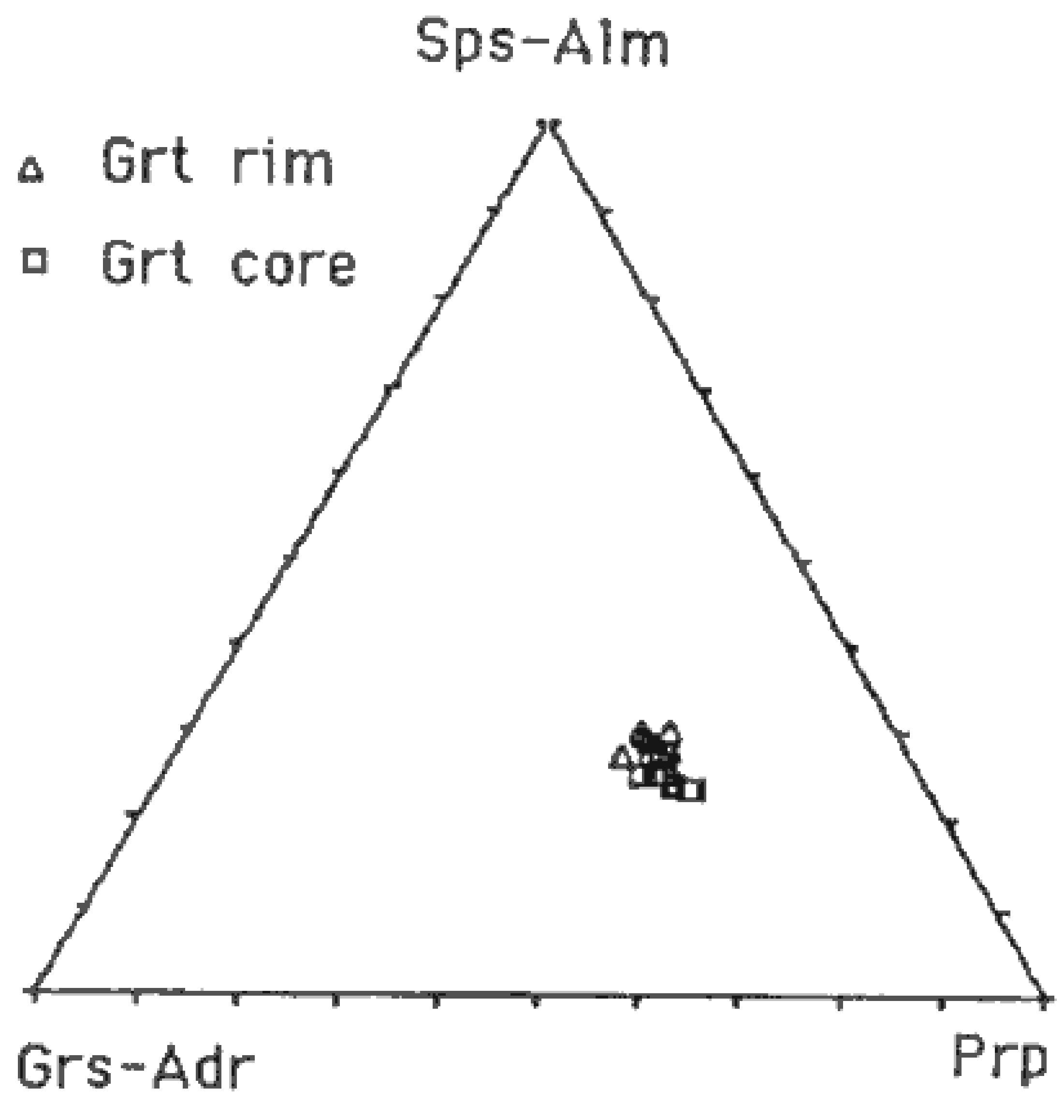

Fig. 6.2 Chemical composition of garnets, garnet pyroxenite. Borehole T7, 404m.

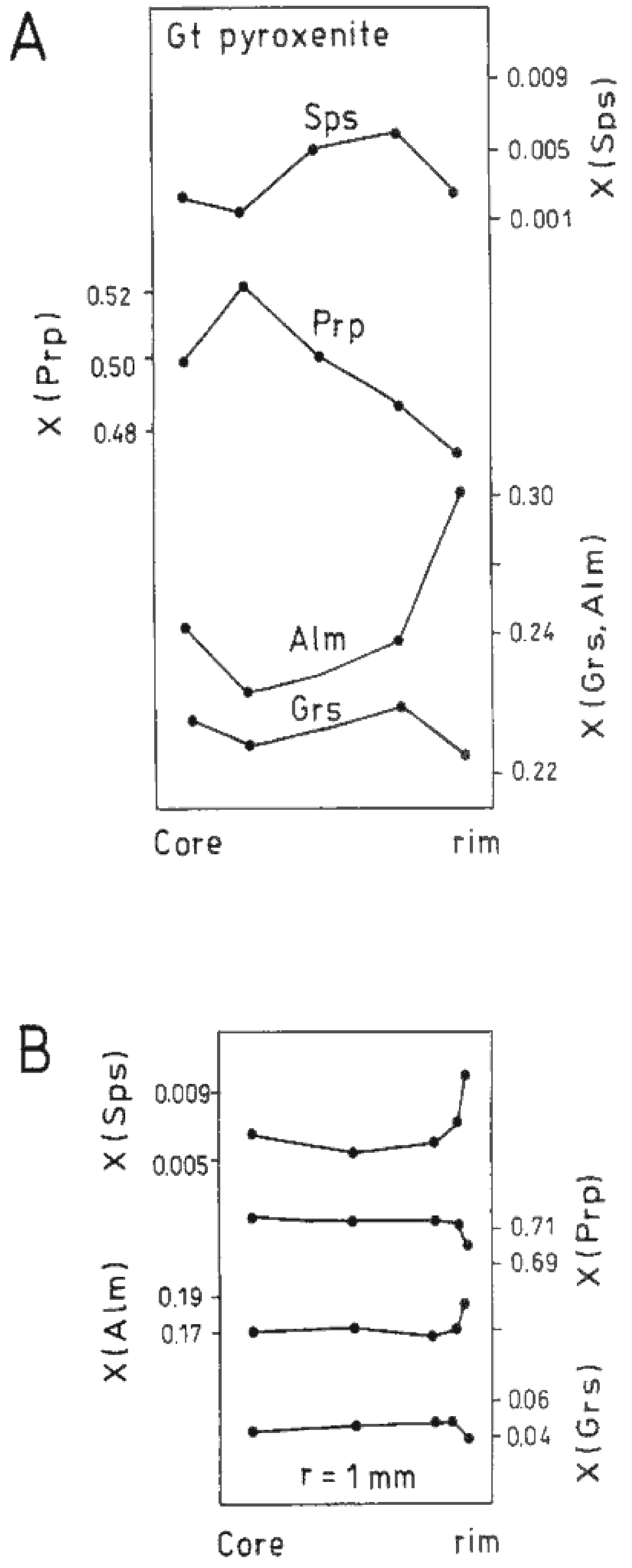

Fig. 6.3 Zonation of garnet - A garnet pyroxenite, B garnet lherzolite. Borehole T7.

Formation of amphibole ± talc at the expense of orthopyroxene at presence of olivine according to the reaction

$$orthopyroxene + H_2O = amphibole + olivine \quad (17)$$

followed by the reaction

$$orthopyroxene + H_2O = talc + olivine \quad (18)$$

is not so widespread.

Reactions (15) to (18) result in development of the assemblage amphibole-chlorite (stage V-a)

and

amphibole-talc-chlorite (stage V-b)

Abundant serpentine was produced by olivine breakdown reaction

$$olivine + H_2O = serpentine + ilmenite\ (magnetite) \quad (19)$$

so that the late stage VI is represented by the assemblage amphibole-chlorite-serpentine.

The use of petrogenetic grid established by Jenkins (1981) allows to trace the evolution from the garnet to spinel lherzolite stability field, corresponding to high temperature decompression. Significant cooling is indicated by transition from spinel lherzolite through chlorite lherzolite, chlorite-talc-amphibole and chlorite-amphibole-antigorite peridotite fields. This corresponds to development from eclogite to granulite and amphibolite-facies conditions.

c) Garnet pyroxenite

The primary assemblage garnet+clinopyroxene+rutile+quartz is well preserved. Pargasitic hornblende can be stable up to very high temperatures, and is considered as a primary phase (see also Fiala & Paděra 1984). No symplectites develop at the expense of clinopyroxene. However, this does not rule out the possibility of the high-temperature retrogression (studied in eclogites - Boland & van Roehrmund 1983, Joanny et al. 1991), as pyroxenes are low-Jd ones.

7. Geochemistry of granulite facies rocks

The rock set (set I) analysed for major and trace elements comprises samples from all the areas A, B and C. The major element contents were determined by the wet chemical analysis, trace element abundances including rare earths by XRF, AAS, SPA and ICP (for REE) methods. Analyses were performed in the laboratories of the Czech Geological Survey, Prague (see Appendix III, V).

The concentrations of Th, U and K (gamma-spectrometric method in the radiometric laboratory of the Geophysical Institute, Czechoslovak Academy of Sciences) together with some other elements (XRF method) were determined for another set of samples (Set II, courtesy Dr. Fiala, Dr. Vaňková; Appendix IV).